# FINANCING CLIMATE JUSTICE THROUGH CLIMATE CHANGE BONDS

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Received: 28 February 2017
Revised 1: 09 October 2017
Revised 2: 10 December 2017
Accepted: 30 December 2017

***Abstract****: Climate control needs have reached momentum. While scientists call for stabilizing climate and regulators structure climate change mitigation and adaptation efforts around the globe, economists are concerned with finding proper and fair financing mechanisms. In an overlapping-generations framework, Sachs (2014) solves the climate change predicament that seems to pit today's against future generations. Sachs (2014) proposes that the current generation mitigates climate change financed through bonds to remain financially as well off as without mitigation while improving environmental well-being of future generations through ensured climate stability. This intergenerational tax-and-transfer policy turns climate change mitigation into a Pareto improving strategy. Sachs' (2014) discrete model is integrated in contemporary growth and resource theories. The following article analyzes how climate bonds can be phased in, in a model for a socially optimal solution and a laissez-faire economy. Optimal trajectories are derived partially analytically (e.g. by using the Pontryagin maximum principle to define the optimal equilibrium), partially data driven (e.g., by the use of modern big market data) and partially by using novel cutting-edge methods – e.g., nonlinear model predictive control (NMPC), which solves complex dynamic optimization problems with different nonlinearities for infinite and finite decision horizons. NMPC will be programmed with terminal condition in order to determine appropriate numeric solutions converging to some optimal equilibria. The analysis tests if the climate change debt adjusted growth model stays within the bounds of a sustainable fiscal policy by employing NMPC, which solves complex dynamic systems with different nonlinearities.*

***Keywords****: Intertemporal decisions, Climate bonds, Climate change mitigation, Economic growth, Intergenerational burden sharing, NMPC, Nonlinear model predictive control, Social discounting alternatives, Truncated finite time horizons*

[1] Financial support of the Austrian Academy of Sciences, Fritz Thyssen Foundation, Eugene Lang Liberal Arts College of The New School, International Institute for Applied Systems Analysis, New School for Social Research, Tishman Environment and Design Center, and University of Vienna is gratefully acknowledged. The author declares no conflict of interest. The author thanks the participants of Young Scientists Scholars Program at the International Institute for Applied Systems Analysis for helpful comments on the presented ideas and Sergey Orlov for his invaluable help with the graphical solution presented. All omissions, errors and misunderstandings in this piece are solely the author's

## Introduction

Climate change accounts for one of the most pressing intertemporal problems in the age of globalization (Centeno & Tham, 2012). While classic economics portrayed balancing the interests of different generations as ethical problem of competitive markets requiring state governance on intergenerational transfers and some economists even opposed discounting of future utilities in the past (Allais, 1947; Harrod, 1948; Ramsey, 1928); climate change has leveraged intergenerational equity as contemporary challenge of modern democracy and temporal justice an ethical obligation for the future (Puaschunder, 2016a, 2017a, b).

In general, resources are balanced across generations by social discounting to weight the well-being of future generations relative to those alive today. Regarding climate justice, current generations are called upon to make sacrifices today for future generations by mobilizing low-carbon energy to cut carbon emissions to avert global warming (Puaschunder, 2017c, e; Sachs, 2014). As a novel alternative, Sachs (2014) proposes to fund today's climate mitigation with bonds financed through taxation faced by future generations. Shifting the ultimate costs of climate change aversion to later generations appears as powerful strategy to immediately instigate current climate change action. Within overlapping-generations, climate change mitigation thereby becomes Pareto improving for all generations.

While intergenerational burden sharing on climate change is a real-world relevant emergent risk prevention strategy (Centeno, Creager, Elga, Felton, Katz, Massey & Shapiro, 2013); we lack information on the impact of climate mitigation through debt on economic growth and the model's sustainability over time. Part 2 of this paper therefore introduces Sachs' intergenerational burden sharing and outlines contemporary growth models with attention to public deficit spending. Part 3 integrates Sachs' model into contemporary growth models. Part 4 tests the integrated model's sustainability by using the NMPC method. Part 5 discusses the results in order to derive conclusions presented in Part 6.

## Theoretical background

### *Intergenerational burden sharing*

Society as a whole outlasts individual generations. Pareto optimality for society over time differs from the aggregated individual generations' preferences. As the sum of individual generations' preferences does not necessarily lead to overall societally favorable outcomes (Bürgenmeier, 1994; Klaassen & Opschoor, 1991), discounting based on individual generations' preferences can lead to suboptimal results over time. On intertemporal problems, social discounting reveals an unjust advantage of living generations determining future living conditions (Rawls, 1971). In general, intergenerational balance is therefore accomplished through individual saving decisions of the present generation (Bauer, 1957). Policies curbing preferences and taxes distributing welfare between the present and future generation may, however, decrease economic growth.

In order to avoid governmental expenditure on climate change curbing economic growth (Barro, 1990); Sachs (2014) introduces financing climate change mitigation through debt as a novel means to amend individual saving preferences in favor of future generations. In Sachs (2014) 2-period model, one generation works in period 1 and retires in period 2. Part of the disposable wage income is saved for consumption in the second period. $CO_2$ emission mitigation imposes immediate costs onto current generations and reduces wages. Greenhouse gas concentrations in period 2 are determined by the

ACRN Oxford Journal of Finance and Risk Perspectives
Vol.6 Issue 3, Special Issue FRAP/SSFII Conference, November 2017, p.1-10
ISSN 2305-7394

emissions in period 1. Wages of the young in the second period are reduced by climate change dependent on greenhouse gas levels. Disposable labor income of the young equals market wage net of taxes. Sachs (2014) proposes to mitigate climate change mitigation by debt to be repaid by tax revenues on labor income in the future. Leaving the current generation with unchanged disposable income allocates the burdens of climate change mitigation across generations without the need to trade off one generation's well-being for another's (Sachs, 2014). While today's young generation is left unharmed, the second period young generation is made better off ecologically. Taxes on later generations are justified as for the assumed willingness of future generations to avoid higher costs of climate change prevention and environmental irreversible lock-ins. Overall mitigation policy is thus Pareto improving across generations. All generations are better off with mitigation through climate bonds as compared to the business-as-usual (BAU) non-mitigation scenario (Sachs, 2014). While future generations enjoy a favorable climate and averted environmental lock-ins; the current populace does not face decreased growth.

*Climate justice*

In order to avoid governmental expenditure on climate change hindering economic growth (Barro 1990); Sachs (2014) introduces financing climate change mitigation through debt to be paid back by future generations through taxation as a novel means to amend individual saving preferences in favor of future generations (Marron & Morris, 2016). Carbon taxes can raise substantial revenue until the economy is largely decarbonized (Marron & Morris 2016). In Sachs (2014) 2-period model, one generation works in period 1 and retires in period 2. Part of the disposable wage income is saved for consumption in the second period. $CO_2$ emission mitigation imposes immediate costs onto current generations and reduces wages. Greenhouse gas concentrations in period 2 are determined by the emissions in period 1. Wages of the young in the second period are reduced by climate change dependent on greenhouse gas levels. Disposable labor income of the young equals market wage net of taxes. Sachs (2014) proposes to mitigate climate change by debt to be repaid by tax revenues on labor income in the future. Leaving the current generation with unchanged disposable income allocates the burdens of climate change mitigation across generations without the need to trade off one generation's well-being for another's. While today's young generation is left unharmed, the second period young generation is made better off ecologically. Taxes on later generations are justified as for the assumed willingness of future generations to avoid higher costs of climate change prevention and environmental irreversible lock-ins. Overall this tax-and-transfer mitigation policy is thus Pareto improving across generations. All generations are better off with mitigation through climate bonds as compared to the business-as-usual (BAU) non-mitigation scenario (Sachs 2014). While future generations enjoy a favorable climate and averted environmental lock-ins; the current populace does not face drawbacks on economic growth. At the same time, a carbon tax on top of the existing tax system should be used to reduce the burden of climate change and encourage economic growth through subsidies (Chancel & Piketty, 2015). Other options to promote growth include investing in infrastructure, education, research and development, and other activities that expand the productive capacity of the economy (Marron & Morris, 2016).

In the following integrated assessment model, a macroeconomic modeling approach calibrates climate change adaptation and mitigation and the optimal mitigation and adaptation policy mix with real-world relevance for climate protection. In addition, the model measured the development versus mitigation versus adaptation policy mix in order to retrieve efficient climate modeling strategies leading to important contributions for the international climate negotiations on the optimal climate policy mix. Using macro- and microeconomic modeling and building on the DICE Model, the outlined costs and benefits of mitigation and adaptation strategies are key in determining security strategies for vulnerable cities, communities and countries and protect them from the variegated climate change risks (Nordhaus, 1994). The results achieved help multivariate stakeholders for shaping economic growth and sustainable development. The described models has the potential to become the basis for modeling climate change burden sharing through bonds. Another important aspect of this type of work is to also allow for compensation if the cost of mitigation has very uneven distributional effects.

*Funding climate policies – Model variants*

In order to implement an intra-and intergenerationally fair solution to ensure climate justice, a three-regime approach is proposed. Intragenerationally the issue is how a fair carbon tax can be achieved where some compensation of losers is integrated. Intergenerationally the current generation may require that future generations also contribute to the cost of climate change. We first start with the latter issue, since this is a relatively new concept.

## Variant 1: Climate Bonds and Three Phases

A three phase model describes intertemporal climate change burden sharing. In this three phase model current costs of climate change abatement is partly shifted to future generations through bonds to be financed by taxing future generations. Though future generations will face some tax, they will also benefit in the sense that the externalities from $CO_2$ emission and climate change are removed. A simplified model version can be sketched as following.

The **Model phase 1** of economic growth without mitigation effort is called business-as-usual (BAU). We call this phase 1. The model economy of this type features households in a production economy that choose consumption in order to maximize a discounted stream of utility. Economic households maximize the discounted stream of utility arising from consumption, $C_t$, is subject to a budget constraint. The utility of this phase is maximized by:

$$\int_{t=0}^{T} e^{-\rho t} U_t(C_t) dt \qquad (1.1)$$

in which ρ>0 is the discount rate.

Economic activities generate emissions of greenhouse gases, as a by-product of capital used in production and expressed in $CO_2$ equivalents. Environmental economics implies that a higher capital stock goes along with higher emissions (Hettich, 2000; Smulders, 1995). Emissions of greenhouse gases indirectly affect the climate of the earth leading to higher surface temperature and weather extremes, like flooding, heatwaves, storms, desert formation and so on.

In the model of phase 1, with an optimization horizon $[T_0, T_1]$, the BAU approach, no climate change mitigation effort $A_t$ is employed. It is a laissez-faire solution, in which there is environmental damage and no climate change mitigation. The evolution of per-capita capital over time is thereby determined by the following differential equation that represents the budget constraint of a household:

$$\dot{K}_t = D_t * Y_t - C_t - (\delta + n) * K_t, K(0) = K_0 \qquad (1.2)$$

with the per-capita production $Y_t$ accounting for environmental damage $D_t$ being reduced by consumption $C_t$ and per-capita capital $K_t$ accounting for the depreciation of capital δ and population growth n. In the stylized model, growth leads to the increase of industrial emission.

In the BAU model, there are no climate change abatement activities. Yet, environmental damage reduces output by

$$D_t = (\mathrm{a}_1 * M_t{}^2 + 1)^{-\Psi}, \tag{1.3}$$

with $\mathrm{a}_1 > 0$, being a function that negatively depends on the temperature on earth as deviations from the equilibrium average surface temperature have feedback effects that influence the reflection of incoming energy (e.g., snow and ice reduction and water evaporation lead to a smaller amount of solar radiation tending to increase the earth temperature even further),$\Psi > 0$ and $M_t$ being the greenhouse gas concentration in the atmosphere (Henderson-Sellers & McGuffie, 1987; Nordhaus, 2008; Schmitz, 1991). The effect of emissions to raise the greenhouse gas concentration,$M_t$, in the atmosphere is determined by

$$\dot{\mathrm{M}}_t = \beta * E_t - \mu * M_t \tag{1.4}$$

in which emissions $E_t$ factored by β ∈ (0, 1), which is the part of greenhouse gas emissions that is not taken up by oceans, are reduced by μ ∈ (0, 1) as the inverse of the atmospheric lifetime of greenhouse gases or decay rate of greenhouse gases in the atmosphere, see Intergovernmental Panel on Climate Change (2001).

The greenhouse gas emissions are described by

$$E_t = (\mathrm{a} * K_t)^{\gamma} * \left(\frac{1}{\mathrm{d} * A_t + \mathrm{p}}\right)^{\gamma} \tag{1.5}$$

with $K_t$ being the stock of capital, γ > 0 representing the exponential growth rate in the emission function and the parameter a > 0 as constants. Emissions are a function of per-capita capital, $K_t$, relative to per-capita climate change abatement activities $A_t$ as indicated by the efficiency factor $\left(\frac{1}{\mathrm{d} * A_t + \mathrm{p}}\right)^{\gamma}$, whereby d and p are parameters (Greiner, Grüne & Semmler, 2009, 2012). During BAU, the abatement $A_t$is 0. The technology index a describes how polluting a given technology is insofar as the larger a is given a stock of capital and abatement, the higher the emission is, which implies a relatively polluting technology (Greiner et al., 2009, 2012).

In contrast to the BAU scenario, **Model phase 2**, with an optimization horizon in (1.1) of [$T_1$, $T_2$], proposes an externality control to mitigate climate change through bonds extending Sachs (2014) and Greiner et al. (2012). In order to overcome output decline in the wake of externality control and the need for capital stock to produce renewable energy, social expenditure improving welfare regarding climate change is considered by issuing climate change mitigation bonds. Instead of assuming a lump-sum tax or a tax on consumption used to finance abatement spending, climate change burden sharing debt bonds are thereby issued by current generations, who are immediately compensated for their climate change abatement costs, to be paid off by taxing future generations. In model 2 the government sells climate change mitigation bonds to reimburse the abatement costs $A_t$ from period [$T_1$, $T_2$], when climate change abatement bond issuing stops and climate change mitigation bond repayment sets in through taxation in model phase 3. Overall, there is environmental damage but mitigation that is reimbursed to be paid back by later generations.

As in model 1, the greenhouse gas emission $M_t$ is determined by (1.4). In $K_t$ (1.2) the production function $Y_t$ denoting per-capita output is given by

$$Y_t = \widetilde{A_t} * K_t^{\alpha}, \qquad (1.6)$$

with $\alpha \in (0, 1)$ being the capital share and $\widetilde{A_t}$ being an efficiency index constant normalized to 1. The greenhouse gas emissions are, as in Model 1, described by (1.5) but with $A_t$>0.

In model 2 bonds are issued from the beginning to period to period $T_2$ arising

$$\dot{B}_t = r_t * B_t + g_t * B_t(0) \qquad (1.7)$$

As public debt $g_t$, where $r_t$ is the interest rate paid on climate change abatement bonds. $B_t(0)$ denotes the starting point of public debt at time 0. We now have a model with three state variables and the abatement cost being reimbursed by the issuing of public bonds. Note that in this period the government subsidizes the generation to compensate for the upfront costs of climate change mitigation. The government reimburses climate change aversion until a regime-change switching, when taxes become positive and later generations pay for earlier climate change abatement through taxation. The later generations are assumed to be willing to pay to avoid the higher costs of climate change relative to a BAU path.

In the **Model phase 3**, the optimization horizon in (1.1.) is [$T_2$, $T_3$], when no further climate change abatement costs exist and the debt of bonds is to be repaid from period $T_2$ on, after switching to the model 3, we then have instead of equation (1.7):

$$\dot{B}_t = r_t * B_t - T_{t_N} \qquad (1.8)$$

Whereby $T_{t_N} = \tau Y_N$ is used for describing the repayment of bonds.

From that period on, the capital stock over time, $\dot{K}_t$, is also reduced by $\tau_{t_N}$in

$$\dot{K}_t = Y_t(1 - \tau_{t_N}) - C_t - (\delta + n_t) * K_t \qquad (1.9)$$

Note that in the model phase 3 neither an externality effect, $D_t$, nor climate change abatement cost, $A_t$, are present. There is no environmental damage but taxation for climate change abatement bonds repayment. Only the previously raised bonds of equation (1.7) will have to be repaid by the generation existing from that period on. These future generations will benefit from the absence of damages from externalities of previous periods. The negative externalities are removed by agents from the previous periods.

## Variant 2: Carbon Tax, Climate Bonds and Three Phases

Next the research and solution strategy to deal with the issue when from **model phase 2** on a carbon tax is introduced, in addition to the climate bonds. The subsequent two model phases are very similar to the models phase 2 and 3 above.

In the budget equation of the households in phase 2, equation (1.2), a carbon tax, representing an abatement cost, is enacted that reduces households' income. The tax rate and abatement effort affect equation (1.5) by increasing the denominator by the amount of the abatement effort. The complication is, however, that the tax rate should only be levied on the remaining polluting capital, and as the capital stock becomes more and more green capital, the tax income and abatement effort will shrink and eventually disappear.

This carbon tax for the model phase 2 will be set to zero when **model phase 3** is reached and only the tax rate for the model phase 3 generation that is repaying the bonds issued in phase 2 will affect the budget equation of the households. The repayment of the issued bonds will in this phase 3 decline the same way as described in equations (1.8) and (1.9). The phase by phase solution can also be obtained by our numerical algorithm, the NMPC algorithm which will briefly discussed next.

## Sustainability of the model

In an optimal control solution, the model's feasibility over time was calculated. For the simulations, MATLAB was employed in order to solve the resulting static optimization problem. Sustainability is measured by planning horizon [0, T], T>0 terminal time in years. In addition, the NMPC method displays the dynamics of the transition process regarding a regime switch from BAU to climate change bonds payments.

In MATLAB, the welfare function is lowest with the BAU Model solution. If the interest rate ($r$=0.03) is equal to the discounting rate of the welfare function ($\rho$=0.03), bonds are not an economically efficient means to financing climate change abatement and therefore do not appear in the optimal control solution graph 1. If the interest rate of the bonds is below ($r$=0.01) the discounting rate of the welfare function ($\rho$=0.03), bonds are an efficient market solution to abate climate change. The results of the stylized model underline that after about 90 years, phasing in climate bonds for about 30 years is an efficient market strategy to maximize the overall societal welfare function (see graph 1).

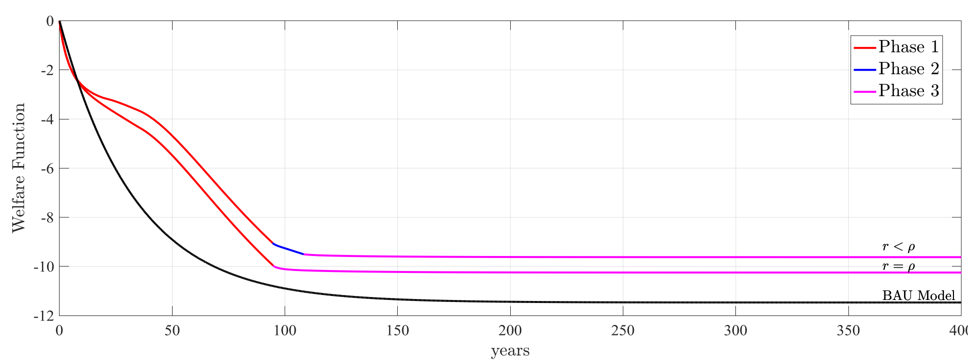


Figure 1: Stylized function graph maximizing welfare of the different model variants

## Discussion

The results yield towards a solution to promote climate bonds through non-tangible assets. For instance, promoting the idea of intergenerational climate bonds as intangible contribution to future generations can be seen as socially conscientious market strategy. Socio-psychological motives for socially responsible investments thus play an important role in the implementation of climate stability financed through bonds (Puaschunder, 2016b, 2017d). Future research should explore what ethical investment strategies can be used to promote the idea of climate bonds (Puaschunder, forthcoming a).

The novel model raises ethical questions if future generations are willing to pay for climate change stability. While prevention is argued to face more resistance than clean-up of damages in public given a loss averse world, the rational is to avert future environmental lock-ins and irreversible global warming tipping points at the expense of reversible monetary overindebtedness (Kahneman & Tversky, 1979). While capital is a replaceable asset and overindebtedness only raises questions of temporal governmental austerity constraints and economic soft or hard landing scenarios, an irreversible global temperature rise and unstable climate imbalances would impose unforeseeable threats to future humankind. Avoiding to pit one generation after the other, earlier generations can enjoy economic growth, while their descendants will benefit from a favorable climate infrastructure.

While this research is focused on the supply side of climate stability financing, future research endeavors could combine these efforts with the demand side of green solutions in order to accomplish a whole-rounded solution for an economically-viable climate public policy balance. Studying both sides concurrently will aid to derive real-world relevant recommendations for climate change policy dynamics. In the future, using methodological advancements in the optimization of basic economic climate stability models will enrich financing of climate policies. For instance, current infinite time horizon simulations could be complemented by a new model with a functional over different time phases and considering finite time horizons to maximize welfare over the different economic model phases. In addition, the one-dimensional constraint of time in the current standard economic climate change burden sharing models could be enhanced by a multiple phase analysis. Optimal trajectories will be derived partially analytically (e.g. by using the Pontryagin maximum principle to define the optimal equilibrium), partially data driven (e.g., by the use of modern big market data) and partially by using novel cutting-edge methods – e.g., NMPC, which solves complex dynamic optimization problems with different nonlinearities for infinite and finite decision horizons. Further NMPC solutions could be programmed with terminal condition in order to determine appropriate numeric solutions converging to some optimal equilibria. For the different time phase models, the Gauss Pseudospectral Optimization Software (GPOPS-II) could enable a pseudospectral discretization of the optimal control problem to turn it into a large-scale nonlinear programming problem and solve it by known MATLAB solvers such as Interior Point OPTimizer (IPOPT) and Sparse Nonlinear OPTimizer (SNOPT).

The prospective results will lead to a precise definition of the optimal proportion of abatement and reimbursement and thus optimum policy mix over time. The wider climate change community will learn the best time structure of levying taxes as well as introducing and repaying climate bonds. Mathematically justified insights will also be gained on when to phase in an optimally-quantified amount of tax-and-bonds transfers. The rational quantitative bottom-line will compare Business-As-Usual (BAU) with Policy-Intervention-Models. In all these endeavors, the pure model logic enriched by mathematical precision will prospectively nail down concrete predictions about optimal conditions over time targeted at aiding multiple key decision makers to agree upon quantitatively-structured solution paths.

To strengthen climate control also from the “demand” side, a second direction of research could thus elucidate how preferences for more “low carbon” and “green” goods and services might evolve in the long run, but also can be changed immediately due to critical life events or external shocks. All these endeavors are targeted at finding innovative ways how to align the demand side with the supply side of climate policies. Technologies are usually, as Brian Arthur (1989) has shown, locked-in through their historical path where they have taken off and are highly interlocked with historical preference formations. As economists, sociologists and social psychologist have demonstrated, there is long run habit or routine formation for traditional economic and social sub-systems, so also for fossil fuel as energy system (Urry, 2013). How to make the private sector and broader public more open for new technologies regarding climate change policy and susceptible for preference changes, should be studied concurrently. This research could target at showing how social representations (Moscovici, 1995) or by habits and routines (Aronson, Wilson & Akert, 2004) guide economic decision making and behavior of economic agents. Social representations are, for example, attitudes towards certain trends and routines that can be referred to as historically evolving habits, as it is frequently the case in economics (Puaschunder, 2015a). In contrast to standard approaches in economics, this research would take into account that agents in their behavior can be constrained by their informational capacities as well as cognitive and computational abilities, by habits, routines or social representations and prospects.

In addition, innovative climate change abatement financialization strategies should be explored. Following a most novel line of research on the gains of a warming earth (Puaschunder, 2017f, forthcoming b), those territories and industries that benefit from climate change could serve as transfer grantors to those countries that lose from a warming earth that should be reimbursed for losses. In climate change winner countries, taxation should become the main driver of financing climate stability strategies. Foremost, the industries winning from a warming climate should be taxed. If climate taxation is thereby perceived as fair and just allocation of the climate burden, this could convince tax payers to pay one’s share. A novel ‘service-and-client’ atmosphere could promote taxpayers as cooperative citizens who are willing to comply if they feel their share as fair contribution to the environment. Taxpayers as cooperative citizens would then be willing to comply voluntarily following the greater goal to promote taxpayer collaboration and enhance tax morale in the environmental domain (Puaschunder, 2015b). Deriving respective policy recommendations for the wider climate change community in the future will ensure to share the burden but also the benefits of climate change within society in an economically efficient, legally equitable and practically feasible way.

Overall, the proposed joint research pillars would consider both the supply side of climate stabilization, where the mitigation of and adaptation to climate change and their fair funding are studied, as well as with demand side models, where preferences and the process of preference formation play a decisive role in order to find a socially acceptable and economically efficient solution to finance climate stability for this generation and the following.

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