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SOZIALWISSENSCHAFTEN

Evaluating Delayed Climate Policy by Cost-Risk Analysis

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WiSo-HH Working Paper Series
Working Paper No. 53
March 2020

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ISSN 2196-8128

Font used: „TheSans UHH“ / LucasFonts

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Accepted as EAERE 2015 paper

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January 14, 2015

Cost-Risk Analysis (CRA) is a method to mathematically deduce preferences in line with a climate target. CRA is a trade-off, where costs of mitigating greenhouse gas emissions are weighted against the risk of exceeding climate targets. CRA enables a community supporting climate targets to evaluate delayed climate policy with an arbitrary length because the scope of CRA is not restricted to solutions that do not violate the target. For the first time we apply this approach to the problem of delayed climate policy using the integrated assessment model MIND-L.

The most important results of our analysis are: (i) Using the most conservative risk metric welfare losses double for a 40 year delay of climate policy, that initially aims at limiting global mean temperature rise to 2 °C with a probability of 66%. (ii) The welfare losses are only driven by an increase in temperature. Mitigation costs are even decreasing, which can be seen as an incentive to delay mitigation efforts for decision makers who ignore risk. (iii) For the 2°C target, we find that maximum mitigation is optimal for any delay scenario beyond 2020, in line with previous studies using other approaches.

1 Introduction

Climatic change has been identified as one of the centennial challenges for humankind (Stern, 2007 and World Bank, 2012). In this article we argue that for at least the upcoming decade, climate targets that are partly defined by policy makers and that are not direct output of an economic analysis will continue playing a major role for climate negotiations. Hence, climate economics should continue illuminating the consequences of such climate targets. Hereby, we particularly stress that in view of uncertainty and delayed participation in a global mitigation policy, temperature targets require a somewhat softer interpretation as previously conveyed. We operationalize such a softer interpretation by "Cost Risk Analysis" (CRA) that has been introduced as a hybrid of Cost Effectiveness Analysis (CEA) and Cost Benefit Analysis (CBA) (Schmidt et al., 2011 and Neubersch et al., 2014) and that will be detailed below. For the first time we apply this approach to the problem of delayed participation and contrast our findings with the more traditional, “harder”, i.e. stricter interpretation of temperature targets.

In 2010 the Conference of the Parties (COP) to the United Nations Framework Convention on Climate Change (UNFCCC) declared the so-called “2° target” as its primary operationalization of UNFCCC’s long-term objective “to avoid dangerous interference with the climate system” (UNFCCC, 2012). Hereby the 2° target is defined as the goal to limit the rise of global mean temperature (GMT) to 2°C compared to its pre-industrial value.

From the point of view of climate economics, the 2° target can be interpreted as a societally (to a certain extent) negotiated composite of anticipated global warming impacts to be avoided, as well as a precautionary attitude (see e.g. Iverson and Perrings, 2012) against entering a temperature regime the consequences of which are presently hard to predict. Such a temperature target may serve as a focal point for climate negotiations, providing the necessary reduction of complexity the policy process might require. In the latter sense a thereby obtained temperature target can be compared to a speed limit for road traffic, in the end politically set under the influence of a precautionary attitude, however strongly informed by objective data (Jaeger and Jaeger, 2011; Schellnhuber, 2010 and Held, 2013).

Within the climate economists’ community the 2° target is subject to a mixed valuation. On the one hand, some argue the 2° target was too politically and too little economically driven (Tol, 2007) and CBA should be used to derive optimal temperature paths (Nordhaus, 1997; 2008; 2013) instead. In fact, generically, a CBA of the climate problem would not result in optimal temperature paths in-line with the 2° target. On the other hand fundamental challenges complicate the application of CBA to the climate problem including a difficult comparison of types of damage as well as the existence of large uncertainties on global warming impacts (Kunreuther et al., 2014; Stern, 2007 and Nelson, 2013) . Hence, according to part of the scientific community, more research into impact models is required to address the issue of finding an at least approximate aggregate global impact function. Since the latter might require a further, decades-scale research effort while major fractions of the world-wide energy system will be decided on within the upcoming decade, bypassing this tedious academic process by a “data-/gut-informed”, politically set temperature target might be a pragmatic way of supporting climate negotiations in the meantime (Patt, 1999).

In summary, climate economists might further engage in the analysis of the consequences of temperature targets for two reasons: firstly, because they share above concerns regarding CBA, or secondly because they pragmatically accept the 2° target as having been embraced by the UNFCCC, and therefore they attribute at least some relevance to that target for future climate negotiations.

In fact IPCC AR5 WG-III, Chapter 6 (Clarke et al., 2014), presents about 1000 scenarios a large fraction of which can be interpreted as welfare-optimal operationalizations of different prescribed climate targets. Hereby in turn, a major fraction prove approximately welfare-optimal under a 2°-constraint. CEA, i.e. economic welfare-optimization under a prescribed – mostly environmental – constraint, served as the dominant decision-theoretic paradigm. As opposed to CBA, CEA does not require a formal specification of a global warming impact function, because aversion against net damages is encapsulated in the prescribed climate target. The orders of magnitude of economic welfare losses (also sloppily called "costs") that would be induced by implementations of various climate targets represent a major product of IPCC AR 5 WG-III.

Generically prescribing a 2° target leads to a significant immediate re-direction of energy system investments from the fossil to the low-carbon sector (Clarke et al., 2014). However such action would require a global policy that comes close to a global climate treaty instead of the currently observed fragmented situation of global mitigation action. It is one very possible scenario that a policy in-line with the 2° target will be delayed by decades. For that reason, Clarke et al. (2014) also report the additional costs induced by delayed action (compared to the optimal solution under an immediate implementation of a 2° policy). As Fig. 13 (right panel) of Edenhofer et al. (2014), i.e. the Technical Summary of the IPCC AR5 WG-III, shows that delay until 2030 is expected to double mitigation costs. Further delay will finally lead to infeasibility of the target. Both effects would gain further weight, if an option to store carbon was eliminated from the economic analysis (Luderer et al., 2013).

According to Geden (2013) the potential infeasibility of the 2° target, due to delayed mitigation policy, undermines the credibility of that very target. This in turn might destabilize the expectations in the guiding and focusing function of that very target that it was expected to unfold in the course of climate negotiations. Such a dysfunctional target might even hamper rather than support net global mitigation. In response to this line of thought, we see it as a major benefit of the softer interpretation of a temperature target outlined below that such infeasibilities are excluded by construction. While the 2° target might be transgressed in some probabilistic sense ex ante, or in reality ex post, the value system supporting the 2° target can prevail in spite of delay. Our method (CRA) would offer one dynamically consistent way of extrapolating the 2° target into a regime of delayed action such that the underlying value system remains invariant under arbitrary delay. Thereby we offer a means to preserve the functionality of that value system that has painstakingly been negotiated over the past decades (Schellnhuber, 2010) even in view of anticipated delay of climate policy. Hence in this article we ask: "How would a 2° target-oriented decision maker invest if society could not comply with the 2° target any longer due to continued delayed action?"

Re-interpreting temperature targets through the lens of CRA proves crucial from an even more fundamental point of view. While CBA has heavily been criticized as delivering potentially divergent results under proper inclusion of uncertainty on climate sensitivity (Weitzman, 2009) (here we define "uncertainty" in-line with the IPCC (Mastrandrea et al., 2010) as comprising any deviation from perfect knowledge, including probabilistic statements), a similar instability hitting CEA has remained almost unnoticed by the target-oriented community. As Schmidt et al. (2011) point out, inclusion of an infinite high-end tail on climate sensitivity in combination with anticipated future learning drives the CEA-based optimal solution towards maximum mitigation, thereby mimicking the effect Weitzman had discovered for CBA.

They introduce CRA as a hybrid of CBA and CEA as the two main decision-analytic frameworks within climate economics to eliminate their counter-intuitive features. In short, temperature targets are re-interpreted through the lens of a CBA, the damage function is replaced by some willingness-to-pay to avoid the transgression of the temperature limit. The partially normative temperature limit is then to be accompanied by an additional normative parameter designed to trade-off the "risk of transgression" against mitigation costs. This parameter might either be elicited (Schmidt et al., 2011) or calibrated at existing agreements (Neubersch et al., 2013; 2014) – e.g. to "likely" be in compliance with the 2° limit (UNFCCC, 2011; 2012). Neubersch et al. (2014) open a venue to systematically replace CEA by a decision-analytic framework that is conceptually more sane to deal with climate sensitivity uncertainty. For the first time, they derive the expected value of perfect climate information under a prescribed 2° target. Moreover, first results show that for climate targets as strict as the 2° target, CEA-based optimal solutions can be interpreted as good approximations of CRA-based optimal solutions. Optimal control paths are similar for the upcoming decades while CEA-based mitigation costs can be interpreted as upper bounds for CRA-based ones that would allow for future learning, hence for potentially lower costs. Although CEA is able to provide reasonable decision guidance it lacks a quantitative evaluation about the effects of delayed climate policy for decision path that violate the target. In contrast, CRA is able to evaluate delayed climate policy with an arbitrary length. The quantitative evaluation yields important information about how much worse things get, if mitigation efforts are further delayed by decades. Accordingly, we ask here: "What is welfare loss, from a 2° target-oriented perspective, when mitigation efforts are delayed up until 2050?"

For demonstration and further development of CRA we employ the IAM MIND-L (Model of Investment and Technological Development including Learning) (Edenhofer et al., 2005; Held et al., 2009; Lorenz et al., 2012). However, learning, i.e. the resolution of uncertainty about climate sensitivity, is not considered in the analysis presented here. Further we point out, that CCS and negative emission technologies are not included in our version of MIND-L. The remainder of the paper is structured as follows: the theoretical framework of CRA is described in detail in Section 2 and the application is treated in Section 3. We conclude and discuss our results in Section 4.

2 The Cost-Risk Framework

This Section summarizes key statements of a corresponding Section in Neubersch et al. (2014). At the heart of CRA lies a trade-off between the cost of mitigation and the excess risk introduced by temperatures transgressing a pre-set temperature limit. We also call this temperature limit guard rail. This Section introduces the formalism required for the following analysis of delayed participation that is exemplified at the MIND model.

Within the version of CRA that we use here, a linear above-threshold risk metric is utilized in a welfare functional that has to be intertemporally optimized.

$$\max W = \sum_{t=0}^{t_{\text{end}}} \sum_{s=1}^{S} p_s \left\{ \underbrace{U(t,s)}_{\text{utility-related}} \underbrace{-\beta R(T(t,s))}_{\text{risk-related}} \right\} e^{-\delta t}. \tag{1}$$

Here δ denotes the pure rate of time preference and $U(t,s)$ the utility from consumption for time t and state of the world s. Each state of the world is associated with a probability p_s. W describes the overall welfare. We preserve dynamic consistency by discounting both utility- and risk-related parts at the same rate rather than individually. We regard dynamic consistency a necessary property of any social planner framework[1] The risk function $R(T)$ is calculated in each time step and state of the world as:

$$R(T) = \Theta(T - T_g) \cdot (T - T_g) \tag{2}$$

where T_g is the specified guard rail, i.e. the temperature limit. Originally Schmidt et al. (2011) proposed a Heaviside function as their risk metric, avoiding the linear term above, in order to mimic CEA's threshold concept as closely as possible. However, Neubersch et al. (2014) argue that any non-convex risk function might lead to a flip back to business-as-usual-like investment behavior, once the temperature limit had been transgressed for a certain state of the world. If one interprets the 2° target more in-line with a speed limit rather than a macro-transition in the natural system (see previous Section), then such flip-flop behavior clearly appears normatively at odds with the preferences of a community supporting climate targets. Neubersch et al. (2014) then select above linear risk metric out of infinitely many possible metrics as the "most conservative metric" (in the sense of "being as close as possible to the business-as-usual normative order") for high temperatures that still ensures convexity. They further motivate their choice by additional arguments to be found in Mastrandrea and Schneider (2004). Our baseline analysis will be focused on the limiting case of a linear risk metric, but we conduct a sensitivity study about this assumption and present the results.

Finally, the above form of CRA now only lacks a specification for β. Here, Neubersch et al. (2014) argue that when the COP adopted the 2° target (UNFCCC, 2012), this already came with the statement "likely". When interpreting this in along the IPCC calibrated language for communicating uncertainty (Mastrandrea et al., 2010), this amounts to 66% (or more). Furthermore, the authors assume that the COP process was under the impression of the need to produce an agreement rather soon, hence anticipated future learning about climate sensitivity was not an issue. Consequently, the authors interpret above 66% statement as one that could be used for their CRA for the limiting case without future learning. Thereby the system is closed and the trade-off parameter β can be determined within a CRA without learning by tuning it such that 66% compliance is reached in the temperature variable. Any other variable would then be diagnosed from the optimal solution. Finally, the calibration also requires a statement about the timing when it takes place. "The scientific view that the increase in global temperature should be below 2°C" was recognized for the first time in the 15th COP in 2009 (UNFCCC, 2010). This statement is used to define the timing of the calibration to 2010. Calibration takes place in that year, independently of the delay.

For the numerical analysis, we use the Model MIND in the stochastic form presented by

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[1] In contrast, Gerlagh and Michielsen (2013) presented a decision-analytic framework that – according to our interpretation – represents a time-inconsistent CRA to excellently model a sequence of policy makers that put only moving targets into operation.

Held et al. (2009). It is an extension to the deterministic model presented by Edenhofer et al. (2005) through the introduction of uncertainty. MIND is an integrated assessment model (IAM) consisting of three parts: the economy, the energy sector and the climate module. It is based on an intertemporal optimizing macroeconomic growth model in the tradition of Ramsey. IAMs are able to assess the interactions between the activities in the socio-economic system and the climate system, especially human induced climate change. MIND comprises induced technological change in the energy sector, the latter consisting of a renewable and a fossil sector. An energy balance model represents the climate module that links emissions to global mean temperature change.

MIND is implemented in the optimization language GAMS. The time horizon reaches from 1995 until 2200 with time steps of 5 years. In order to account for the infinite horizon of the decision problem, the terminating discount factor is modified (Neubersch et al., 2014).

An illustration of the structure of MIND and its application to CRA can be found in Figure 1. From the visualization one can directly see the difference between the application of CRA and CEA. In Edenhofer et al. (2005) the climate module is linked to the welfare function only indirectly through a constraint, whereas in CRA the influence of the temperature change on welfare through the risk metric is qualitatively equivalent with the utility from consumption.

The uncertainty in the model stems from uncertainty about climate sensitivity (CS) correlated to the ocean heat uptake. This provides the possibility to focus on the source of uncertainty, which is most relevant for the analysis under CRA. Climate sensitivity is assumed to be distributed in a log-normal form: $\mathrm{pdf}(CS) = \mathcal{LN}(0.973, 0.4748)$ (Wigley and Raper, 2001). This distribution function represents an intermediate evaluation of the uncertainty, incorporating a wider range of possible values compared to Schneider von Deimling et al. (2006), but not the fat tails as in Weitzman (2009). A perfect correlation between climate sensitivity and climate response time scale is assumed, to simplify the description of uncertainty to the decisive one-dimensional manifold, as described in Lorenz et al. (2012). We use the sampling by Neubersch (2014), who divide the distribution into 20 realizations or so called states of the world (SOW). Each 5% quantile is represented through the respective expected value.

We use a constant relative risk aversion utility function with a risk aversion of η=2. Further, we apply exponential discounting using a pure rate of time preference of 1% pa. The substitutability between the three production factors labor, capital and energy is limited through the choice of an elasticity of substitution of 0.4 in the CES production function.

The scenario design we employ is similar to Luderer et al. (2013). We consider different starting points of climate policy. Until climate policy is implemented, emissions follow a BAU scenario. The starting point of climate policy denotes the period in which risk originating from increased temperature is being included in the optimization. In the subsequent period emissions are adjusted accordingly. Delay scenarios for a delay up until 2050 are considered.

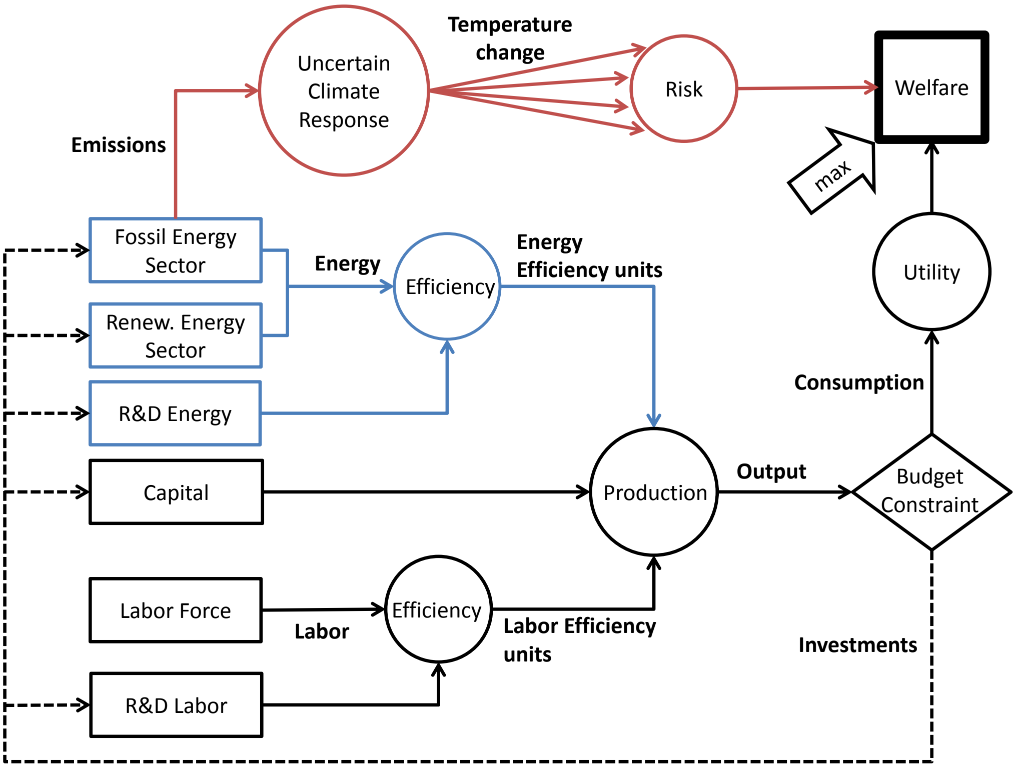

Figure 1: A sketch of MIND and its application to CRA. Black lines indicate traditional parts of a growth model, blue lines the energy module and red lines the climate module. Boxes represent stocks. Circles represent converters. Labeled arrows represent flows. Dashed arrows indicate control variables. The diamond box illustrates the point of the decision. (Own illustration, adapted and simplified from Edenhofer et al., 2005)

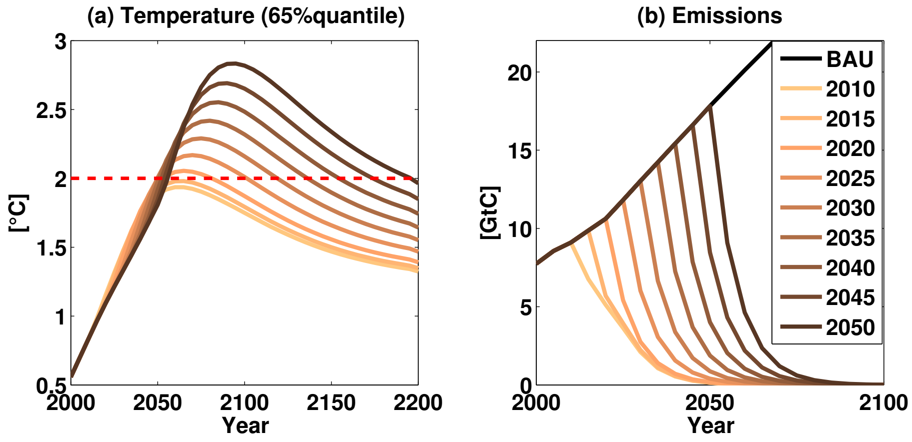

Figure 2: Effect of delayed climate policy on (a) temperature paths of the 65% quantile and (b) on CO_2 emissions. Legend indicates the delay scenario.

3 Results

Temperature and Emission Paths

Figure 2a shows global mean temperature paths for different delay scenarios of climate policy, that is aiming at limiting global mean temperature rise to 2°C with a safety of 66%. The graph displays the 65% quantile, because this quantile approximately corresponds to the safety of 66%.[2] Consequently, global mean temperature for each scenario is equal to or less than depicted in the graph with a probability of two-thirds. A delay until 2030 will lead to a likely temperature increase up to 2.3°C. 20 years additional delay cause a likely temperature increase of approximately 2.8°C.

Any delay of mitigation efforts leads to increasing temperatures and a violation of the aspired target. The driving force behind the temperature development are CO_2 emission paths which are shown in Figure 2b. As soon as climate risk is included in the optimization, emissions are reduced very drastically and approach zero in the long run. The latter is in line with previous studies conducting CEA, (e.g. Luderer et al., 2013). Although emission reductions are remarkable, the excess emissions in early periods caused by the delay are not compensated, in contrast to CEA-based analyses. Consequently, the delay causes cumulative CO_2 emission to rise. This explains the increase in temperature.

For the 2010 scenario, the transition to a carbon free economy takes 40 years, leading to emissions equal to zero in 2050. A delay in climate policy leads to even steeper emission paths, such that for a delay until 2020 the transition needs to be done in 30 years. A faster transition is not possible due to a constraint on annual relative emission reductions of 13.3% implemented in MIND (Lorenz et al., 2012). This constraint is included to reflect inertia of the energy system and to represent political or societal processes that are not

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[2] Due to the numerical implementation of the uncertainty, only steps of 5% in the distribution function are possible.

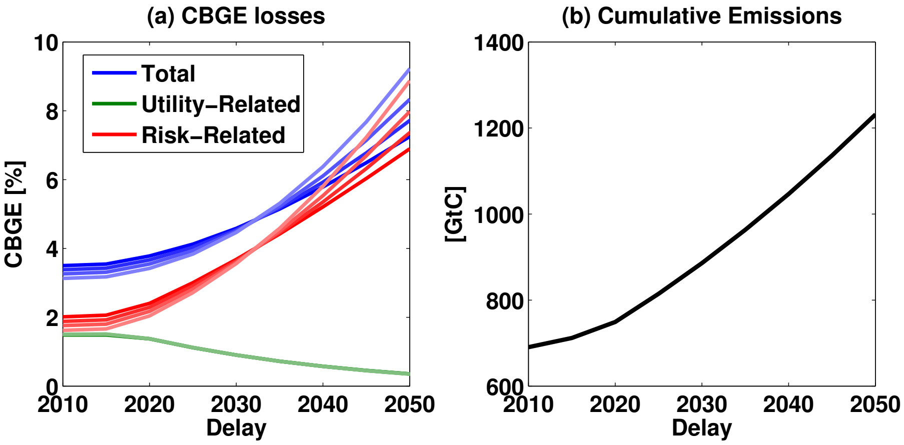

Figure 3: (a) Effect of delayed climate policy on welfare, relative to BAU for different risk-functions. Welfare changes are separated by origin of the CBGE change (red: risk-related, green: utility-related). The risk metric is indicated by the tone - dark to pale: T^4, T^3, T^2, lin. Panel (b) depicts overall cumulative emissions until 2200. The abscissa indicates the delay scenario.

possible to include in the model. Our number lies at the upper end of values considered in the literature (compare e.g. with Stocker, 2013). It is necessary to bear in mind that this magnitude would be unprecedented (Riahi et al., 2013).

Evaluation of Scenarios

The different scenarios can be evaluated using their consumption and temperature paths to calculate welfare. Welfare is measured in Certainty and Balanced Growth Equivalent (CBGE, see Anthoff and Tol (2009) for details). The difference in welfare between two scenarios is translated into a difference in initial consumption, assuming a constant equal growth of consumption for both scenarios. The CBGE change corresponds to the relative change in initial consumption that would be necessary in order to represent the difference in expected welfare. More intuitively it can be interpreted as a constant relative change in consumption. The different scenarios are compared on the basis of their CBGE change relative to a BAU scenario.

The functional form of the applied risk-metric is an important choice for the evaluation of scenarios because the risk-metric directly affects welfare. Therefore, we present results for the use of four different risk metrics, ranging from the most conservative (see Section 2) linear one to a function of power 4. The explicit functional form of the metrics can be found in Table 1. They are based on propositions made by Neubersch (2014).

The CBGE changes relative to a BAU scenario for the different delay scenarios are depicted in Figure 3a. The corresponding risk metric is indicated by the tone. Paler curves indicate a less convex functional form. Additionally, the CBGE changes are separated by origin (Neubersch et al., 2014, Supplementary Material). Therefore it is possible to dis-

Shorthand	Risk Function $R(T)$
lin	$\Theta\left(T - T_{\mathrm{g}}\right)\left(T - T_{\mathrm{g}}\right)$
T^2	$\Theta\left(T - T_{\mathrm{g}}\right)\left(T^2 - T_{\mathrm{g}}^2\right)$
T^3	$\Theta\left(T - T_{\mathrm{g}}\right)\left(T^3 - T_{\mathrm{g}}^3\right)$
T^4	$\Theta\left(T - T_{\mathrm{g}}\right)\left(T^4 - T_{\mathrm{g}}^4\right)$

Table 1: The four considered functional forms of the risk function from Neubersch (2014). $\Theta(x)$ denotes the Heaviside function of x. T is the temperature in one point in time, for one SOW. T_{g} is the specified temperature guard rail.

entangle and attribute the welfare change in a risk-and a utility-related part. The former is driven by an increase in temperatures, the latter by an decrease in consumption.

Independent of the risk metric used, welfare losses convexly increase with the length of the delay. For the linear risk metric, total welfare losses relative to BAU more than double for a delay until 2050 compared to a climate policy in 2010, from 3.55% to 7.25% CBGE. Compared to a delay until 2050, a delay until 2020 has only a relatively moderate effect on welfare losses (increase by 0.58% points. to 4.13% CBGE). The effect is more pronounced, when a more convex risk metric is applied. For the T^4 risk metric, total welfare losses almost triple form 3.18% (2010 scenario) to 9.22% CBGE (2050 scenario).

The same analysis is infeasible with CEA as it lacks a metric that evaluates temperature increases. Delay scenarios that all violate the climate target are not meaningfully comparable. Only scenarios for which CEA finds feasible solutions can meaningfully be compared. However, it is restricted to the utility-related part of welfare losses (green curve), since welfare losses in CEA do not include any measure related to temperature. Comparing the results of the 2010 scenario for CRA using a linear risk metric to CEA, Neubersch et al. (2014) find that the mitigation costs for immediate action are slightly higher in CRA (1.3% vs. 1.49% CBGE). The reason for the difference is the consideration of the whole temperature path under CRA, which rewards temperature reductions above the guard rail. In contrast, CEA does not account for the temperature paths for SOWs which are already above the guard rail. Therefore, no incentive exists to further reduce emissions, when the target is met. Consequently, mitigation and their costs accordingly are higher in CRA.

Risk-related welfare losses drive the increase of total welfare losses due to the delay. They are caused by increasing overall cumulative emissions, as depicted in Figure 3b. Cumulative emissions increase by 540 GtC from 690 GtC (2010 scenario) to 1230 GtC (2050 scenario). This leads to an increase in global mean temperature and consequently is driving risk.

In stark contrast, the utility-related welfare losses decrease. For the linear risk metric, they decline from 1.49% (2010 scenario) to 0.36% (2050 scenario). This effect is caused by decreasing mitigation efforts i.e. rising cumulative emissions. However, this effect is dominated by the increase in risk-related CBGE losses. Nevertheless, the decreasing utility-related welfare losses can be seen as an incentive to delay climate policy for decision makers who ignore climate risks that are implicitly implied by the 2°C (66% safety) target.

The effect of the delay on utility-related welfare losses is invariant to the choice of the risk metric. Hence, the green curves in Figure 3a coincide. This is due to cumulative emissions not being substantially affected by the functional form of the risk metric, as shown in the following.

The Role of the Risk Metric

MIND comprises several control variables representing investments into capital, factor productivity and different energy sources. All of these choices affect the emission trajectories. For the sake of reduced complexity and improved graphical representation we reduced the decision problem to one dimension, i.e. the decision about cumulative emissions E. The time dimension can be prescinded aggregating discounted values over time. This reduced decision problem can be represented through the simplest formulation of CRA:

$$\min_{E} \{C(E) + \beta_{\text{cal}}\, \mathbb{E}[R(E)]\} \tag{3}$$

with the mitigation cost function $C(E)$ and the risk function $R(E)$. $\mathbb{E}[.]$ represents the expected value operator. Both functions can be determined numerically. We derive the mitigation cost function in MIND through simulation runs that maximize utility (not considering risk) with varying constraints on cumulative emissions E. The associated utility loss to reach a given level of cumulative emissions compared to an unconstrained optimization can be interpreted as mitigation costs measured in welfare units.

Applying the approximation by Allen et al. (2009), which states that maximum temperature is a linear function of cumulative emissions, we can reasonably neglect the timing of emissions. This enables us to determine a temperature path for each cumulative emissions level. In a second step, risk is calculated according to the predefined metric. Finally, risk is discounted and aggregated over time, averaged over all states of the world and weighted with the calibrated trade-off parameterβ_{cal}.

The optimum of the decision problem stated in Equation (3) is found where welfare losses, i.e. the sum of mitigation costs and risk are minimized. The optimum level of E is the point where marginal costs (MC) and marginal (calibrated expected) risk (MR) equal each other, i.e. $-\text{MC}\,(E^*) = \text{MR}\,(E^*)$. We determined the marginal functions through finite differences.

The numerically found marginal functions are depicted in Figure 4 for two different temperature guard rails, i.e. 2°C in panel (a) and 3°C in panel (b). Continuous colored lines represent MR curves for four different risk metrics. Brown dashed lines represent MC curves. For lucidity, MC curves for only half of the delay scenarios are shown.

In both panels all MR curves intersect with the MC curve for the 2010 scenario in one point. This has to be the case, because the model was calibrated, such that the predefined cumulative emissions level E_g is optimal independent of the risk metric used. E_g corresponds to the predefined climate target. In MIND the guard rail 2°C with a safety of 66% corresponds to $E_g = 690$ GtC, whereas for the guard rail 3°C this almost

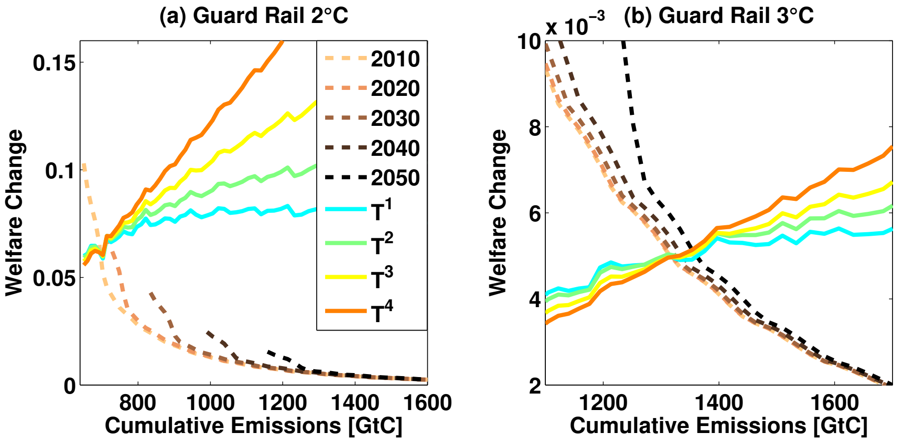

Figure 4: Marginal costs (MC) and marginal risk (MR) as functions of cumulative emissions for two different temperature guard rails, i.e. 2°C (panel a) and 3°C (panel b). Colored lines indicate MR curves for four different risk metrics. Dashed lines indicate MC curves for different delay scenarios. Note the different scale of the axes in the two panels. The intersection of MR and MC reflects the optimal solution with regard to cumulative emissions.

doubles to $E_g = 1320$ GtC. To make the curves in panel (b) visible, the figure is displayed zoomed in compared to panel (a).

Under the approximation by Allen et al. (2009), the delay does not affect the MR curve because the constraint is set on cumulative emissions and it is irrelevant when they are emitted. The MC curves do get affected by the delay because a delay requires stronger mitigation efforts in a smaller period of time (Bertram et al., 2013; Acemoglu et al., 2012). Three different qualitative regimes of the effect on the MC curves can be distinguished: (i) low levels of E become infeasible after the delay. The MC curve after the delay is not defined anymore for these low levels. (ii) MC for the most ambitious levels of E, which are feasible after the delay, are higher. Any delay of an additional decade increases MC only in a limited range of E of approximately 100 GtC.[3] MC for higher values of E are not affected, lower values of E are infeasible. (iii) Any delay until 2050 only has a negligible effect on the MC curves for $E{>}1400$ GtC.

Focusing on panel (a), it becomes clear that the preferences implied by the 2°C guard rail represented by the MR curves are quite challenging, i.e. they imply to accept strong mitigation efforts and corresponding mitigation costs. For any delay beyond 2020 maximum mitigation becomes optimal from a CRA perspective. The MC curves lie below the MR curves, i.e. the additional risk of an emission unit is always larger than the costs to mitigate it. Consequently, it is optimal to mitigate as much as possible in order to minimize the welfare losses. This is why cumulative emissions, as depicted in Figure 3b are increasing that strong. Lower levels of E would be beneficial, but are not feasible anymore after the delay. This result holds for all non-concave risk metrics, because the

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[3] For example, comparing scenarios 2030 and 2040, marginal costs are increased for $E \in [1000; 1100]$.

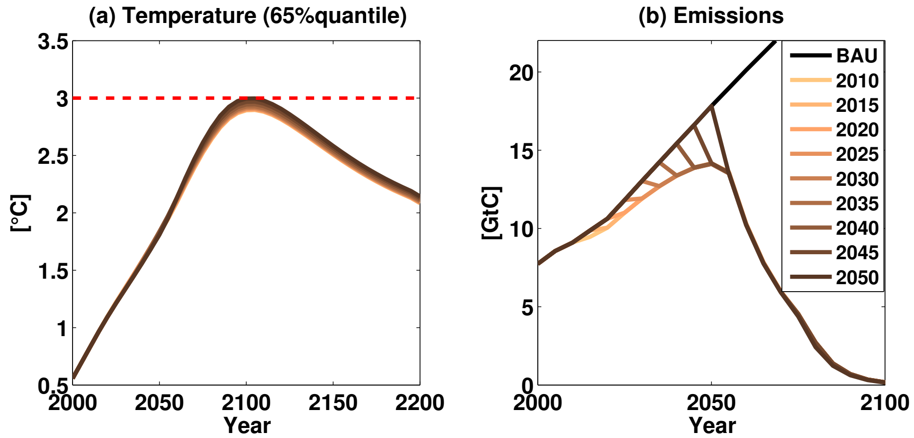

Figure 5: Effect of delayed climate policy on (a) temperature paths of the 65% quantile and (b) on CO_2 emissions for a calibration target with guard rail 3°C and safety 66%. Legend indicates the delay scenario.

limiting case of a linear risk metric already yields these corner solutions. More convex risk metrics will not make a difference. This explains why utility-related welfare losses in Figure 3a are not affected by the chosen risk metric.

A modified Guard Rail

A relaxation of the climate target increases the associated cumulative emissions level E_g and thereby provides more flexibility. As an exemplary relaxation a modified guard rail of 3°C is chosen. The MC and MR curves for this climate target are shown in panel (b) of Figure 4. It is directly visible that any considered delay only has a small or even negligible effect on mitigation costs in the relevant range of E. The MC curves of all delay scenarios are quite similar. Therefore an intersection with the MR curves still exists even for the 2050 scenario. The overall cumulative emissions increase by 60 GtC (4.5%), from 1320 GtC to 1380 GtC for a delay of 40 years. This increase can be called small, compared to the increase of 540 GtC (78%) for the same delay, but a temperature guard rail of 2°C. Differences due to the chosen risk metric are small, because in the relevant range of E, the MR values are equalized through the calibration.

To underline the difference between the two considered climate targets Figure 5 shows temperature (panels a) and CO_2 emission (panel b) trajectories for a climate policy aiming at limiting temperature increase to 3 °C with a safety of 66%. A comparison with the temperature trajectories shown in Figure 2a makes it obvious that the effect on temperatures caused by a delay up to 40 years is bearable for the relaxed guard rail. The reason can be seen in the emission paths. The difference in emissions between the climate policy scenarios and the BAU scenario until 2050 is small. Consequently excess emissions that cause temperatures to rise above the guard rail are moderate.

4 Discussion and Conclusion

CRA is the first method that enables a community supporting climate targets to evaluate a delay in climate policy with an arbitrary length because the scope of CRA is not restricted to delays that do not violate the target.

Our analysis yields the following results: (i) Using the most conservative risk metric i.e. a linear one, welfare losses double for a 40 year delay of climate policy, that initially aims at limiting global mean temperature rise to 2 °C above the preindustrial level with a safety of 66%. (ii) The welfare losses are only driven by increasing risk. Mitigation costs and associated welfare losses are even decreasing, which can be seen as an incentive to delay mitigation efforts for decision makers who ignore risk. (iii) For the 2°C guard rail with safety 66%, independently of the applied risk metric, maximum mitigation is optimal for any delay scenario beyond 2020. A 2° target-oriented decision maker would therefore invest "as much as possible" to reduce emissions and risk-related welfare losses. This conclusion is qualitatively in line with previous works conducting CEA. However, our analysis helps to understand the preferences implied by this climate target and underline its stringency. (iv) For any climate target the effect of the delay depends on the excess emissions during the delay. We exemplify, that a delay of 40 years only causes moderate effects for a 3°C guard rail with safety 66% compared to the 2°C target. (v) On a methodological level, we find that the choice of the risk metric only plays a minor role for optimal decisions, at least for the climate targets considered. Nevertheless it is an important choice, when evaluating and comparing different scenarios.

We highlight the important role of the applied IAM MIND, especially the representation of the energy system as it determines mitigation costs. The prominent role of maximum mitigation in our results demand for improved investigations about the determinants of maximum mitigation. In MIND it is defined through a simple bound on relative emission reductions. It may be crucial to consider determinants of the social-political system that usually lie beyond the scope of an IAM. We did not include negative emission technologies in the analysis. However, this could make a difference and therefore is the next step in the further development of the analysis. Further, it is an interesting task to combine our work with the study by Neubersch et al. (2014), who include learning about climate sensitivity. It would be of special interest to investigate the incentives to postpone climate policy beyond learning in CRA.

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