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# Costs of avoiding net negative emissions under a carbon budget

Kaj-Ivar van der Wijst[1,2,*], Andries F Hof[1,2] and Detlef P van Vuuren[1,2]

[1] PBL Netherlands Environmental Assessment Agency, Den Haag, The Netherlands
[2] Copernicus Institute of Sustainable Development, Utrecht University, Utrecht, The Netherlands
[*] Author to whom any correspondence should be addressed.

**E-mail:** kajivar.vanderwijst@pbl.nl

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Supplementary material for this article is available online

## Abstract

The 2 °C and 1.5 °C temperature targets of the Paris Agreement can be interpreted as targets never to be exceeded, or as end-of-century targets. Recent literature proposes to move away from the latter, in favour of avoiding a temperature overshoot and the associated net negative emissions. To inform this discussion, we investigate under which conditions avoiding an overshoot is economically attractive. We show that some form of overshoot is attractive under a wide range of assumptions, even when considering the extra damages due to additional climate change in the optimisation process. For medium assumptions regarding mitigation costs and climate damages, avoiding net negative emissions leads to an increase in total costs until 2100 of 5% to 14%. However, avoiding overshoot only leads to some additional costs when mitigation costs are low, damages are high and when using a low discount rate. Finally, if damages are not fully reversible, avoiding net negative emissions can even become attractive. Under these conditions, avoiding overshoot may be justified, especially when non-monetary risks are considered.

At the 21st Conference of the Parties to the United Nations Framework Convention on Climate Change in 2015, 174 countries ratified the Paris Agreement. They agreed to limit global mean temperature change to well below 2 °C and pursue efforts to stay below 1.5 °C above pre-industrial levels. Different interpretations of such temperature targets can be found in the literature, i.e. either a value that can never be exceeded or something that needs to be achieved this century (allowing a temporary overshoot). Given the near-linear relationship between $CO_2$ emissions and global temperature change, the former translates into a peak carbon budget, i.e. the cumulative net $CO_2$ emissions until net-zero $CO_2$ emissions is reached. In contrast, the latter translates into a net carbon budget during the 21st century (in both cases assuming an equivalent reduction of non-$CO_2$ greenhouse gas emissions). Many of the scenarios developed by integrated assessment models (IAMs) used in the fifth assessment report of the IPCC followed the second approach: first, they exceeded the carbon budget (for a short period), after which the excess emissions were compensated by net negative emissions towards the end of the century [1, 2]. In response, there has been a lively debate in the literature about both the risks related to (net) negative emissions and the allowance of overshoot [3, 4].

In this context, Rogelj *et al* [5] proposed to replace the end-of-century budgets with so-called peak budgets. Interestingly, in their proposal, little consideration was given to the related costs and benefits of avoiding net negative emissions. On the one hand, avoiding overshoot avoids the extra damages from climate change incurred throughout the century as a result of exceeding the temperature target. On the other hand, it also leads to less flexibility in the timing of mitigation, leading to higher mitigation costs (up to 80% higher in current IAM literature scenarios [6]). In this paper, we fill this gap by investigating the net effect of these opposite economic impacts of avoiding overshoot. More specifically, we determine under which conditions peak budgets might be an attractive strategy from an economic perspective and under which conditions it would not be.

The answer to these questions depends on several factors, such as the severity of damages, discount rate, climate sensitivity, and mitigation costs. We perform a sensitivity analysis covering the literature ranges for each of these factors to investigate the economic effect of the decision not to allow overshoot—therefore providing evidence of the rationality of such a choice based on abatement costs and damage costs. This informs the debate about the (dis)advantages of net negative emissions. It should be noted that this is not accounting all factors. Negative emissions could also impact biodiversity and food security [7, 8] (depending on the choice of technology and uncertainties regarding efficiency and management; some amount of negative emissions can probably be generated with relatively little impacts [3]).

An additional novel aspect of our research in the discussion of the role of negative emissions related to carbon budgets is that we take into account partially irreversible damages. Most, if not all, traditional IAMs assume that when temperature decreases, damages decrease accordingly [9]. However, some types of damages, such as disappearing glaciers and species extinction, are irreversible, and, therefore, will remain even when temperature declines. We propose a modelling framework including partially irreversible climate damages in an IAM setting.

## 1. Economic impact of avoiding net negative emissions

We analyse the economic impact of avoiding net negative emissions using a simple and transparent IAM similar to DICE [10] (see section 5). Gross GDP is calculated in this model using a production function based on technological progress (total factor productivity, TFP), capital and population. Both climate mitigation costs and damage costs resulting from climate change impacts are subtracted from the gross GDP. The resulting net GDP is divided in a fixed share to consumption and investments. Therefore, the mitigation and damage costs induce a direct loss of consumption and an indirect effect on economic growth by affecting investments. The model maximises the total discounted per capita utility, which is a concave function of per capita consumption, using pure rate of time preference (PRTP) values spanning the current literature range. The temperature is calculated as a linear function of cumulative emissions using the transient climate response to emissions (TCRE) relation [11]. We calibrated all factors in the model based on the literature (see section 5). For mitigation costs, the mitigation potential as a function of costs is calibrated to the literature range in the IPCC scenario database for AR5 and SR1.5 (underlying a range of mitigation options). In a scenario where net-negative emissions are allowed, the yearly $CO_2$ emissions are limited to $-20$ $GtCO_2$ $yr^{-1}$ representing the limits due to biophysical, technical, economic and sustainability constraints. In the literature a wide range of values for the contribution of net negative emissions can be found, ranging from 0 to more than 40 $GtCO_2$ $yr^{-1}$ [3, 12], similar to the literature range for high overshoot scenarios in the IPCC SR1.5 database (5–30 $GtCO_2$ $yr^{-1}$) [13, 14]. Avoiding net-negative emissions sets this limit to 0 $GtCO_2$ $yr^{-1}$. Unless stated otherwise, the end-of-century carbon budget is set to 600 $GtCO_2$, in line with a 1.5 °C target [13] (median climate temperature estimate). Finally, for damage costs, we use a stylised function that can be scaled (using a damage coefficient) to mimic the entire range from the DICE damage function [10] to the long-run damage function from Burke *et al* [15], with as default medium damage estimate, the meta-model damage estimate from Howard *et al* [9]. For baseline assumptions, we use the SSP2 scenario (covering medium estimates for GDP, population and emission growth, see section 5).

The economically optimal emission paths and associated macroeconomic costs of a scenario with and without net negative emissions are shown in figure 1. These results are created using a medium mitigation cost level, medium damage function (i.e. Howard Total, see section 5), medium TCRE and the three PRTPs spanning the current literature range: 0.1% $yr^{-1}$, as used in the Stern review [16], 1.5% $yr^{-1}$, as used in DICE-2007 and following versions [17], and 3% $yr^{-1}$, as used in the original DICE model [18].

In a scenario where net negative emissions are avoided, strong emission reductions need to occur in the first half of the century to stay within the carbon budget (figure 1(a); dotted versus solid lines). In the scenarios that allow for net negative emissions, some mitigation effort is delayed to the second half of the century, reaching net zero around 2075 instead of 2050. While the net negative emissions have a higher marginal cost, the fact that they occur later in combination with discounting makes their use economically attractive. This also means that a lower PRTP significantly reduces the amount of net negative emissions, from 469 $GtCO_2$ with a 3% PRTP to 115 $GtCO_2$ for 0.1% PRTP (figure 1(b); see also figure 1(a) for time profile). This corresponds to a temperature overshoot of 0.29 °C and 0.07 °C respectively (similar results were found in previous studies [19]).

Avoiding net negative emissions leads to a reduction in damage costs varying from 10% to 34%, caused by a combination of avoiding overshoot and earlier mitigation effort (figure 1(c)). Simultaneously, the mitigation costs increase between 9% for low discount rates and 37% for the highest discount rate assumed, leading to an increase in total costs (sum of damage and mitigation costs) of 5% to 14%. Both damage and mitigation costs are calculated using their net present value (NPV) (2020–2100) with a fixed 4% social discount rate, regardless of their PRTP value (see section 5).

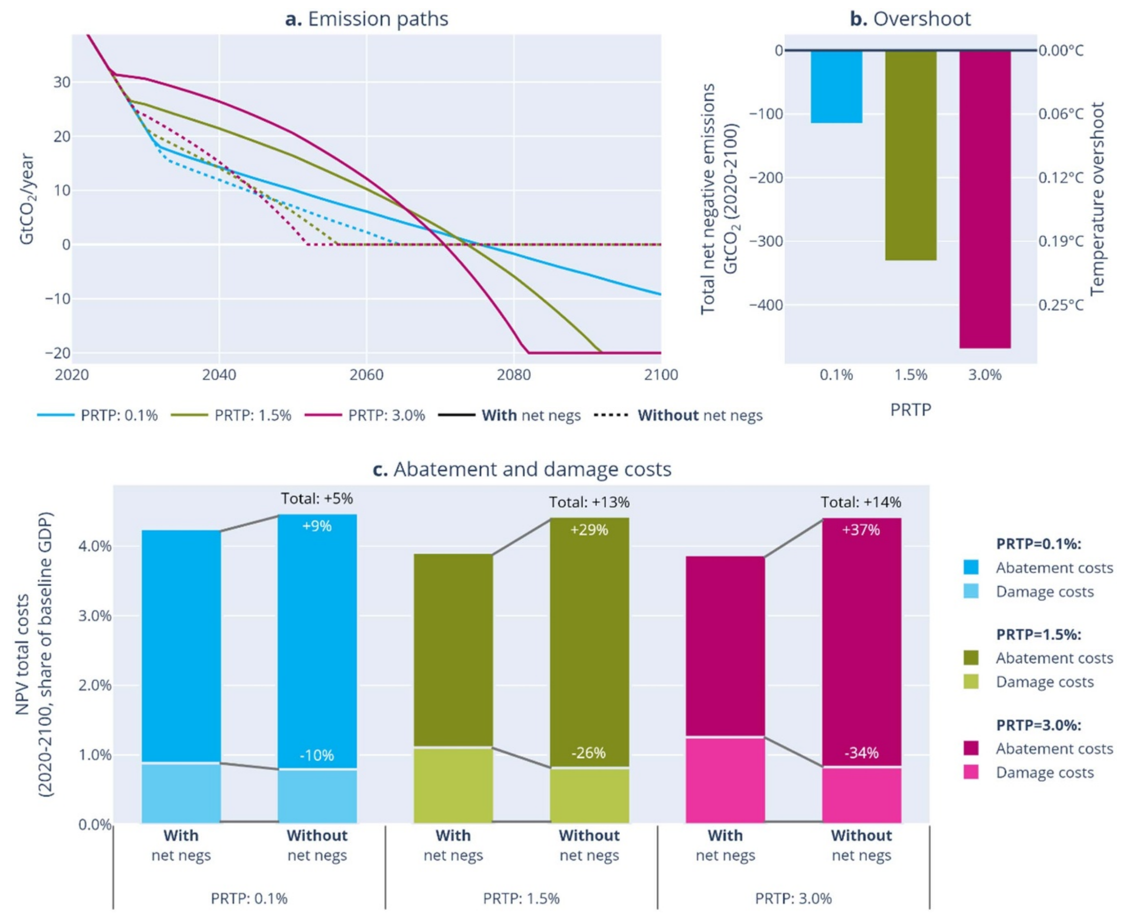

**Figure 1.** Difference in emission paths (a), (b) and costs (c) between a scenario with and without net negative emissions. These results are calculated for medium mitigation cost, medium TCRE and medium damage function (Howard Total) settings. The NPV of the damage and mitigation costs are calculated with a fixed discount rate of 4% $\text{yr}^{-1}$, regardless of the PRTP used.

In other words, in all cases, allowing for some negative emissions is for medium parameters settings for mitigation and damage costs, from an economic perspective, attractive (even if damages are accounted for). The level of this preference, however, depends on the discount rate.

An important aspect to consider is the timing of mitigation effort and incurred damages. In figure 2, we show the abatement costs and damage costs over time. For medium parameter values, the peak of total costs (abatement plus damage costs) occurs towards the end of the century when allowing net negative emissions (2%, 5% and 8% of GDP for respectively 2030, 2060 and 2090). When net negative emissions are not allowed, the peak in total costs is much earlier, albeit slightly lower (4%, 6.5% and 4% of GDP for 2030, 2060 and 2090). Once the minimum emission level is attained, the relative mitigation costs decrease due to technological learning and the increasing baseline GDP of SSP2. The corresponding global carbon prices are shown in supplementary figure 7 (available online at stacks.iop.org/ERL/16/064071/mmedia) and reach a maximum of 800–1000 USD/tCO when avoiding net negative emissions and 810–1250 USD/tCO when net negative emissions are allowed (as a comparison, the European Trading System carbon prices are around 40 €/$\text{tCO}_2$ in 2021).

Besides discounting, the assumed level of climate damages plays an important role in determining the economic attractiveness of net negative emissions as well. In figure 2, we perform a sensitivity analysis on the damage function (specifically, the damage coefficient, see section 5). We use a low damage function (DICE, giving 2% GDP loss at 3 °C warming), a medium one (Howard Total, 9% GDP loss at 3 °C) and a high damage function (Burke LR, 22% GDP loss at 3 °C). For the low damage function, the extra mitigation effort early in the century when avoiding net negative emissions leads to much higher total costs (19% to 29% increase in NPV of total costs). However, when the damage function is high, the early emission reduction leads to significantly lower damages, making the total cost difference smaller.

For the Burke damage function with low PRTP, the total costs are minimal when no net negative emissions are used. For such a high damage function, the economically optimal emission path is to reduce as much as possible at any point in time. Allowing net negative emissions allows for deeper reductions throughout the century, with corresponding

**Figure 2.** Timing of abatement costs (light shade) and damage costs (dark shade) for scenarios without (yellow) and with (purple) net negative emissions, as a percentage of GDP. The columns represent three levels of damage functions (low, medium and high), the rows represent three values of the PRTP. The grey bars give relative change in NPV (2020–2100) of total costs (abatement plus damage costs) when avoiding net negative emissions. The NPVs are calculated using a fixed social discount rate of 4% $\mathrm{yr}^{-1}$. When this change is negative, the economic benefits of allowing net negative emissions only happen after 2100.

higher mitigation costs but lower damages. The effect of these lower damages increases further after 2100. Since in figure 2, we report the NPV from 2020 to 2100, but we optimise discounted utility until 2150, it is possible to obtain higher total costs until 2100 in a scenario with no net negative emissions than in a scenario with negative emissions.

The damage function (specifically, the damage coefficient, see section 5) and the mitigation cost level have an equally strong influence on the difference in total costs. We perform a sensitivity analysis on these three factors: PRTP, damage coefficient and mitigation cost level. For each combination of parameter values, we run a scenario with and one without net negative emissions and calculate the increase in total costs between the two (supplementary figure 11). The extra costs, from low mitigation costs to high mitigation costs, range from +0% to +24% (with medium values for the other parameters). For damage cost uncertainty, the extra costs range from +0% to +28% from low damages (DICE) to high damages (Burke), again with all other values medium.

Higher mitigation costs always lead to higher additional costs of avoiding negative emissions, as depicted by the differences between the panels in supplementary figure 11. The impact of damage cost uncertainty is similar to the impact of mitigation cost uncertainty: the higher the damage coefficient, the earlier the mitigation effort occurs to avoid high climate damages later in the century. Early abatement action leads to a decrease in total net negative emissions (supplementary figure 8). In fact, the emission paths, and associated cost differences between allowing and avoiding net negative emissions of a scenario with low mitigation cost and medium damage function are very similar to a scenario with medium mitigation costs and high damages. The total costs, relative to GDP, are, of course, significantly higher in the latter scenarios.

Interesting interactions between these parameters can be observed. First, the influence of damage costs uncertainty on timing increases with lower mitigation costs, simply because the relative importance of damages in total costs increases. As a result, in the case of low mitigation costs and high damages, avoiding negative emissions hardly leads to additional total costs. The additional costs even become slightly negative, as was already shown for high damages and low discounting in figure 2, which is possible as utility until 2150 instead of total costs until 2100 is optimised. It can also be noted that the impact of higher damage estimates becomes non-linear for the combination of low mitigation cost levels and low PRTP: in that case, the optimal emission path stays significantly below the set carbon budget (see supplementary figure 9). For this set of parameters, a higher damage coefficient

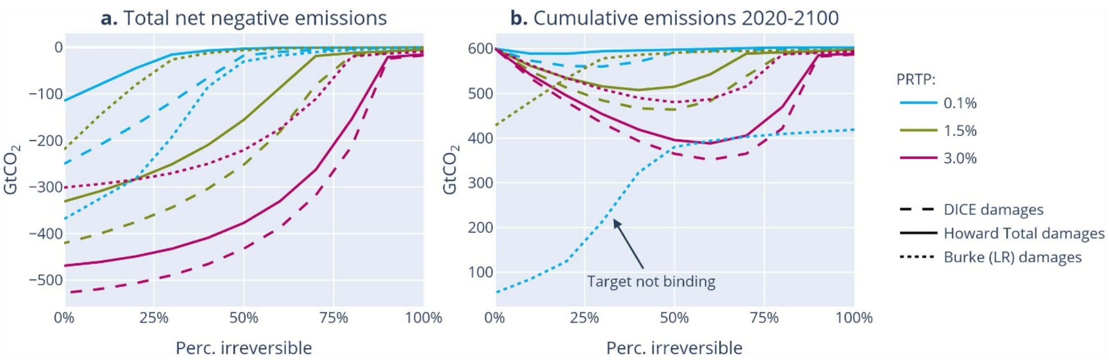

**Figure 3.** Effect of assuming partially irreversible damages. (a) The total amount of net negative emissions. (b) The cumulative emissions from 2020 to 2100, as a function of the percentage of irreversible damages. The colours represent the PRTP, while the dash/dot respectively the low and high damage function. All scenarios are run with a maximum damage target for 2100 derived from a carbon budget of 600 $GtCO_2$.

leads to more net negative emissions to keep climate-related damages at a minimum.

The costs differences become significantly lower when using a less stringent carbon budget. When using a carbon budget reaching 2 °C instead of 1.5 °C, avoiding net negative emissions only leads to extra costs when mitigation costs are high, or damages low (supplementary figure 18).

The effect of using the low or high instead of the median value of the TCRE is only significant for high damage coefficients. A high TCRE accentuates the effect of climate impacts resulting in more negative emissions if allowed in the scenario (supplementary figure 8).

## 2. Partially irreversible climate damages

We have shown that if climate damages are reversible, it is in most cases *economically* optimal to allow some net negative emissions (and thus exceed the peak budget). However, not all damages are likely to be fully reversible. While climate impacts like reduced yields, health impacts and extra energy consumption for air conditioning are likely to be reversible, disappearing glaciers, species extinction and biodiversity loss are clearly irreversible processes. For other impacts, reversibility is more uncertain: while sea-level rise could be considered an irreversible process due to ice melting, the slow timescale at which it occurs also makes it relatively insensitive to a limited period of temperature overshoot.

Here, we investigate the consequences of assuming that a share of the damages is irreversible. The implementation details are discussed in SI 1.1. However, to properly assess the impact of (ir)reversibility of climate impacts, the carbon budget constraint must be changed. The reason is that the damages (and thus the optimal pathways) do not depend anymore on the cumulative net emissions. In fact, enforcing a carbon budget goal could be so restrictive that the model shows negative emissions even without any reversibility, which does not make any economic sense. We therefore translate the carbon budget to a maximum damage target for 2100 (see section 5). Such a maximum damage target inevitably depends on the assumed damage function. The 600 $GtCO_2$ carbon budget translates to maximum damage costs in 2100 of respectively 0.25%, 1% and 2.7% of GDP for the DICE, Howard Total and Burke (LR) damage functions.

Figure 3(a) shows that the amount of economically optimal net negative emissions is strongly dependent on the percentage of irreversible damages. For low discounting, net negative emissions are almost entirely unattractive when 30% of damages are irreversible. This happens at around 70% of irreversibility for medium discounting—but the use of net negative emissions is already lower by a factor of 2 if 50% of damages are irreversible. For high discounting, the irreversibility of damages only becomes significant beyond a share of 50%.

As a consequence of the irreversibility of damages, net negative emissions need to be compensated by extra mitigation effort to reach the maximum damage target (figure 3(b)). When damages are (almost) fully reversible, the cumulative emissions are close to the original carbon budget from which the damage target was derived, even when using a high amount of net negative emissions (left part of figure 3(b)). When damages are partially irreversible, it becomes economically attractive to have some overshoot (155 $GtCO_2$ for medium assumptions), even at the cost of extra mitigation effort (85 $GtCO_2$ for medium assumptions, middle part of figure 3(b)). When damages are even more irreversible, net negative emissions become less attractive, leading again to cumulative emissions close to the original carbon budget (right part of figure 3(b)).

An exception for this is the combination of high damage function and low discounting (dotted blue line in figure 3(b)): the damage target constraint is not economically optimal anymore, resulting in lower cumulative emissions than prescribed by the maximum damage target.

## 3. Discussion

### 3.1. Time evolution of GDP

Avoiding an emission overshoot requires earlier mitigation effort, leading to increased total discounted costs (figure 1(c)). This influences the GDP growth path. As shown in supplementary figure 6, the mitigation costs in 2030 are twice as high when avoiding the overshoot, while the damages are still the same with and without net negative emissions. By 2070, the total costs (mitigation and damage costs) reach the same level in both scenarios. At the end of the century, the absolute GDP level of the scenario avoiding overshoot is significantly higher since the mitigation costs for the negative emissions start to increase after 2070. However, since we optimise on cumulative discounted utility and not on final GDP, the overshoot scenario is still economically favourable. Moreover, since the net negative emission costs are assumed to be phased out after 2100 to keep the same carbon budget, the GDP paths of both scenarios will gradually converge.

### 3.2. Non-monetary aspects

In this paper, we only consider the macroeconomic effects of different emission paths: the increased monetary cost of climate policy (abatement costs) and the reduction of climate change damage due to earlier abatement effort. However, as mentioned in the introduction, this does not include the extra pressure on ecosystems and biodiversity due to the increased use of land-use related negative emission options such as BECCS and afforestation [3, 7, 8], the massive logistical and political bottlenecks associated with upscaling negative emission technology [20, 21], or the risks of non-performance at any point in the future. While it seems that some amount of negative emissions can be achieved without too many negative side effects [3] (or that some technologies, like afforestation and soil carbon management, could even have some co-benefits), the negative other consequences should still be weighed against the economic results presented in this paper.

### 3.3. Reversibility of climate damages

We have shown that the amount of net negative emissions is strongly dependent on the extent to which climate damages are reversible. However, 'reversibility' in climate change is a broad concept. In the literature on reversibility and climate change, three distinct effects are described, mostly independently of each other. First, climate reversibility, describing how temperature behaves under decreasing concentrations of atmospheric $CO_2$. Second, the impact reversibility, which analyses how, and if climate damages decrease when temperature decreases. Third, the economic persistence, which treats the long term economic effects of a shock due to climate change.

Regarding the first topic of climate reversibility, our model assumes that temperature is directly proportional to cumulative emissions. Previous research has shown [22–24] that the assumption of fixed temperature/concentration relation might not fully hold: under decreasing atmospheric $CO_2$ concentrations, temperature decreases at a slower rate than when concentrations are rising. The impact is relatively small for a relatively small overshoot and the discrepancy with our modelling method, which focuses on the reversibility of damages is expected to be small.

The second concept, impact reversibility, is what we consider in this paper as irreversible climate damages. As already described, due to irreversible processes in biodiversity loss, melting glaciers and socio-economic tipping points, not all damages will decrease when temperature decreases.

The third concept is economic persistency. Empirical economic research has shown that climate change does not only induce direct monetary losses (like destroyed real estate after a flood) but also impacts economic growth [15, 25, 26]. The latter has a much longer-term effect. This paper considers this indirectly by using the Burke *et al* [15] damage function at the high end of our sensitivity range on climate damages. While we have translated the growth effects of Burke *et al* to a direct temperature–GDP loss relation (therefore not affecting growth rate), the underlying calibration still uses growth impacts (see section 5).

While the second and third concepts (impact reversibility and economic persistence) might be related, the exact relationship is still unclear. In fact, economic persistence also happens when temperatures are increasing, whereas impact reversibility is only relevant for decreasing temperatures.

### 3.4. Comparison to other literature

The increased mitigation costs when avoiding net negative emissions have already been assessed by Hilaire *et al* [6] They analysed recent IAM mitigation scenarios reaching 1.5 °C and 2 °C with varying levels of negative emissions. For the 1.5 °C target, mitigation costs go from 2.26% of GDP for unconstrained BECCS to 4.1% of GDP with limited BECCS (both cost values are NPV 2010–2100, 5% $yr^{-1}$), an increase of over 80%. In this study, we find an increase in mitigation costs of 9% to 37% for medium parameter values. This large discrepancy comes from two reasons. First, we calculate the NPV using a smaller discount rate of 4% instead of 5%, giving more weight to future generations (if we used 5%, the cost increase would be up to 53% for medium values). Second, and most importantly, we take damages into account when calculating the economically optimal emission trajectory, whereas most traditional IAMs under carbon budget calculate the cost-effective path, ignoring climate damages.

## 4. Conclusions and implications

Our results suggest that economically, some form of overshoot is attractive, even when considering the extra damages in the optimisation process. The choice to avoid negative emissions, and thereby interpreting the Paris Agreement target as a 'no overshoot' target will lead to a sum of abatement costs and damage costs that is around 13% higher than without the restriction when using a PRTP of 1.5% and the medium damage function. Still, the cost differences are much smaller if mitigation costs are assumed to be relatively small (compared to the literature median), damages high, or when a low discount rate is used. Moreover, assuming that climate damages are not fully reversible significantly reduces the attractiveness of net negative emissions. Assuming that 50% of damages are irreversible leads to 50% lower total net negative emissions, since extra mitigation effort is required to reach the same maximum damage target when using net negative emissions. Under a wide range of assumptions on damages, mitigation costs, time preference, reversibility of damages, we find that the attractiveness of negative emissions is much lower than often shown in scenarios based on optimisation of mitigation costs only.

## 5. Methods

In this paper, we use a simple and transparent IAM described in detail in the SI. The model is similar to DICE [10]. Gross GDP is calculated using a production function based on technological progress (TFP), capital and population. The mitigation costs and the damage costs resulting from climate change impacts are subtracted from the gross GDP. The net GDP is divided in a fixed part (21%) of investments and the rest to consumption. The model maximises the total discounted per capita utility, which is a concave increasing function of per capita consumption. Greenhouse gas emissions are calculated by multiplying economic activity with an emission factor.

Each timestep, the emissions are added to the cumulative emissions. The cumulative $CO_2$ causes a change in global mean temperature, modelled through the instantaneous and linear TCRE relation [11]. This relation includes a linear relation between non-$CO_2$ and $CO_2$ emissions. The global mean temperature, in turn, determines the damage costs. In response, the model can determine to mitigate emissions. The mitigation level (or equivalently the carbon price) over time is determined by maximising the NPV of utility. The mitigation costs are subtracted from investments and consumption.

### 5.1. Calibration

The parameters are as much as possible calibrated against existing literature. Population, baseline emission intensity and TFP are exogenous and calibrated to match the growth rates of the shared socio-economic pathways (SSPs) [27]. We use the SSP2 ('Middle of the Road') scenario which has medium assumptions about population growth, emissions, GDP, technological growth and lifestyle. For details, see Riahi *et al* [27] and for the exact implementation in our model see SI 1.2.

Emission reductions are quantified through a quadratic marginal abatement cost (MAC) curve. The area under the MAC gives the mitigation costs. The resulting mitigation costs are calibrated using the consumption loss range of the 5th Assessment Report of the IPCC [1]. To consider the wide range in mitigation costs, we perform a quantile regression on the AR5 data points to the 5th, 50th and 95th percentiles to represent the low, medium and high end of the mitigation cost range. The 5th percentile leads to mitigation costs 2.5 times smaller than the median costs, the 95th percentile 2.5 times larger.

The damage function is defined as a quadratic function of global mean temperature $T$:

$$D(T) = c \cdot T^2,$$

where $D(T)$ is the fraction of GDP loss due to climate impacts. The damage coefficient $c$ is calibrated to capture the full literature range.

At the low end, we choose the DICE-2013R damage function [10] with $c = 0.00267$. The medium estimate is based on the results from a meta-analysis of literature damage functions by Howard *et al* [9], with a damage coefficient of $c = 0.01004$. The high end of the range is parametrised by the long-run empirical damage from Burke, Hsiang and Miguel [15]. While their damage estimates are quantified as impacts on growth rates and not directly on GDP, we use the iterative strategy from recent literature [28] to create a damage function usable by IAMs like our model. The idea of this method is to calculate which direct GDP losses would result in the same GDP path as when Burke's growth impacts are used. Iteratively, a damage curve (as function of temperature change) is created giving the same damages as the growth impact definition [29]. A quadratic function is then fitted to the resulting approximation ($R^2 = 0.99$), leading to $c = 0.02835$, about ten times higher than the DICE damage function.

The utility discount rate, called throughout this paper the PRTP, is chosen to be 0.1% $\text{yr}^{-1}$, as used in the Stern review [16], 1.5% $\text{yr}^{-1}$ and 3% $\text{yr}^{-1}$, as used in DICE-1999, DICE-2007 and following versions [17, 30]. The elasticity of marginal utility is

1.001. The combination of PRTP and elasticity of marginal utility are in line with the expert elicitation by Drupp *et al* [31].

The minimum yearly emission level in the scenarios without net negative emissions, is, by definition, set at 0 $GtCO_2$. The potential for net negative emissions is limited by biophysical, technical, economic and sustainability constraints. In the literature a wide range of values for the contribution of net negative emissions can be found, ranging from 0 to more than 40 $GtCO_2\ yr^{-1}$. For instance, Fuss *et al* [3] estimated a maximum sustainable supply of about 5 $GtCO_2\ yr^{-1}$ for individual CDR options in 2050—but the combination of these options could be higher, while Hanssen *et al* [12] showed a maximum potential of 40 $GtCO_2\ yr^{-1}$ in 2100. The literature range for 1.5 °C scenarios in the IPCC Special Report on 1.5 °C is around 5 $GtCO_2$ to 30 $GtCO_2\ yr^{-1}$ for overshoot scenarios. Here, we limit the contribution of net negative emissions to a maximum of 20 $GtCO_2\ yr^{-1}$. Moreover, to account for technological and political inertia, we assume that the emissions cannot be mitigated faster than 2.2 $GtCO_2\ yr^{-1}$ (based on the maximum reduction speed of the IPCC 1.5 °C database [14]) for each scenario. Finally, from the year 2100 onwards, the cumulative emissions from 2020 cannot exceed a carbon budget. Unless stated otherwise, the carbon budget is set to 600 $GtCO_2$, in line with a 1.5 °C target [13].

Finally, the TCRE determines the increase in global mean temperature per unit of extra $CO_2$ emissions [11]. Using the method from van Vuuren (2020) [32], the TCRE used here is calibrated to key results from the Working Group I from the IPCC AR5 report [33]. In this paper, three values are considered, corresponding to the uncertainty range's 5th, 50th and 95th percentile. Unless mentioned differently, we use the median value for the TCRE, equal to 0.62 °C per 1000 $GtCO_2$.

The percentage of climate damages which is irreversible has, to the best of our knowledge, not been fully estimated in current literature. While several studies have shown that impacts like decreased precipitation [34] and sea level rise [35, 36] can continue to increase after atmospheric $CO_2$ concentrations have stabilised, there is notoriously less literature quantifying how these impacts behave when emissions become net negative. For this reason, we cover the full range from 0% (fully reversible) to 100% (fully irreversible), even though neither of these extremes is realistic.

### 5.2. Cost comparison

The abatement and damage costs in this paper are presented as NPV relative to baseline GDP:

$$\text{relative costs} = \frac{\text{NPV}\left(\text{abat. costs}\right)}{\text{NPV}\left(\text{baseline GDP}\right)}$$

and similar for the damage costs, where NPV is calculated as discounted sum until timestep $T$:

$$\text{NPV}\left(x\right) = \sum_{t=0}^{T} e^{-rt}\left(x\left(t\right)\right).$$

A fixed social discount rate of 4% $yr^{-1}$ is used, in line with our medium PRTP value and elasticity of marginal utility (see SI 1.2). In order to compare the macroeconomic costs of a scenario with and without net negative emissions, the ratio of their NPV GDP losses are calculated:

$$\text{cost diff.} = \frac{\text{relative costs}_{\text{with net negs}}}{\text{relative costs}_{\text{without}}} - 1.$$

## Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: http://doi.org/10.5281/zenodo.4890041, http://doi.org/10.5281/zenodo.4889971.

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## ORCID iDs

Kaj-Ivar van der Wijst https://orcid.org/0000-0002-9588-7059
Andries F Hof https://orcid.org/v000-0002-7568-5038
Detlef P van Vuuren https://orcid.org/0000-0003-0398-2831

## References

[1] IPCC 2014 *IPCC, 2014: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge: Cambridge University Press) (https://doi.org/10.1017/CBO9781107415416)

[2] Van Vuuren D P, Deetman S, Van Vliet J, Van Den Berg M, Van Ruijven B J and Koelbl B 2013 The role of negative $CO_2$ emissions for reaching 2 °C—insights from integrated assessment modelling *Clim. Change* **118** 15–27

[3] Fuss S *et al* 2018 Negative emissions—Part 2: costs, potentials and side effects OPEN ACCESS negative emissions—Part 2: costs, potentials and side effects *Environ. Res. Lett.* **13** 063002

[4] Van Vuuren D P, Hof A F, Van Sluisveld M A and Riahi K 2017 Open discussion of negative emissions is urgently needed *Nat. Energy* **2** 902–4

[5] Rogelj J, Huppmann D, Krey V, Riahi K, Clarke L, Gidden M, Nicholls Z and Meinshausen M 2019 A new scenario logic for the Paris agreement long-term temperature goal *Nature* **573** 357–63

[6] Hilaire J, Minx J C, Callaghan M W, Edmonds J, Luderer G, Nemet G F, Rogelj J and Del Mar Zamora M 2019 Negative emissions and international climate goals—learning from and about mitigation scenarios *Clim. Change* **157** 189–219

[7] Smith P *et al* 2016 Biophysical and economic limits to negative $CO_2$ emissions *Nat. Clim. Change* **6** 42–50

[8] Boysen L R, Lucht W, Gerten D, Heck V, Lenton T M and Schellnhuber H J 2017 The limits to global-warming mitigation by terrestrial carbon removal *Earth's Future* **5** 463–74

[9] Howard P H and Sterner T 2017 Few and not so far between: a meta-analysis of climate damage estimates *Environ. Resour. Econ.* **68** 197–225

[10] Nordhaus W 2014 Estimates of the social cost of carbon: concepts and results from the DICE-2013R model and alternative approaches *J. Assoc. Environ. Resour. Econ.* **1** 273–312

[11] Dietz S and Venmans F 2019 Cumulative carbon emissions and economic policy: in search of general principles *J. Environ. Econ. Manage.* **96** 108–29

[12] Hanssen S V, Daioglou V, Steinmann Z J N, Doelman J C, Van Vuuren D P and Huijbregts M A J 2020 The climate change mitigation potential of bioenergy with carbon capture and storage *Nat. Clim. Change* **10** 1023–9

[13] Masson-Delmotte V *et al* 2018 *Global Warming of 1.5 OC: An IPCC Special Report on the Impacts of Global Warming of 1.5° C above Pre-industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Chang* (Geneva: World Meteorological Organization)

[14] Huppmann D *et al* 2018 IAMC 1.5 °C scenario explorer and data hosted by IIASA 10.22022/SR15/08-2018.15429

[15] Burke M, Hsiang S M and Miguel E 2015 Global non-linear effect of temperature on economic production *Nature* **527** 235–9

[16] Hof A F, Den Elzen M G J and Van Vuuren D P 2008 Analysing the costs and benefits of climate policy: value judgements and scientific uncertainties *Glob. Environ. Change* **18** 412–24

[17] Nordhaus W D 2008 *A Question of Balance: Weighing the Options on Global Warming Policies* (New Haven, CT: Yale University Press)

[18] Nordhaus W D 1992 The 'DICE' model: background and structure of a dynamic integrated climate-economy model of the economics of global warming *Cowles Foundation Discussion Paper*

[19] Emmerling J, Drouet L, Wijst K-I V D, Vuuren D V, Bosetti V and Tavoni M 2019 The role of the discount rate for emission pathways and negative emissions *Environ. Res. Lett.* **14** 104008

[20] Field C B and Mach K J 2017 Climate: rightsizing carbon dioxide removal *Science* **356** 706–7

[21] Shue H 2017 Climate dreaming: negative emissions, risk transfer, and irreversibility *J. Hum. Rights Environ.* **8** 203–16

[22] Wu P, Ridley J, Pardaens A, Levine R and Lowe J 2015 The reversibility of $CO_2$ induced climate change *Clim. Dyn.* **45** 745–54

[23] Zickfeld K, Macdougall A H and Matthews H D 2016 On the proportionality between global temperature change and cumulative $CO_2$ emissions during periods of net negative $CO_2$ emissions *Environ. Res. Lett.* **11** 055006

[24] Frölicher T L and Joos F 2010 Reversible and irreversible impacts of greenhouse gas emissions in multi-century projections with the NCAR global coupled carbon cycle-climate model *Clim. Dyn.* **35** 1439–59

[25] Piontek F, Kalkuhl M, Kriegler E, Schultes A, Leimbach M, Edenhofer O and Bauer N 2019 Economic growth effects of alternative climate change impact channels in economic modeling *Environ. Resour. Econ.* **73** 1357–85

[26] Estrada F, Tol R S J and Gay-García C 2015 The persistence of shocks in GDP and the estimation of the potential economic costs of climate change *Environ. Model. Softw.* **69** 155–65

[27] Riahi K *et al* 2017 The shared socioeconomic pathways and their energy, land use, and greenhouse gas emissions implications: an overview *Glob. Environ. Change* **42** 153–68

[28] Glanemann N, Willner S N and Levermann A 2020 Paris climate agreement passes the cost-benefit test *Nat. Commun.* **11**

[29] Van Der Wijst K-I, Hof A F and Van Vuuren D P 2021 On the optimality of 2 °C targets and a decomposition of uncertainty *Nat. Commun.* **12** 1–11

[30] Nordhaus W D and Boyer J 2000 *Warming the World: Economic Models of Global Warming* (Cambridge, MA: MIT Press)

[31] Drupp M A, Freeman M C, Groom B and Nesje F 2018 Discounting disentangled *Am. Econ. J. Econ. Policy* **10** 109–34

[32] Van Vuuren D P, Van Der Wijst K-I, Marsman S, Van Den Berg M, Hof A F and Jones C D 2020 The costs of achieving climate targets and the sources of uncertainty *Nat. Clim. Change* **10** 329–34

[33] IPCC 2013 Climate change 2013: the physical science basis *Contrib. Work. Gr. I to Fifth* vol 1535, ed T F Stock *et al*

[34] Solomon S, Plattner G-K, Knutti R and Friedlingstein P 2009 Irreversible climate change due to carbon dioxide emissions *Proc. Natl Acad. Sci. USA* **106** 1704–9

[35] Nauels A, Gütschow J, Mengel M, Meinshausen M, Clark P U and Schleussner C-F 2019 Attributing long-term sea-level rise to Paris agreement emission pledges *Proc. Natl Acad. Sci. USA* **116** 23487–92

[36] Hinkel J, Lincke D, Vafeidis A T, Perrette M, Nicholls R J, Tol R S J, Marzeion B, Fettweis X, Ionescu C and Levermann A 2014 Coastal flood damage and adaptation costs under 21st century sea-level rise *Proc. Natl Acad. Sci. USA* **111** 3292–7