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Climate policy options and the transformation of the energy system

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Summary. — The key lines of argument to estimate a meaningful degree of efforts to mitigate global warming are outlined. Potential implementations of a policy that strives to limit global warming to 2 °C compared to pre-industrial values are discussed. A recent model intercomparison study on mitigation costs is summarized. Conceptual difficulties when internalizing uncertainty in these types of analyses are highlighted and first attempts to overcome them are outlined. For the mitigation technology "carbon capture and storage" it is illustrated that mitigation technologies also require a proper treatment of their side-effects rather than just focusing on their cost-reduction potential in the context of mitigation. Finally, the prospects of climate policy are sketched.

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1. – Introduction

In 2007, the Intergovernmental Panel on Climate Change (IPCC) released its latest report. The IPCC's goal is to summarize the present status of research on the causal link between greenhouse gas emissions and global warming, on impacts of global warming and on adaptation or mitigation measures, respectively. It is a unique instance in the history of science([1]) that a whole research field organizes a process which every 5-7 years culminates in the release of a report stating not only the degree of academic consensus, but also dissent among scientists on a certain matter. This in turn represents a unique service to society which thereby gets access to the state of knowledge of a whole field in a balanced way and in relatively short time —compared to the "trickle-down time" it usually takes for the dissemination of fundamentally new academic insights.

One of the key findings of the last IPCC report in 2007 was the statement "Most of the observed increase in globally averaged temperatures since the mid-20th century is very likely([2]) due to the observed increase in anthropogenic greenhouse gas concentrations" [1]. For the remainder of this article, I assume the causal link from greenhouse gas emissions and the increase of global mean temperature as given in order to concentrate on the question what could be rational responses to global warming by the global society.

Given the phenomenon of anthropogenically caused global warming one may now ask: Should society take action in mitigating part of the anticipated future global warming? There are two traditions of thought that come with subsequent tools of analysis within climate economics to tackle this question. The first rests on "positive knowledge", *i.e.* the explicitly known consequences of global warming. The second working group of the IPCC [2] is mainly devoted to impacts of global warming that comprise inter alia changes in extreme weather event statistics, loss of ecosystems, or sea level rise. After having introduced key elements of economic reasoning below, I will briefly summarize some findings along this school of thought.

A second stream of argument rests on the notion that human action might drive the system into modes of operation the consequences of which would be hard to predict. This is an instance where some actors would find that the precautionary principle should be applied. (In fact, the EU commission has officially subscribed to the precautionary principle [3].) The latter would state that as the uncertainty coming with the outcome of an action is currently too large, we should avoid that action. The question then is: how would one operationalize the precautionary principle in the case of global warming? For major parts of the discussion, the academic construct of the "global mean temperature" (GMT) serves as an indicator for the "state of the climate system". This has scientific backing, as

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([1]) I hereby use "science" in the generalized sense that I comprise any academic endeavor that comprises a cycle of observation, hypothesizing, theory building, theory/model-observational data intercomparison and thereby further stimulated observation. In particular, this comprises the natural sciences but also *e.g.* those parts of economics or social science that would subscribe to this cyclic paradigm.
([2]) Here "very likely" denotes a probability of at least 90%.

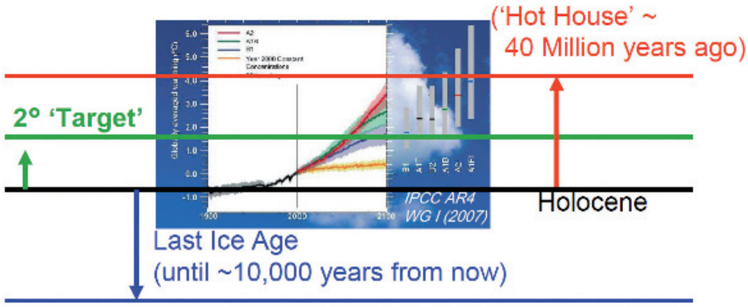

Fig. 1. – Operationalizing the precautionary principle for the global mean temperature (GMT) rise. The 2° target (which should more correctly be called "2° limit") is closer to the Holocene (black line) rather than to the Holocene temperature elevated by the "natural GMT scale", *i.e.* the difference between Holocene GMT and last ice age GMT (red line). That GMT was realized during the Eocene 40 million years ago [4]. Note that the latter is in fact in reach for this century under the more aggressive warming scenarios.

GMT change strongly correlates with impacts. On the other hand it serves as a politically useful simplification of the discussion when it comes to negotiating targets. So if we accept that GMT is a useful quantity to discuss climate policy, we would then ask: What could be a natural scale that would allow us to calibrate what is a "small" or a "large" deviation from the "natural state"? One scale that suggests itself is the GMT difference between the last ice age and the current pre-industrial "standard climate", the Holocene that has prevailed for the last 10000 years. This temperature difference is 5 K [5]. One way to operationalize the precautionary principle would then be to request that GMT should be closer to the Holocene GMT than to a Holocene GMT elevated by 5 K (see fig. 1).

In fact the so called "2° target" (which should rather be called "2° limit") implies that the rise of GMT should be limited to 2 °C as against pre-industrial values. It was supported by the German Advisory Council on Global Change (WBGU), then by the EU and finally on the global level by the Conference of the Parties [6]. There are three lines of argument that support the target. Firstly, it can be interpreted as a realization of the precautionary principle along the lines as indicated above. That a notion of precautionary action might be in order is also illustrated by the ongoing discussion about sea level rise. While the latest IPCC report predicts global sea level to rise in the order of 0.5 m by 2100 in response to the driving temperature scenarios explicated in fig. 1, Archer and Brovkin [3] derived a statistical relation between GMT and sea level on geological time scales. According to this relation, a GMT rise by 2–3 °C might in the long term come with a sea level rise in the order of 50 m, therefore two orders of magnitude more. This illustrates that on the impact side, we might have only a small fraction of triggered mechanisms adequately represented in our impact module libraries.

Secondly, the 2° target does also recognize positive knowledge about climate damages, in particular about ecosystem loss. "Approximately 20 to 30% of plant and animal species assessed so far (in an unbiased sample) are likely to be at increasingly high risk of extinction as global mean temperatures exceed a warming of 2 to 3 °C above preindustrial levels" [2].

Thirdly, the 2° target is a political target in that it massively reduces complexity of the debate by channeling it into a single number. In that sense it also acts in analogy to a speed limit on motorways, without claiming any sort of phase transition in the natural system, when the 2° limit would have been transgressed. The latter point is extremely important to note in case it might have become clear one day that it will be impossible to observe the target any longer, after mitigation has been postponed for further decades. If it indicated a phase transition, this might support the notion that then it would not matter any longer how much mitigation we still would implement — it was "too late" anyhow. However, if it was merely a political target, still as much mitigation as possible might be regarded as desirable.

2. – Cost benefit *versus* cost effectiveness analysis

Above, two schools of thought have their counterparts within the economic community: how to advise on the climate problem from an economic point of view?

Within environmental economics, the standard tool is cost benefit analysis (CBA). Costs of an environmental intervention (in our case: implementing a mitigation policy) are to be traded off against avoided (environmental) damages (in our case: damages minus some benefits from global warming). The archetypical analysis of this kind was undertaken by Nordhaus [7]. Typically, the analysis involves positive knowledge on global warming impacts. Generically, results of this kind of analysis would recommend emission trajectories that would be at odds with observing the 2° target (see, *e.g.*, Nordhaus [8]) — in the sense that they would regard higher emissions as "economically optimal". This reveals that either both camps have opposing normative views or different objective data bases at their disposal — or at least one of them would behave in a somewhat "irrational manner".

CBAs of this kind have been criticized for various reasons (*e.g.*, Azar and Lindgren [9]). The arguments can be divided into the following three classes: i) it is rather impossible to get the library of impacts of global warming on the natural system any closer to complete, ii) for many of these impacts no markets exist, hence non-market based evaluation methods would have to be applied. For many of such impacts, however, societal discussions rather than economic extrapolations would be in order, which have not yet been realized. iii) CBA of the climate problem necessarily involves trading off costs of transforming the energy system over the next decades with avoided damages that would occur over the next 50–1000 years([3]). But how to trade off the present against

([3]) Due to the twin-integrating effect from emissions to concentrations to warming the upper ocean, in combination with the existing pools of carbon and the heat capacity of the ocean, the climate system would likely respond to a climate policy only within the next 50 years.

the future is presently an unsettled conceptual issue within climate economics.

$$\text{Max! Welfare} := \int_{t_0}^{\infty} \mathrm{d}t\, U(t) \mathrm{e}^{-\rho(t-t_0)}. \tag{1}$$

The latter appears conceptually more salient, as standard macro-economic tools involve optimizing the linear time-average of exponential discounted utility (the latter denoting the material basis for "happiness"). One can show that this functional does deliver recommendations that are "time-consistent" ([4]) if and only if the discounting is an exponential. There is an ongoing debate on whether the discounting parameter ρ was a descriptive or normative parameter, the key arguments of which are already summarized in Dasgupta [10]. If it was to be interpreted as a descriptive parameter, it should be linked to the current interest rate and accordingly some would then discount the future to that extent that the utility of the grandchildren's generation would be worth in the order of percent of that of the present generation. That is why others would set ρ almost to zero [11] arguing that when applying eq. (1) to the climate problem, it represents a normative approach to shaping the future and ρ is to be politically negotiated accordingly. Finally, others argue that the whole model represented by eq. (1) was too narrow and the normative *versus* descriptive trade-off ill-posed [12].

All of these conceptual difficulties have led a fraction of climate economists to the conviction that for the time being a less ambitious approach is necessary (for some overview on this type of discussion see, *e.g.*, Patt [13], or Held and Edenhofer [14]). Cost effectiveness analysis (CEA) (or, more precisely, "constrained welfare-optimization") just asks for the economic loss of a certain environmental target without attempting to trade off that loss against future benefits, and hence without judging to what extent that target would be economically optimal in any sense. As in business-as-usual scenarios of climate change the energy sector would be responsible for most of the reasons for future global warming, a CEA of the 2° target simply addresses the question: What are the costs of transforming the energy system in line with the 2° target? In case the costs turn out to be "low", society could take action from a macro-economic point of view: environmentalists could be satisfied because at least a minimum environmental standard would be implemented. Economists might say that the target was not economically optimal, but at least the economic loss would be "acceptable". In that sense, the 2° target would act as an "insurance premium" to avoid uncertainty.

Thereby, CEA elegantly bypasses unsolvable problems of CBA for the time being: having to express all damages economically (because CEA does not account for damages at all), and depending strongly on ρ. In fact, also CEA utilizes eq. (1) to maximize welfare. However, it does so under the constraint that 2° shall not be transgressed. Numerically it will turn out that this implies that a transformation of the global energy system towards low-emission technologies would have to be carried out over the next

([4]) *I.e.* a decision-maker would stick to the once announced original plan, when having the chance to revise the plan later.

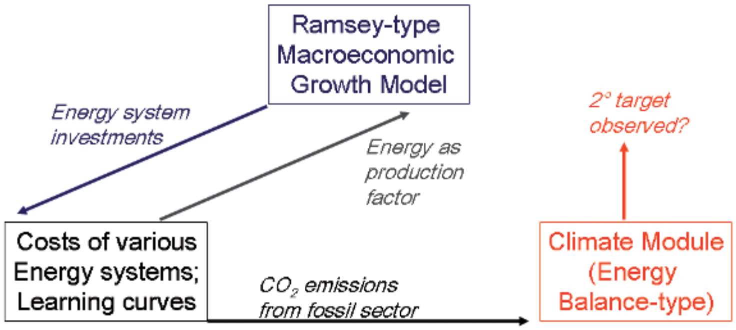

Fig. 2. – Scheme of integrated assessment models that execute a cost effectiveness analysis of temperature targets, such as the 2° target. In the model, an economic kernel would supply investments to various energy technologies and receives energy as an input for macro-economic production. Depending on the energy technology used, greenhouse gases will be produced that are handed over to the climate module. The latter would test whether the emission time series is compatible with the 2° target. If it violates the target, fewer investments into emitting technologies would be undertaken. In the end, investment time series are derived that optimize economic welfare under the constraint that 2° warming is not transgressed.

decades — thus, the damages are considered basically now and not in a hundred years as in CBA. As a result, ρ does matter for CEA as well, but its numerical influence is much smaller for CEA than for CBA.

Consequently, the key question is: Are the costs of the 2° target in fact so "small" that a consensus on mitigation action could emerge within society? Integrated assessment modeling tries to address this question as outlined in fig. 2.

3. – Integrated assessment models for CEA of the climate problem

Models that represent sectors as remote in the academic system such as economy, energy, and climate and dynamically link them are called "Integrated Assessment Models" (IAMs). In our case the three mentioned sectors are represented by individual modules. Figure 2 depicts the coupling scheme of the economic, the energy and the climate module in an IAM of CEA of the climate problem for an assumed 2° target. Such a scheme would deliver the optimal investment time series, optimal in the sense that welfare would be optimized under the constraint that the 2° target is observed. Without that constraint we would get a "business as usual" (BAU) case that describes a world without a mitigation policy and without any climate damages. The welfare difference between the two scenarios is called "mitigation costs" — the costs to transform the energy system. Note that saved damages are not part of that equation, hence the net costs of the 2° target are much smaller or even negative:

$$\text{Max!}_{(c(t_0),\ldots,c(\infty))}\ \text{Welfare} := \int_{t_0}^{\infty} \mathrm{d}t\ \text{Utility}'(t)[(c(t_0),\ldots,c(t))]\mathrm{e}^{-\rho t} \tag{2}$$
$$\text{subject to}\quad \forall_t\ T(t)[(c(t_0),\ldots,c(t))] < T_{\max}.$$

The macroeconomic kernel starts off with a production function. What is produced in any period is partly consumed and partly further invested into capital, labor, or various energy technologies ("budget equation", a kind of conservation law: what is produced per period is exactly what is invested per period plus consumption per period). There is an incentive to invest because capital, labor, and energy are assumed to be "production factors" (*i.e.* production monotonously increases as a function of any of the latter). Hence the social planner([5]) anticipates to produce more in the future and, accordingly, also plans to be in a position to consume more in the future if not all of today's production is consumed. The control variable's time series $c(t_0), c(t_1), \ldots$ is made up by the time series of investment into various energy technologies. (Economists have a somewhat different lingo than physicists here: for them, a "time series" is a "path", hence they speak of a "control path".) "Utility", the material basis for "happiness", is a monotonously increasing, concave function of consumption. Finally, the optimizer would utilize ρ to trade off future and present-day utilities. Through the climate module a temperature constraint is superimposed (see eq. (2)). Thereby the optimization problem is closed.

The energy system module must resolve problems in connection with presently relatively cheap fossil fuels in the near future and, even earlier, more expensive low-carbon energy technologies. Technologies are assumed to have some potential for cost reduction. In fact so called "learning curves" (more precisely "experience curves") have been observed for most products, including energy technologies. The costs per unit of energy delivered in terms of electricity have fallen by orders of magnitude for photovoltaic and wind power [15]. Academia knows two extreme models to explain this phenomenon: "exogenous" and "endogenous" technological change.

The former hypothesis states that there is overall learning in the globalized market across all sectors and hence, also a particular energy technology would benefit from numerous technological improvements occurring across all sectors. If that were the case, a policy-maker could not directly influence the costs of that individual energy technology (say, wind power), except for stimulating world-wide spending on research and development of technology in general. In that sense, costs of wind power were primarily a function of time. Quite the contrary, the latter hypothesis ("endogenous technological change") assumes that costs are primarily a function of total installed capacity of wind power, *i.e.* the learning is primarily driven by the making of wind power plants and would not so much benefit from the overall progress in technology. As a consequence, the policy-maker could actively drive down the costs of wind power by investing into that very technology.

It is obvious that the choice of the model on learning has consequences for the mitigation costs. The 2° target forces the social planner to rapidly invest into relatively new, low-carbon technologies. In a world with exogenous technological change their costs would fall only slowly during that investment horizon and would be large compared to the mature fossil sector. Accordingly, mitigation costs would be relatively high. Quite

([5]) Economists' lingo for "a maximally cooperative and forward-looking society".

the contrary, in a world with endogenous technological change, those very investments would actively reduce the costs of low-carbon technologies, hence mitigation costs would be smaller. Nordhaus [8] argued that it was impossible to distinguish the two models econometrically. However, he assumed quasi-exponential time-dependencies in all variables. While the academic debate about the adequate mix of the two extreme models is still ongoing, my personal, subjective judgment is that the model of endogenous technological change is not too bad an approximation. This rests partly on the observation that the majority of climate economists prefer the endogenous rather than the exogenous model. Also, the costs of concentrated solar power closely followed the investments, the latter have not seen a break for more than a decade in the past. This discontinuity in costs cannot be explained by the exogenous model.

Investment in research and development is seen as a third predictor, whereby this investment channel, similar to above endogenous learning, would allow to actively accelerate cost reduction through investment.

4. – Results on mitigation costs according to an IAM intercomparison study

In the following I would like to summarize results from an IAM intercomparison study. For the study, three IAMs were employed all of which are designed to perform CEAs of climate targets. In particular, a 450 ppm CO_2 concentration target has been calculated. 450 ppm CO_2 represents roughly half a chance o for observing the 2° target(6).

The list of assumptions on which the calculations are based are described in Luderer *et al.* [16]. The ReMIND model described in more detail in Luderer *et al.* [17] utilizes endogenous technological progress. It also employs so called "grades" for renewable energy, a geographical effect on the cost structure. This implies that an optimizer would harvest the best locations first for each renewable technology and would then successively invest into the not so rewarding locations. From the grade effect, there results a cost-increasing effect as a function of total installed capacity that counteracts the learning curve effect. Which one dominates, depends on the technology and continent under consideration. ReMIND's energy system is more flexible than that of the WITCH model. WITCH focuses more on investments in research and development rather than the cost reduction potential through installed capacity as predictors of cost reduction. Finally, the IMACLIM-R model is more myopic (short-term driven), but is rather optimistic on side-effects of a mitigation policy on the labor market.

Despite their structural differences, all three models report mitigation costs in terms of consumption losses lower than 1.5% (see first row in table I)(7). For a large fraction

(6) By not restricting temperature but another quantity such as CO_2 concentration, one gains numerical simplicity on the expenses of economic flexibility in the model. Hence, the results obtained thereby can be interpreted as an upper bound for the costs one would calculate with full flexibility.

(7) Here, some assumptions are made: perfect cooperation of actors; solved integration of renewables in the electricity grid.

Table I. – *Global mitigation costs expressed in terms of consumption losses relative to the baseline scenario discounted at* 3% *(taken from Luderer et al.* [16]*, table* 3*). The first row shows the consumption losses with all technologies available to the optimizer without restrictions. The following* 5 *rows introduce scenarios of restricting one or two technologies to a no-mitigation-case.*

Scenario name	Mitigation costs (% losses relative to baseline)		
	IMACLIM-R	ReMIND-R	WITCH
Default 450 ppm	0.1	0.6	1.4
fixNUC	0.2	0.7	1.3
fixRET	0.2	1.5	3.3
noCCS	1.0	0.8	1.9
fixBIO	0.2	0.8	1.5
noCCS/fixNUC	1.4	0.9	3.3
Delay2030	Infeasible	Infeasible	Infeasible
Delay2020	0.8	1.0	2.1
EUonly	0.7	0.8	1.9
ICfonly	0.3	0.6	1.6
IC + CHN + IND	0.1	0.6	1.4
410 ppm	1.3	0.8	4.0

of economists this is a rather small number. They interpret it as a delay of economic growth only for a couple of months. In that sense, the CEA has delivered a result upon which society could move forward in the sense that was discussed at the end of the CBA *vs.* CEA section. However, the academic debate on whether a society can easily afford such a kind of loss is still yet to come.

Once such a suite of models is available, a couple of variants of scenarios can be calculated as well. One may ask, *e.g.*, how the cost structure might change if one particular technology was confined to a BAU scenario. In the case of nuclear or renewables, this would imply not building any additional plants due to a climate policy. For CCS (carbon capture and storage, extracting CO_2 from the flue gases, compressing it to supercritical state, transporting it and injecting it into deep (at least 800 m below ground) geological formations) this would mean not to employ it at all.

In table I, rows #2-6, the thereby derived cost numbers are indicating or restricting nuclear, renewables, CCS, bioenergy, and simultaneously nuclear and CCS, respectively. As the optimization is performed under an additional constraint (compared to row #1), the welfare losses must be larger than in the case described in row#1. This general thought is described in fig. 3. From table I the following ranking is read in terms of relative importance of that technology for mitigation (in the sense of: which would induce the largest welfare loss when restricted to the BAU case): renewables, CCS, nuclear. Hereby the scale of additional loss due to fixation of nuclear is 0.1%, an almost negligible number. In that sense the models suggest that a mitigation-driven nuclear policy is not necessary if the other options are regarded acceptable and mitigation policy was readily implemented.

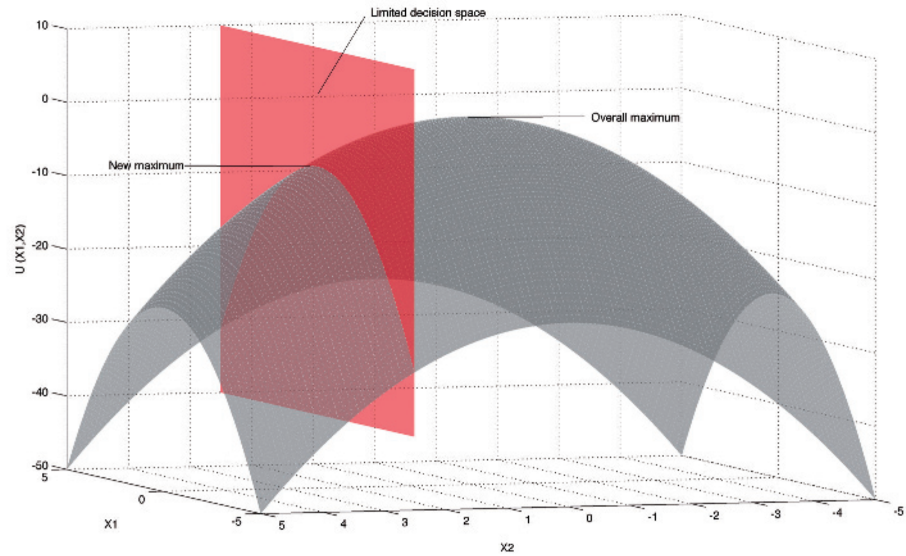

Fig. 3. – Illustrating that welfare losses must be larger when individual technologies are constrained (table I, rows #2-6 *vs.* row#1). In the above figure, the "overall maximum" depicts the welfare level U with all technologies allowed (here symbolized by decision variables $X1$ and $X2$). If one of them is pinned down to a particular value, the overall maximum cannot be assumed any longer. Instead the optimization is confined to a "limited decision space". The difference in U from the overall to the new maximum is the welfare loss induced by the new technology restriction.

5. – Investment under uncertainty

One argument for utilizing CEA rather than CBA had been that the damage function was highly uncertain. CEA bypasses the damage function. However, also other elements of the cause-effect-chain are uncertain, whereby only to such an extent as it seems adequate to express these uncertainties in formal terms. This refers to the link from emissions to temperature rise and the effects of investments on cost reduction.

One key system property that has attracted a lot of attention in the climate community is the so-called climate sensitivity (CS). CS is defined as the equilibrium GMT response to a doubling of the CO_2 concentration as against the pre-industrial value. CS also encapsulates more than 50% of the uncertainty about future transient GMT response to greenhouse gas emissions. At present, there is no way to give an upper limit for CS on the basis of climate science [1]. An average value is assumed to be 3 °C, and an at least 60% quantile 2 °C–4.5 °C [1]. As one can show that the allowed time-cumulative amount of CO_2 scales with the time-asymptotic GMT T_∞ as $2^{T_\infty/\mathrm{CS}} - 1$ [18], the total amount of CO_2 still allowed tends to zero, as CS to infinity. This in turn means that the asymptotic GMT unavoidably would transgress 2 °C, if CS was only large enough. But then, maximum GMT would transgress 2 °C all the more so, hence from this thought experiment we conclude: As long as no upper limit can be put on CS, we cannot formulate a mitigation policy that could observe the 2° limit with certainty.

Instead Kleinen [19] suggested a generalization of the 2° target that involves observation of the 2° limit only in a probabilistic sense. Hence, now *two* normative parameters have to enter the analysis: the temperature limit and the probability of observing it([8]). When transferring this idea to CEA, one adds the notion of optimization to it, resulting in so-called "chance constrained programming" (CCP – whereby "programming" means "optimization"; Charnes and Cooper [20]). CCP for the 2° target with a probability of observing the limit of 75% was implemented in the MIND model (which is the precursory version of the above ReMIND) by Held *et al.* [21]. Compared to a deterministic CEA version, investments into low-emission technologies would have been chosen decades earlier. In part this is a trivial effect, as running a deterministic CEA with mean values of uncertain quantities such as CS would roughly imply observing the 2° limit with only half a chance. When now asking for 75%, this naturally would trigger earlier investments into low-carbon technologies. However, as Held *et al.* [21] show, this only partly explains the effect. It remains to be shown whether non-linear interactions of uncertainties in the climate and the technology module are co-responsible for this suggested massive acceleration of investments.

While this extension of CEA into the probabilistic domain was conceptually straightforward and seemed to be rather a book-keeping exercise (although requesting some degree of numerical innovation, as CCP is not delivered off-the-shelf by suppliers of the standard intertemporal optimization software package GAMS), CCP does not yet fully address society's decision problem under uncertainty. One key aspect that CCP is lacking is anticipated future learning. CCP suggests ways how to internalize probabilistically formulated uncertainty in a CEA-based decision, but silently assumes that our state of knowledge would not significantly change while our decision process is ongoing. Since we can actively accelerate learning about the climate system by doing more climate research or by building new power plants, this approximation precludes certain options that society has. Hence, a further conceptual generalization in including anticipated future learning appears desirable.

However, as early as 1974, Blau [23] showed that strict environmental targets might be fundamentally at odds with anticipated future learning. Schmidt *et al.* [24] showed that this argument readily applies to CCP regarding the climate problem: If we anticipate that we might learn in future that CS is "very high", we anticipate a future in which we cannot reach the politically set probability of observing the target any longer — or only at the price of complete shutdown of emission right away. Schmidt *et al.* argue that there is no obvious way to include learning into CCP of the climate problem in a self-consistent manner. Instead they suggest an alternative to CCP: the so-called cost-risk analysis (CRA).

([8]) This concept was taken up further in literature, see *e.g.* den Elzen *et al.* [22].

Like CCP, CRA contains two normative parameters. Like CCP and CEA, it requests defining a temperature limit. Unlike CCP, it asks for a linear trade-off parameter that weighs mitigation costs against the probability of overshooting. The latter could be interpreted as a very special case of a generalized damage function, and in that sense we would be back to some sort of CBA. But still, no true damages need to be formulated, and in that sense one could interpret CRA as the climate-problem adjusted hybrid out of CBA and CEA under uncertainty and anticipated future learning. The properties and consequences of this new decision analytic tool are at present subject of academic investigation([9]).

All of this shows that a probabilistic extension of CEA is not a matter of course. What does this imply for the interpretation of the huge set of deterministic CEA studies? In any case, we can conclude from studies by, *e.g.*, Luderer *et al.* [16] that likely costs of massive emission reduction are rather modest. How this relates to society's preferences regarding global warming impacts as encoded in the 2° target, however, remains to be further debated.

Finally, does above development of a new decision-analytic tool like CRA imply in part a "rehabilitation" of CBA from the perspective of the "CEA community"? My impression is: yes. CBA formally can deal more easily with uncertainty and has even a very strong axiomatic basis: according to the von Neumann-Morgenstern axioms, under a given probability measure linking our actions to the consequences of those actions, a "rational decision-maker" would optimize expected utility (or welfare), which means in the context of the climate problem nothing else than applying a probabilistic version of CBA (like done in a pioneering work in Nordhaus [7]). What would then be the effect of explicitly involving uncertainty in CBA compared to the simpler deterministic treatment? The effect ranges from being minuscule to a recommendation of complete shutdown of emissions right now [25] due to uncertainty. Thus, in fact, the recommendations of CBA for dealing with uncertainty appear even more unstable than the treatments of their deterministic counterparts. It remains a conceptual challenge to develop the adequate decision-analytic tool, given our present state of knowledge about the climate system. Future research needs to show to what extent CRA can serve as a bridge, representing the limiting case of learning about the climate response, but not about damages.

6. – A plea for an integrated risk analysis

At present, the "climate community" is about to re-formulate the climate problem into a risk management problem. In that sense it is also becoming more and more obvious that it does not help society if certain temperature targets were observed, but at the expenses of other sorts of damages such as biodiversity loss or rising food prices due to unsustainable bioenergy production.

([9]) *E.g.* at KlimaCampus, Hamburg.

Recently, another mitigation technology has received considerable attention: CCS. CCS is special in the sense that it is mitigation technology which without the prospect of mitigation policy would not make sense to be used at all — at least not on the otherwise anticipated scale. Since supercritical CO_2 has a lower density than water, it would tend to propagate upwards, once injected into the geological underground. Our calculations have shown that on average 10000 years rather than 1000 years should be considered in order to result in a positive balance for mitigation [26]. If Germany were to capture its present exhaust from coal-fired power plants for a couple of decades and sequester it in its geological formations, this would involve 1–5% of the area of the German state territory — an environmental management case of unprecedented scale(10). It appears very unlikely that any environmental state agency would be able to handle that dimension on its own.

Already in 2005, Edenhofer *et al.* [27] had published a scheme that would allow to shift the burden of proof regarding the responsible operating of the injection site from the state to the operator ("bond scheme"; see also Held and Edenhofer [28] for a discussion of pros and cons on such a scheme). In doing so, the capital market in its decentralized power would assist the state in managing the distributed risks of massive-scale deployment of CCS. This seems even more necessary, as leakage of CO_2 might not be the only risk associated with CCS. While that leakage is confined to the area where the CO_2 is pumped into (typically 10 km in diameter per power plant), the displaced brine waters would build up a pressure gradient in the underground that propagates an order of magnitude further(11). The discussion about how to handle this risk has just started.

In any case society will have to decide soon what kind of risk management on the natural science side of CCS might seem adequate: one in terms of "best practice": if a certain practice has been followed by an operator, society would grant a reward — no matter, where the injected CO_2 was moving; or one in terms of "proven balance" which poses tremendous challenges on observation technologies. My personal impression is that for the detection of leakage, at least one order of magnitude in terms of accuracy is still lacking in order to achieve the rates that would correspond to the above-mentioned minimum residence times of 10000 years.

However, since society cannot be sure about the costs and functioning as well as the side-effects of other mitigation technologies, and also because mitigation policy will be massively delayed (compared to the necessities in relation to the 2° target), it would be wise to test CCS in demonstration projects. The latter aspect points to the idea that society may overshoot its emission budget in the first half of this century if we could produce net negative emissions in the second half of this century. This could be achieved with biomass use in combination with CCS. However, bioenergy potential is lim-

(10) For these numbers we involved the volume-to-area conversion factor as published by the German Environmental Agency's report on CCS as of 2006.
(11) Kühn and Liebscher, 2011, personal communication.

ited. Therefore, additional, anorganic technologies to remove CO_2 from the atmosphere, highly exergy-intensive, should be researched as well ("CO_2-removal" [29]). In that sense it would also be unwise to exclude additional unconventional mitigation technology such as nuclear fusion from the mitigation portfolio at an early stage, without proper consideration of an investment-under-uncertainty analysis.

7. – Prospects of Climate Policy

While proponents of a stringent mitigation policy might see it as a success that the 2° target was embraced by the Conference of the Parties, binding international agreements on emission cuts dramatically lag behind this embracement (they are currently equivalent to a 2.4–4.2 °C target (80% quantile [30])). This has several reasons. First, the 2° target can roughly be converted into a carbon emission budget — if this was distributed equally per capita, a citizen of the OECD would run out of emission allowances within the next decade [31]. Hence, global society has to negotiate how to distribute the remaining emission allowances. The fact that least developed nations might not be able to fully use their rights over the next decades and hence could sell those to OECD nations could mitigate part of that negotiation problem.

Secondly, a 2° target would massively depreciate the rents of owners of fossil resources. In principle this would not have to be a problem from the point of view of the global society, however, pressure groups might use information asymmetries quite efficiently. Part of this effect is that actors in their networks hold a geat deal of the necessary technological knowhow to operate an energy system in a stable manner.

Thirdly, the 2° target is perceived as being increasingly ill-posed and increasingly impossible to observe, the longer mitigation is delayed. In fact, a global treaty on emission cuts in line with the 2° target appears rather unlikely over the next decade. This makes it difficult for early movers such as the EU to proceed on their mitigation path, as at present it is academically unclear how much front-running is affordable before the front-runner ruins his or her competitiveness. However, a global treaty is not the only channel towards mitigation. Coalitions of mitigation-motivated actors could be stabilized by modest border tax adjustments or club goods [32]. Also, it will certainly be possible to spell out the preference order implicit in the 2° target for the modified conditions and re-interpret the target in a generalized sense accordingly. I regard the new tool of CRA as promising in that respect.

Fourthly, it is at present unclear whether a low-cost low-emission energy system would work in reality, in spite of an increasing number of CEAs that claim rather low mitigation costs. Hence, it would help (from the point of view of a supporter of the 2° target) if OECD countries could come up with successively upscaled demonstration projects — a key role for Europe. This should be supported much more by concerted, problem-oriented efforts within academia in the techno-economic field and frontier research in social science.

In the end, climate policy will be to a large extent a matter of removing information asymmetries within our global society. If the proponents of a stringent mitigation policy are correct in that their suggestions in some sense would maximize the "global cake" (including humankind's desire for some security standards) — then there should be some ways to negotiate fair deals. Or, quite the reverse, they may find themselves convinced that they have just followed some romantic ideal of nature conservation, out of touch with the preference order of global society. The negotiations about what a desirable and fair future is have just begun. They can be informed but not substituted by imaginations of a handful of well-meaning brilliant scientists. However they can be massively supported by an academia that internally stronger rewards dealing with real-world problems of this century, strictly observes political neutrality, and opens up option spaces for policy makers. The climate problem is increasingly attracting curious minds from all disciplines and triggers a massive cross-fertilization of academic quality standards across disciplines. This certainly will give academia a boost and hopefully society an increased chance to negotiate what kind of future it wants — in such a way that in retrospect we would find that academia has helped society to get closer to "its social optimum"!

* * *

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