Economics of Atmospheric Stabilization
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To talk about the climate policy, there are four questions to ask:

- Who is responsible for climate change?
- Why should we worry about the increase in the global mean temperature?
- Can we avoid worst climate change at a low cost?
- What institutions do we need to deal with this problem?

All the different projections of global mean temperature have demonstrated that there has been an increase in temperature in the last several years especially since 2000.

There are several potential policy-relevant tipping elements that could be triggered by global warming in this century. These include melting of Arctic summer sea ice, Greenland ice sheet, and west Antarctic ice sheet; dieback of Amazon rainforest and Boreal forest; instability of Indian monsoon and Sahara/Sahel and West African monsoon; El Nino southern oscillation amplitude, and Atlantic meridional overturning circulation. The tipping points are an important source of concerns because they may bring inequilibrium and imply that we are facing non-linear and high risk issues. What we need is to limit the increase of the temperature.

On comparing carbon debt and monetary wealth for various countries, regional data and analysis show that the relationship between carbon debt (as expressed by carbon emissions per person from fossil fuel burning) and wealth (as expressed by capital stock per person) is highly related. The carbon debt and wealth have a one to one relationship. There is a trade-off between economic growth and climate change. The critical question is: Who has to sacrifice economic growth in order to achieve climate stabilization? Do we have solutions at hand to decouple economic growth from climate change?

Let us start with the Kaya identity (AKA Kaya decomposition):

$$CO_2 \textit{ Emissions = Population (Pop) x Per Capita Production (GDP/Pop) x Energy Intensity (E/GDP) x Carbon Intensity (}CO_2\textit{/E) x }CO_2\textit{ Released (}CO_2\textit{ (A) / }CO_2\textit{).}$$

Solution space includes life-style change technologies, non-fossil energy, and CO_2 capture at plant (CCS), carbon cycle and management, radiative forcing, radiation management (i.e. geo-engineering), ocean acidification, and adaptation to changes. Measures to decrease carbon intensity include substituting coal and oil by natural gas, which is a limited option. Coal, tar sands, and oil shale are abundant; substituting fossil fuels by renewable energy (biomass, wind, solar thermal, PV), nuclear energy (thermal reactors, fast breeders), hydropower (limited potential), and carbon capture and storage. New storage technologies open new potentials to integration, for example, concentrating-solar-thermal-power-plant with molten salt thermal storage system with 7 hour capacity (bridging nights). Carbon sequestration options through terrestrial sequestration, power station with CO_2 capture, geologic disposal, chemical conversion, and deep saline formation. Various geo-engineering options and carbon management include aerosols in stratosphere, iron fertilization of sea, giant reflectors in orbit, chemicals to save ozone, cloud seeding, grow trees, genetically engineered crops, greening deserts, pumping liquid CO_2 to the deep sea, and pumping liquid CO_2 into rocks.

Science is not clarified yet in terms of assessment of controlling the radiation balance. If geo-engineering can work, it will transform the climate debate substantially: The climate problem can then be solved unilaterally. However, geo-engineering might then resemble the arms race problem. Are there limits to adaptation? Are Dutch cows ready for sea-level rise?

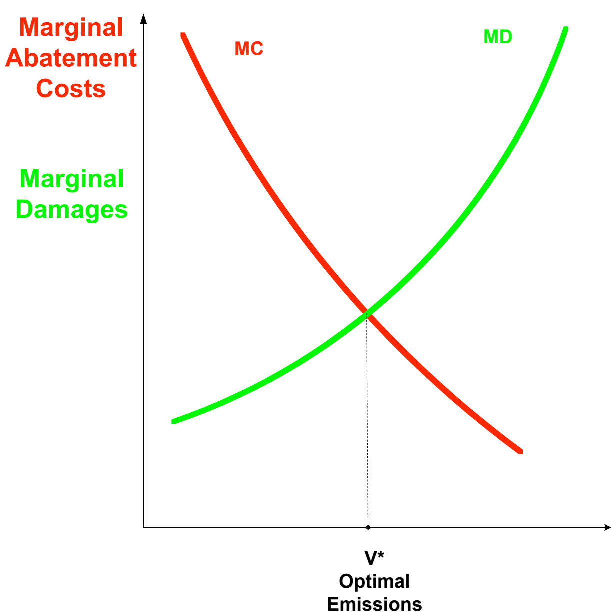
How to assess the solution space? What are unintended consequences of the different solutions? Do we have all tools to analyze and evaluate the "solution spaces"? Answer is not yet. Need to look at the whole "solution spaces." Economists invented three tools for identifying acceptable portfolios of options:

- Cost-benefit analysis
- Cost-effectiveness analysis
- Multi-criteria analysis

The publication of Mckinsey (2009), *Pathway to Low Carbon Economy*, assessing costs of various mitigation options is an example of cost-benefit analysis, in which it lists from most efficient technology to the highly cost technology.

However, Prof. Edenhofer argues that the conventional cost-benefit analysis is not suitable and thus should not be applied to the analysis of the climate change problems.

Cost-benefit analysis finds the point where marginal abatement equals the marginal damages and leads to efficient pollution! But this analysis not relevant when optimal emissions rate is zero!



The intersection of the MC and MD curves above determines the level of the optimal emissions.

Efficient pollution versus efficient abatement:

Benefits from emissions = costs of abatement
Benefits from abatement = avoided damages

- When adaptation increases, the MD curve shifts downwards, given other things equal, the optimal emissions shift from V* to V** (increased).

Cost-Benefit Analysis and Stock Pollutant:

$$\frac{\partial D}{\partial V_i}\left(\frac{\alpha}{\alpha + r}\right) = \frac{\partial R_i}{\partial V_i}$$

For $\alpha \to 0,\ V^* \to 0$

where α - natural decay rate.

Discounting future: If a -> 0, V* -> 0 then the cost-benefit analysis cannot be applied.

- With lower decay rate, the MD curve shits to the left, for each emission, the marginal damage is higher, the optimal emissions shift from V* to V** (decreased).

Discounting issue is very important for cost-benefit analysis. Debate on this has generated much more heat since Stern Review published!

- With lowered discount rate, the MD curve shifts to the left, for each emission, the marginal damage is higher, the optimal emissions shift from V* to V** (decreased).

What can we learn from this simple model: first, the *discount rate* determines climate policy. However, the debate on discounting is driven by *ethical judgments*. This might be the reason why many economists are puzzled by this issue. Second, the assessment of *mitigation, damage and adaptation* costs determines also the climate policy ramp. This latter assessment is driven by *scientific insights*.

The debate on discounting: first, a low discount rate leads to more ambitious climate policy because as shown above, with lower discount rate, the marginal damage is higher. Second, however, it is not easy to justify a low discount rate. This is because inter- and intra-generational justice has to be taken into account and there is uncertainty.

Stern's welfare function is:

$$W = \int_0^\infty \frac{C^{1-\eta}}{1-\eta} e^{-\delta t} dt$$

where:

W = Welfare
C = Consumption

η = Intergenerational equity
δ = Pure rate of time preference (i.e. intergenerational fairness)

$$\eta = -\frac{\frac{\Delta U'}{U'}}{\frac{\Delta C}{C}}$$

The problem of ethical duality: both parameters determine the overall investment rate *i* in a simple Ramsey model:

$$r = \delta + a\eta$$

$$s = \frac{a+n}{\delta + a\eta}\beta$$

where:

r = discount rate
s = saving rate
a = labor productivity (or growth rate of the whole economy)
β = capital income share
n = population growth

$\delta\downarrow \rightarrow \eta\uparrow$: This is because δ = pure time preference rate which also reflects intergeneration fairness. $\delta\downarrow$ means that one cares about the equity of intergeneration, based on ethical duality, such a person, to be ethical consistent, should also care about the equity of the intra-generation, thus $\eta\uparrow$. As a result, they keep the discount rate $r = \delta + a\eta$ almost constant. In other words, the discount rate *r* has no impact on climate policy.

Arguments for low time preference: some economists argue that the assumption of *intergenerational equality* is ethically binding. This leads to an exactly zero pure rate of time preference δ. But even taking intergenerational equality as given, the exogenous risk of *civilizational extinction* might legitimate a small nonzero δ. However, as shown a low time preference rate does not justify a low discount rate. This implies that an option for more inter- and intragenerational justice does not lead to an ambitious climate policy.

Uncertainty: Subjective uncertainty about the growth rate *g* of consumption leads to smaller expected discount rates that can then be represented by risk aversion.

Capital Asset Price Models (CAP): The choice between the risk-free discount rate r^f and the risky rate r^E depends on the correlation β between mitigation investments and the growth rate of consumption *g*. To what extent are mitigation options correlated to economic growth? The CAP tells us that the choice of appropriate discount rate is an empirical issue.

Risk-free discount rate

$$r^f = \delta + \eta\mu - \frac{1}{2}\eta^2 s^2$$

Risky Discount Rate

$$r^E = \ln E[R^E]$$

where: r^E is the gross arithmetic return on equity.

The relevant discount rate for climate policy is:

$$r = -[\ln(\beta \exp(-100r^E) + (1-\beta)\exp(-100r^f)]/100$$

(Benefits 100 years from now).

Lessons Learned from CAP: Using historical data

$\beta = 0 \Rightarrow r = r^f = 1\%$
$\beta = 1/2 \Rightarrow r = 1.7\%$
$\beta = 1 \Rightarrow r = r^E = 7\%$

We found that

- Interestingly, the discount rate for medium values of β is much smaller than what could be expected from a linear relationship.
- This could be used to argue for smaller discount rates and thus for more stringent mitigation action.
- Finally, the CAP tells us that the choice of the appropriate discount rate is an empirical issue.

What we have learned are (i.e. the implication of ethical duality):

- If both ethical parameters are chosen in a proper way, ethics basically has no impact on climate policy. Thus need to take ethics out of picture, otherwise, no way to justify aggressive mitigation actions. The arguments between Stern/Nordhaus over choice of discount rate is irrelevant; if choose terms in equations consistently, ethics has no impact on decision.
- The information required to determine h in all its roles is not available.
- Ethics is not of much help to resolve the discounting issue.
- It is much more important to understand the nature of damage and mitigation costs.

However, cost benefit analyses can be problematic because of kinks in marginal cost curve (due to tipping points in climate system). At the tipping points, the marginal damage (MD) curve becomes vertical which are at the tolerable emissions.

Prof. Edenhofer argues for choosing concentration target with certain probability, then trying to generate most inexpensive scenarios possible to reach target. The reasons for a target approach to be justified are: Climate change might activate tipping points and the basis for calculating the social costs of carbon is weak.

Technological change will shift the MC curve downwards which makes the marginal abatement costs lower for every level of emissions and leads to a new optimal emissions to move from E* (the tolerable emissions) to a lower level E** (the optimal emissions).

Multiple Equilibrium and Non-Convex Optimization

There is no reason why there should be one equilibrium only. Several options are along the curve. It is purely speculative about the adaptive curve shift because so many parameters are not known yet. This is the way many economists think about. Only the points E1 and E2 are stable at the high cost and the low cost. Point in between the low cost and the high cost are unstable.

The Economics of Atmospheric Stabilization: Three stabilization targets with different probabilities to reach the 2° target: 550ppm-eq, 450ppm-eq, and 400ppm-eq. This is an empirical question but not ethnic issue.

β = is the covariance of the market

We should stop debating the ethics issue. By the end is the issue of how technology will allow us to reduce the carbon emissions.

The model REMIND: Energy system model coupled with macroeconomic model. One scenario shows that discount rate plays an important role in rate of technological change. High discount rates penalize “learning” technologies, i.e. most renewables. (Investors want returns in near future with higher discount rates.)

There are many models, with a lot of differences among them but also a lot of similarity among the models. It is better not to rely on only one model, need more models. We need integrated assessment tools to look at solution space. There is more than one path towards a carbon-free economy! 400 ppm can be achieved by all five different models (i.e. multiple paths possible to this target): REMIND, MERGE, TIMER, POLES, and E3MG. Renewables & biomass are important in all the models.

High discount rate, such as 3%, will penalize learning technology and causes under investment. Learning curve is externality which benefits for all others. Short-sight invests low and long-term perspective invests high in learning technologies. Both discount rate and future fossil fuel prices affect mitigation portfolio & total cost! Costs of crude oil and natural gas have been increasing very fast since about 1999, but price of coal also rising (but not as fast.) We are facing a renaissance of coal worldwide! Investments in exploration of oil fields are increasing, as well as investment in non-conventional sources.

There has been a remarkable decrease in energy intensity & carbon intensity (due to fuel switch) worldwide until 2000, but since then, both have been increasing! Only Europe has been able to reduce energy & carbon intensity in recent years. If oil price has larger increase than coal price, we will see ongoing renaissance of coal. Gas competes directly with goal, but gas price coupled to oil. Also, can a coal-to-liquid option can compete with oil? Gas is coupled to oil because of an institutional reason. Gas and oil are scarce, while coal is cheap and abundant.

If oil price stays high, will see renaissance of coal (oil price and natural gas price are correlated, and natural gas competes with coal; conversion of coal to liquids also a factor). Nuclear is beyond current baseline and not important climate mitigation option. The key message is that most of coal must stay underground; how to do this is important challenge for climate policy (supply side of problem currently neglected, demand side not enough to solve the problem.) There is a strong role for governments in levying taxes and subsidies to keep coal in ground. Need to take into account what does the availability of resources and look at their relative prices. Otherwise, China, and India will not take part in the negotiation process. In the end, we need to come up with price on CO2.

Mitigation costs: technology options for 550ppm target -> basically need CCS & high biomass potential to reduce costs.

Rent income of suppliers of coal has to be reduced substantially! It is the most important issue for climate policy (in Edenhofer's view). Most conventional oil could be used, but need to postpone extraction (can make a deal with oil producers.) The same is true with gas producers. Need to understand neglected supply side! How to convince gas/oil/coal suppliers to sacrifice their rent incomes? Climate policy based only on demand side will ultimately not be successful. Without dealing with coal issue, neither China nor India will become part of any global mitigation framework!

To solve climate problem, can't just rely on market. The market no long works to address this issue. Need strong role for government to intervene and additional subsidy. To solve climate issue cannot be achieved without government intervention.

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There is a great deal of debate about the best form of government intervention, how much it should cost, what that money should be spent on, and who should pay for it. Dr Edenhoffer's second lecture compared the strengths and weaknesses of different policy tools that could be used to reduce global carbon emissions. Edenhoffer concludes that a cap and trade scheme combined with a fixed global carbon budget is the best tool available.

When attempting to determine the socially optimal amount of resources to be spent on climate change mitigation, several factors make using a cost benefit approach less efficient than using a global carbon budget approach. A cost benefit approach sets the cost of one additional unit of abatement equal to the total global damages for the rest of time of one additional unit of emitted carbon dioxide. When there is a high level of confidence in the cost and damage curves, this is an efficient approach. However, in the climate system, the possibility of irreversible "tipping points" in the damage curve, where damages increase by a vast amount when some, possibly unknown threshold is crossed make calculating the damages for a given level of carbon much more risky. Additionally, the possibility of technological change could reduce the marginal cost of abatement, changing the optimal emissions levels. Finally, both the cost and damage functions may be non-convex, and may have multiple stable equilibria. High levels of uncertainty regarding both cost and damage functions lead Edenhoffer to recommend choosing a fixed global carbon budget rather than an emissions tax as the best policy option to combat global climate change.

If we agree on a total carbon budget, then several other tools are available to provide guidance for the amount of resources that should be spent on carbon abatement. A carbon budget calculates the total amount of carbon dioxide that can be emitted by humans on earth in order to achieve a fixed temperature target with a given probability. Because the stocks of carbon based energy sources like oil, natural gas and coal are much larger than the "stock" of carbon that the atmosphere can safely absorb the carbon budget allowed to prevent dangerous climate change becomes a non-renewable limiting resource.

A type of economic model called the "Hotelling model" can be used to find the optimal extraction paths for the non-renewable resource, which in this case is the amount of carbon dioxide that should be emitted in each year in order to maximize profit from using things like coal, oil, and gas. The extraction paths resulting from each different policy option can be compared to and ideal one.

Once a goal for an emissions path is chosen, many policy tools exist to encourage extraction (release of CO_2) along that path. Taxes on emissions could be used, subsidies could be provided for companies that invest in clean technology, a governing body could centrally control emissions and investment in clean technology, a there could be a tax on income generated through high carbon use, or an emissions trading scheme. Each of these methods has flaws, but the most robust method is the emissions trading scheme.

A conventional Pigouvian tax is equal to the damages that one additional unit of carbon dioxide in the atmosphere causes for the rest of time. However, the amount of damage one unit of CO_2 creates rises with the stock of carbon already in the atmosphere. Therefore, the tax should rise to infinity as more and more CO_2 is emitted, in order to prevent emissions when they need to be stopped. This means that producers, knowing the tax on carbon will only increase, will increase their emissions in order to produce as much as possible before the tax becomes very high. The unfortunate effect of this type of emissions tax would be that carbon emissions would rise, rather than fall. This would have the same effect as creating a common pool resource out of the carbon that can be safely emitted into the atmosphere.

Subsidies on non-extraction are another method of reducing carbon emissions, but the costs to government could become nearly infinitely high, because the regulator must be credible for an infinite time horizon. Pure command and control methods have major political implementation difficulties. They would also require a very high level of knowledge from the regulating agency because it requires the regulator to make all decisions regarding emissions control and the technologies used by each firm, and then credibly enforce that decision.

A high capital income tax would flatten the extraction path, but it would also induce other distortions that would create welfare losses. Effective use of income taxes would also require international cooperation on tax policy, and that tax havens be closed.

This leaves an emissions trading scheme combined with a global carbon budget as our best choice. The basic concept begins with a fixed amount of carbon emissions that will be allowed, for the whole world and the forseeable future. The amount of carbon emissions allowed is chosen to leave a set probability, say 50 or 75% chance, that global temperature will rise by less than an amount deemed safe, 2 degrees C for example. Once the budget has been fixed based on some consensus of global tolerance for risk, an emissions trading scheme is implemented. Permits to emit some amount in a particular year are allocated to different groups. If a firm, or country would like to emit more than their permits allow them to, they can buy permits from some other group that is willing to sell. This concept includes inter-temporal carbon trading. A company could save up its emissions credits for later years if they planned to grow, or borrow emissions credits from future years while they develop cleaner technology. This mechanism would allow firms to chose their own emissions path and the technology they invest in. The only centralized regulation required would be enforcement of the allowed emissions, a requirement for every policy option that seeks to reduce carbon emissions. Other hurdles to implementation of an emissions trading scheme are how the permits are initially allocated, and making the interemporal trading mechanisms work correctly.

However despite its challenges, a cap and trade emissions scheme combined with a global carbon budget is the best option, and so we need to find solutions in order to make it work.