Macro-Financial Implications of Climate Change and the Carbon Transition

By Frederick van der Ploeg[1]

Abstract

We review what needs to be done to ensure a smooth transition to the carbon-free economy. If policy internalises global warming damages, the carbon price rises at the same rate as economic activity and the level depends on economic and climatic uncertainties. If policy makers keep temperature below a ceiling, the carbon price must grow at a rate equal to the risk-adjusted interest rate. Both approaches benefit from asset pricing insights. We also discuss how climate policy is frustrated by the motive to diversify assets across carbon-intensive and green assets. We then contrast business-as-usual and optimal outcomes with outcomes where there is a risk of policy tipping. The latter leads to sudden changes in market valuation and risk of stranded assets. We review empirical evidence for effects of anticipated green transitions on asset returns. Finally, we discuss macro-financial policies for the green transition and policies to avoid disorderly green transitions.

1 Introduction

"*Carbon prices that increase in a gradual and predictable way are one key element of any policy package.*" (Group of Thirty, 2020)

The Group of Thirty's recent report "Mainstreaming the Transition to a Net-Zero Economy" co-chaired by Marc Carney, former Governor of the Bank of England and Janet Yellen, former Chair of the Board of Governors of the Federal Reserve System, hits the nail on the head. It argues that the evidence that climate change is posing unprecedented risks to our livelihoods is overwhelming: higher sea levels, food insecurity, higher frequency of national disasters, more dangerous heat dates, and world GDP dropping by 25% as temperature rises to 3 degrees Celsius above preindustrial levels by 2100. The window for an orderly transition to a net-zero economy is closing fast as the safe carbon budget consistent with limiting global warming to 2 degrees Celsius will be exhausted in 25 years if nothing changes, so

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[1] Department of Economics, Manor Road Building, University of Oxford, Oxford OX1 3 UQ, United Kingdom. Email: rick.vanderploeg@economics.ox.ac.uk. Also affiliated with the Faculty of Economics and Business, University of Amsterdam, P.O. Box 15551, 1001 NB Amsterdam, Netherlands, and research fellow of CEPR and CESifo. Prepared for the session "Implications of fundamental global changes for central banks" of the ECB Forum on Central Banking, 11-12 November 2020. I am grateful for helpful suggestions from Philipp Hartmann, Glenn Schepens, and an anonymous referee. Rough conference draft 3 November 2020.

the world needs to act now and the quicker the lower the cost. To avoid such an existential threat, green technologies should be embraced across all sectors of the economy which offers significant opportunities for rebooting the economy in a carbon-free direction. This requires long-term credible public policy commitments and actions from many more countries, the main one being that carbon prices should increase in a predictable way so that companies get a clear signal to anticipate the new green business models and make their businesses ready for the net-zero economy. To get broad political support, some of the proceeds of carbon prices should be used to support low-income households. It may also help to delegate responsibilities to independent "Carbon Councils". Countries that move first can use border carbon tax adjustments in line with WTO rules to avoid carbon leakage and ensure their markets are not flooded with carbon-intensive imports. In addition, policy makers need to boost investment in low-carbon infrastructure, loans and grants for green R&D, and support for developing countries.

This Group of Thirty report also asks companies to rebuild their business model in a way that is compatible with the net-zero economy and adhere to the recommendations of the Task Force on Climate-Related Financial Disclosures. Stock exchanges, central banks and financial supervisors need to be more strategic and forward looking and actively accelerate and monitor this process and to make sure that climate-related risks are factored in and ensure resilience of the financial system as a whole making use of the Network of Central Banks and Supervisors for Greening the Financial System Reference Scenarios. Central banks and supervisors should conduct regular climate stress tests that are comparable across firms and assess the risks of system-wide feedback loops. The financial system including insurers should unlock the commercial opportunities that the green transition offers.

To shed further light on the important issues in this timely report of the Group of Thirty, we consider the macro-financial implications of climate change and the transition to a carbon-free economy. We first discuss in section 2 the need to credibly commit to a steadily path of growing carbon prices and the many political obstacles at home and abroad that must be faced to make this possible. We then discuss in section 3 integrated assessment of climate policy and contrast and compare, on the one hand, the standard Pigouvian approach to internalising the expected present and future damages of emitting one ton of carbon (i.e. the social cost of carbon) favoured by economists, and, on the other hand, the Paris Agreement approach of a 2 or 1.5 degrees Celsius relative to preindustrial temperature cap on temperature used by the Intergovernmental Panel on Climate Change (IPPC) and policy makers in governments and central banks. Section 4 then applies asset pricing insights to gain further understanding of the best way to price carbon under economic growth, climatic uncertainties and damage uncertainties and the risks of tipping points and tail risks. In section 5 we analyse carbon pricing when there are carbon-intensive and carbon-free sectors in the economy. We identify a trade-off between the benefits of diversification and the need to decarbonise the economy. We also analyse the relative share of carbon-intensive capital and the effects on green and carbon-intensive equity prices and risk premia. Section 6 discusses the effects of policy uncertainty and policy tipping on global warming, macroeconomic and financial market outcomes, and the risk of stranded assets. Section 7 reviews the empirical evidence of the effects of anticipated stepping up of climate policy, green technological breakthroughs and more generally the green transition on stock market returns and risk premia. It highlights that investors demand a higher and increasing return on carbon-intensive assets to be compensated for the risk of a carbon bubble. Section 8 analysis the need for macroeconomic policies to complement the green transition. Section 9 discusses the dangers of disorderly green transitions and the risk of stranded assets and highlights the need for green prudential policy and climate stress tests. Section 10 concludes and remarks on the implications of the Covid-19 crisis for climate policy and the economy.

2 Need to price carbon and challenges that must be met

The royal way to achieve the internationally agreed drastic reduction in carbon emissions is to price carbon. It is best to commit in advance to a rising path of carbon taxes as Finland, Norway, Sweden, Switzerland, and the United Kingdom have done. An alternative is to set up a competitive market for tradable emission permits such as the European Union (EU) Emissions Trading Scheme (ETS). Elsewhere in the world (especially China) these schemes are being introduced at a rapidly. Trading of permits will ensure that emission reductions take place in those economic sectors and countries where this can be achieved in the most cost-effective way, i.e. the cost per abated tonne of emitted carbon is minimised. A possible problem with permit markets is that the price of a permit can be quite volatile. This blunts the signal and the incentive for firms and households to move towards carbon-free production and consumption. After the global financial crisis, the ETS has been reformed by the introduction of stability reserves. This implies that emission permits are bought on the open market when the price is too low. This has led to more substantial prices of ETS permits.

The problem with a carbon tax, on the other hand, is that policymakers do not have enough information to know exactly how high the tax should be to achieve the required cut in emissions. To get the best of both types of policies, policy makers could announce and commit to a rising time path for the CO2 price, and top up the ETS price if it is below this announced path. If the price of carbon on the ETS market is too low, then an extra charge is levied to close the gap with what is needed. Such a combination policy gives clarity and certainty for the longer term, so that businesses can take account of this when they prepare their investment plans for future years to come and switch from a carbon-intensive to a carbon-extensive production structure.

Pricing carbon helps the transition to the carbon-free era in many ways. Of course, pricing carbon curbs demand for fossil-fuel-based energy (coal, oil, and gas). However, pricing carbon also encourages substitution from carbon-intensive types of energy such as coal to less carbon-intensive forms of energy such as gas. Furthermore, pricing carbon encourages green R&D and innovation, and speeds up the move towards a circular economy. Carbon pricing is also essential for making carbon capture and sequestration economically attractive. It also reduces the incentive to explore and exploit fossil fuel reserves. Carbon pricing thus forces fossil-fuel-based companies such as BP, Shell, Chevron, and ExxonMobil, but also countries with substantial oil, gas and oil reserves, to lock more fossil fuel in the Earth and in this way limit global warming.

Finally, by implementing effective climate policies various collateral benefits can be obtained. The main ones are that less use of coal, oil and diesel improves air quality in cities and avoids large numbers of early deaths, especially of schoolchildren near busy roads in the cities. China has been stepping up climate policy. An important driver of this are such collateral benefits. The reason is that these collateral benefits are locally visible, whilst the direct costs of global warming affect the whole of humanity and concern a global externality. Collateral benefits thus attenuate the notorious free-rider problems in international climate policy.

Carbon pricing and climate policy more generally makes eminent sense, and this has been for many years. So why is it that such little progress has been made? The following obstacles are the culprit. The first one is that it is a huge ask because climate policy faces international free riding problems as carbon mixes immediately and completely throughout the atmosphere) and because current generations are asked to make sacrifices to curb future global warming to the benefit of future, possibly richer generations. Although one could think of side payments, border tax adjustments or climate clubs to tackle the first problem (e.g. Nordhaus, 2015) or to run up government debt to compensate current generations and generate intergenerational win-win situations to tackle the second problem as well as curb the risk of climate disasters (Kotlikoff et al., 2020), not much progress has been made with such solutions. If a sub-set of countries prices carbon, part of the tax is borne by consumers and the other part by fossil fuel producers. This means that non-participating countries face lower prices and increase fossil fuel consumption and emission. This spatial carbon leakage can offset roughly 20% of emission reductions unless border tax adjustments or output-based rebated for industries that suffer from dirty competition from abroad are implemented. Another problem is that politicians are notorious for procrastination and preferring the carrot to the stick, hence they tend to postpone carbon taxes and to give excessive solar and wind energy subsidies rather than price carbon. This leads to green paradox effects, where oil sheiks pump up the oil faster to avoid capital losses which accelerates global warming (Sinn, 2008). Another obstacle to successful climate policy is that explicit and implicit fossil fuel subsidies are around 6.5% of world GDP and it has been difficult to get rid of these inefficient and climate-threatening subsidies. The best is to replace these subsidies which are biggest for coal and electricity use by general tax deductions for the poor as this is a much more efficient way to distribute incomes, but in less developed countries this may be a less effective option. More generally, to avoid “yellow vests” movements policy makers must make sure that carbon pricing does not work out to be regressive. This can be done by rebating the carbon tax revenues via a visible carbon dividend for all citizens and a via lowering the labour income taxes. In some cases, it may be better to recycle via insulation subsidies for low incomes or tax credits for energy-efficient buildings. Another obstacle to the green transition is that there are huge spatial needs for all the windmills, solar panels, and CCS sites which compete with nature and other claims on the space. Yet another obstacle arises from politicians tending to pick winners, succumb to lobbies, and to use non-price controls (energy-efficiency standards, mandates, etc.) which are susceptible to capture and corruption. Another a big obstacle is the emergence of populism and climate scepticism. It turns out that the costs of doing nothing if the climate scientists are right are much higher than the costs of pricing carbon if the climate sceptics are right (e.g. Hassler et al., 2020). This means that a mini-max or max-min-regret policy is always to price carbon (van der Ploeg and Rezai, 2019). Finally, a disorderly transition to the carbon-free economy risks stranding of financial assets (see section 6).

3 Integrated assessment of climate policy: economists versus the IPCC

How high should the carbon price be? Most economists following the Nobel prize winner William Nordhaus answer this question by equating the price to the Pigouvian tax. This corresponds to the expected present discounted value of all current and future marginal damages to global production resulting from emitting one tonne of carbon today (also known as the social cost of carbon). Since greenhouse gases mix very quickly, it does not matter in which part of the world the emission takes place. Furthermore, the price of carbon should be the same throughout the world. If it is necessary to compensate poorer countries to participate in a scheme for pricing carbon uniformly throughout the globe, transfers should be given by the rich countries to poor countries. The cost of pricing carbon to say Africa and India are much less than the costs to the OECD countries if carbon is not priced in those countries (e.g. Hassler, 2020), hence the transfers or side payments are worth it.

3.1 The Pigouvian approach and the social cost of carbon

The Pigouvian tax or social cost of carbon typically follow maximising welfare subject to the constraints of an integrated assessment model of the economy and the climate. The most prominent one is the DICE (Dynamic Integrated Climate-Economy) model developed by William Nordhaus (e.g. Nordhaus, 2017), but others such as the FUND model[2] and the PAGE model (e.g. Hope, 2013) have been used a lot for policy simulation purposes too. More recently, more analytical integrated assessment models have been put forward. The most prominent one of these is perhaps the one by Golosov et al. (2014). This study offers a simple formula for the optimal carbon price that maximises welfare subject to the constraints of a general equilibrium model of the economy and the constraints of a model of the dynamics of atmospheric carbon and temperature. Others have extended this formula for more general productive functions, depreciation rates, and utility functions (e.g. van den Bijgaart, 2016; Rezai and van der Ploeg, 2016).

We make four key assumptions. First, damages from global warming are proportional to aggregate output, which will imply that the optimal carbon price turns

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[2] Developed by Anthoff and Tol: https://github.com/fund-model/MimiFUND.jl .

out to be proportional to world GDP (or aggregate consumption). We assume that the ratio of damages to aggregate output is a linear function of temperature and denote the marginal effect of temperature on the damage ratio by MDR. Second, recent insights in atmospheric science and climate science indicate that temperature is a linear function of cumulative emissions (e.g. Allen, et al., 2009; Matthews et al., 2009; Dietz et al., 2020). The marginal effect of cumulative emissions on temperature is called the transient climate response to cumulative emissions or the TCRE for the short. A ballpark value for this parameter is 1.6 degrees Celsius per trillion tons of carbon.[3] Third, we suppose exponential discounting of consumer utility where UDR indicates the rate of time impatience or the utility discount rate and IIA the coefficient of relative intergenerational inequality aversion (i.e. the inverse of the elasticity of intertemporal substitution). Fourth, the trend rate of growth of the economy is constant and denoted by g.

It then follows that the optimal carbon price at time *t*, say *P*(*t*), equals

$$(1) \qquad P(t) = \frac{\mathrm{MDR} \times \mathrm{TCRE}}{\mathrm{SDR} - \mathrm{g}} \times \mathrm{GDP}(t) = \frac{\mathrm{MDR} \times \mathrm{TCRE}}{\mathrm{RTI} + (\mathrm{IIA} - 1) \times \mathrm{g}} \times \mathrm{GDP}(t),$$

where the social discount rate $\mathrm{SDR} = \mathrm{RTI} + \mathrm{IIA} \times \mathrm{g}$ follows from the Keynes-Ramsey rule. The optimal carbon price is thus proportional to world GDP. The constant of proportionality increases in the marginal effect of temperature on the damage ratio (the MDR) and the transient climate response to cumulative emissions (the TCRE). However, it decreases in the growth-corrected social discount rate (SDR – g). The correction for growth takes account of the fact that global warming damages grow with economy activity, which boosts the carbon price. Higher growth also means that future generations are richer than current generations and thus that the *SDR* is higher and there is less appetite for climate action, especially if IIA is large. This latter negative affluence effect of growth on the carbon price dominates the growing damages effect if IIA > 1. The two effects exactly cancel out with logarithmic utility (Golosov et al., 2014), since then IIA = 1. As a result, the optimal carbon price is unaffected by IIA and the rate of economic growth. Note that there has been a fierce debate about what discount rate to use. If a high UDR is used (e.g. Nordhaus, 2017), the optimal carbon price is much lower if a lower UDR is used (Stern, 2007). The optimal carbon price is driven by ethical considerations (the utility discount rate and intergenerational inequality aversion), geo-physical considerations (the transient climate response to cumulative emissions) and economic considerations (the level of economic activity and its trend rate of growth) as well as by the marginal effect of temperature on the damage ratio.

To get an order of magnitude for the optimal carbon price, suppose that it is unethical to discount the welfare of future generations (i.e. UDR = 0) and set the coefficient of intergenerational inequality aversion equal to 2 (IIA = 2). Nordhaus (2017) calibrates the damage ratio as 0.236% loss in global income per degree Celsius squared, so the damage ratio is 2.1% and 8.5% of word GDP at, respectively, 3 and 6 degrees

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[3] Miftakhova et al. (2020) derive a statistical approximation of high-dimensional climate models which give an estimate of the TCRE with some simple temperature dynamics.

Celsius. The marginal damage ratio thus equals 0.472% loss of global income per degree Celsius. At 2 degrees Celsius this gives a MDR of 0.944% of global income.[4] With TCRE = 1.8 °C/TtC, GDP = 80 trillion U.S. dollars, and g = 2%/year, the SDR = 4%/year and we get from (1) an optimal carbon price of $68 per ton of carbon or $18.5 per ton CO2. Each year this price must be adjusted for inflation. Nordhaus (2017) uses a higher UDR of 1.5%/year in which case SDR = 5.5%/year and the optimal carbon price is much lower, i.e. $39 per ton of carbon. Lower growth prospects, say g = 1%/year, pushes up the carbon price from $68 to $136 per ton of carbon. As future generations are expected to be poorer, current generations pull their weight more.

3.2 Temperature ceilings and the carbon budget approach

Climate scientists and the Intergovernmental Panel for Climate Change (IPCC) typically reject the welfare-maximising approach. One of the reasons for this is that the Pigouvian approach to finding the optimal carbon price leads to a wide range of estimates. For example, the carbon price depends on ethical measures of the utility discount rate and intergenerational inequality aversion on which there is a lot of disagreement. There is also a wide range of estimates of global warming damages which further expands the range of the optimal carbon price. For example, the Nordhaus (2017) damages are so modest that they lead to temperatures above the 2 degrees Celsius targets of the Paris Agreement whilst Burke et al. (2015) have damages up to 100 times larger. The IPCC has therefore chosen a more pragmatic approach.

It is easy to understand why many government and central banks have adopted the more pragmatic approach of a temperature cap too. This is also the case for the Network of Central Banks and Supervisors for Greening the Financial System (NGFS) whose climate scenarios are based on a temperature cap (NGFS, 2020bc) and are used by European central banks in their analysis of climate policies. The ECB has also endorsed these climate scenarios and considers them as an important pillar in the climate policy strategy of central banks. An important reason why central banks and financial regulators want to play such an important role in the low-carbon transition is that market imperfections in a second-best world would lead to so-called Green Swans and Climate Minsky Moments (e.g. Bolton et al., 2020), which are further discussed in sections 6, 8 and 9.

The objective is to choose a cost-minimising time path for the carbon price that keeps temperature always below its ceiling. Since temperature is a function of cumulative emissions, this corresponds to a cap on cumulative emissions or a carbon budget. Typically, this is about 300 Giga tons of carbon depending on the risk tolerance, which means that at current use of fossil fuel (10 Giga tons of carbon per

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[4] Burke et al. (2015) show that overall economic productivity is non-linear in temperature for all countries with productivity peaking at an annual average temperature of 13 °C and declining strongly at higher temperatures. They find that expected global losses are approximately linear in global mean temperature, with median losses 2.5-100 times larger than prior estimates for 2 °C. It is thus assumed that the damage ratio is linear in temperature.

year) the planet has about 30 years left before temperatures exceed 2 degrees Celsius. If warming is to be kept below 1.5 degrees Celsius, the carbon budget drops to 65GtC from 2015 onwards in which case only 6 or 7 years are left (van der Ploeg, 2018). McGlade and Ekins (2015) argue therefore that to have a 50-50 chance of limiting temperature below 2 degrees Celsius the world must stop burning fossil fuel: a third of oil reserves, half of gas reserves, and more than 80% of coal reserves must be left untouched.

Table 1 shows how this pans out for the different parts of the world. All Canadian tar sands and all Antarctica's fossil fuel deposits must be left untouched. The big challenge is for the world, especially China and India, to stop using coal. While this analysis has some shortcomings related to supply and transportation constraints, limiting the time span to 2050, development of demand and possibility of technological breakthrough, it is clear that a substantial fraction of oil, gas, and coal reserves should be left unburnt and that the burden of abandoning these reserves will be felt differently by different parts of the world. Furthermore, as coal emits much more carbon per unit of energy than oil or gas, not burning coal has priority.

Table 1
Unburnt fossil fuel compatible with a maximum temperature of 2 degrees Celsius

Percentage Unburnt Reserves (%)	Oil	Gas	Coal
Middle East	38	61	99
OECD Pacific	37	56	93
Canada	74	25	75
China and India	25	63	66
Central and South America	39	53	51
Africa	21	33	85
Europe	20	11	78
United States	6	4	92

Source: McGlade and Ekins (2015)

The carbon price at the time when fossil fuel is no longer used is determined by the costs of total decarbonisation of the economy, $b(T)$, at that future point in time T. The cost-minimising carbon price before the green transition is fully completed must grow at a rate that equals the rate of interest or SDR. This Hotelling rule reflects the increasing scarcity of permitted emissions as the carbon budget for cumulative emissions gradually becomes exhausted as fossil fuel use is used. The optimal carbon price thus follows the time path

$$(2) \qquad P(t) = \mathrm{e}^{-SDR \times (t-T)}\, b(T).$$

The main difference with the Pigouvian approach summarised in equation (1) is that the carbon price now grows at a rate equal to the rate of interest rather than the rate of economic growth. The carbon budget approach thus leads to a steeper price path than the Pigouvian approach provided the interest rate exceeds the rate of economic growth. In the current climate it has been argued that the interest rate is lower than the growth rate. That is true, but what is relevant is the risk-adjusted interest rate corrected for the uncertainties regarding growth of emissions and the reduction of the cost of renewable energy. Gollier (2020) calibrates a two-period model and suggests that the appropriate risk-adjusted interest rate is 3.75% per year. The initial carbon price in 2020 could be at least 15 to 40 euros per ton of CO2 and, from then onwards, it should grow steeply at a rate of 3.75% per annum, excluding the inflation correction.

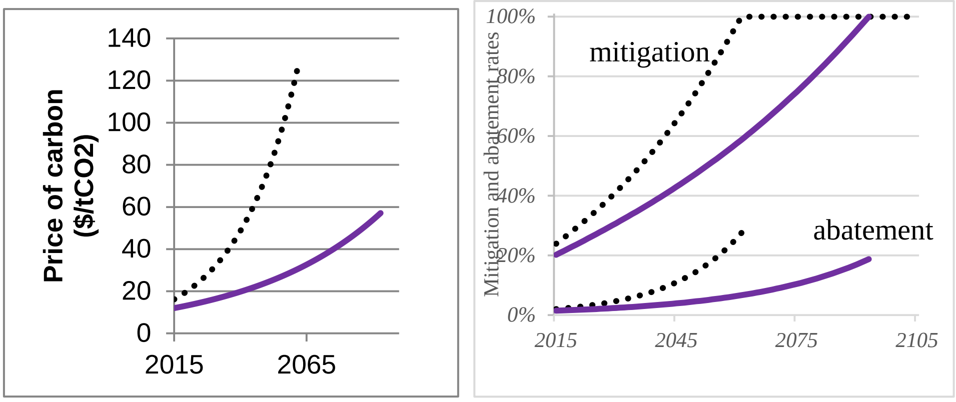
According to a recent report under the chairmanship of the Nobel Prize winner Joe Stiglitz and Lord Nicholas Stern, such a carbon price path is necessary to meet the Paris targets. This rapidly rising carbon price is necessary for a cap of 2 °C. The initial price would need to be much higher for a cap of 1.5 °C. The alternative Pigouvian approach leads to a carbon price that grows less rapidly than the price necessary to implement a temperature cap; that is, a rate of growth that corresponds to the growth rate of the economy (say 2% per year excluding the inflation correction). A combination of the Pigouvian approach and the temperature cap approach leads to a carbon price path that grows at a rate that lies between the growth rate of the economy and the interest rate (van der Ploeg, 2018). The main lesson is that the high growth rates of the carbon price that are used in many countries (e.g. 15% per year in the United Kingdom) should be avoided, since these imply very low current carbon prices and thus very little climate action. Such excessively rising carbon price paths also carry the danger that oil, gas and coal producers bring production forward when the carbon price is still low, thereby accelerating global warming. This has become known as the Green Paradox (Sinn, 2008).

3.3 Comparison

To compare the Pigouvian and the safe carbon budget approach to climate policy, Chart 1 gives the optimal (solid lines) and cost-minimising (dotted lines) time paths for the carbon price, the mitigation rate, and the abatement rate. These paths have been calculated from a simple rendition of the DICE model. The point is not so much the exact numbers as the qualitative conclusions. First, the Pigouvian approach leads to a much longer period of the fossil era, which ends when the mitigation rate reaches 100%. This is because damages in DICE are too small to keep temperature below 2 degrees Celsius.

Chart 1

Pigouvian versus carbon budget approach to climate policy



Notes: The mitigation rate is the share of renewables in total energy. The abatement rate is the fraction of emissions that is abated via CCS or other means. The solid lines correspond to the Pigouvian and the dotted line to the carbon budget approach.

Source: van der Ploeg (2018)

The carbon budget keep temperature below 2 degrees Celsius and therefore has a quicker transition to the green economy. Second, as the rate of economic growth exceeds the rate of interest in the illustration of Figure 1, we see that the carbon price rises more steeply under the carbon budget approach than under the Pigouvian approach.

4 Effects of risk and uncertainty: asset pricing insights

Here we discuss how asset pricing theory can be used to understand how to price carbon in uncertain and risky environments.

4.1 The Pigouvian approach and the social cost of carbon

We now focus on the effects of uncertainty about future economic growth and damages from global warming on the optimal risk-adjusted carbon price. We suppose that the growth rate of the economy follows a Geometric Brownian motion where μ denotes the drift and σ the volatility of the stochastic process. Expected growth thus equals $g = \mu - \frac{1}{2}\sigma^2$. Following Epstein and Zin (1989), we separate the coefficient of relative risk aversion, denoted by RA, from the IIA or the inverse of the elasticity of intertemporal substitution. It follows that the optimal carbon price at time t is given by (van den Bremer and van der Ploeg, 2020)

(3) $$P(t) = \frac{\mathrm{MDR} \times \mathrm{TCRE}}{\mathrm{SDR} - \mathrm{g}} \times \mathrm{GDP}(t) \text{ with } \mathrm{SDR{=}UDR{+}IIA{\times}g} - \frac{1}{2}(\mathrm{IIA} - 1)\times\mathrm{IIA}\times\sigma^2.$$

We can decompose the social discount rate SDR in four terms. The first term UDR is the impatience effect: more impatient policy makers use a higher SDR, so have a lower carbon price. The second term $\mathrm{IIA} \times \mathrm{g}$ is the affluence effect. The third term $-\frac{1}{2}(1 + \mathrm{IIA}) \times \mathrm{RA} \times \sigma^2$ is the prudence effect: more risk-averse policy makers with higher intergenerational inequality aversion and a higher volatility of economic growth demand a lower SDR and higher carbon price (e.g. Kimball, 1990). These three terms boil down to $\mathrm{RTI} + \mathrm{IIA} \times \mu - \frac{1}{2}\mathrm{IIA}^2 \times \sigma^2$ if IIA = RA. The fourth term $\mathrm{RA} \times \sigma^2$ is the self-insurance effect: in future states of nature when economic growth is high, damages are high too as damages are proportional to world GDP. Abatement is a procyclical investment with higher yields in good times. Hence, the SDR is higher and policy makers take less climate action. Finally, there is the term –g in the denominator of (3), which is the growing damages effect and calls for a higher carbon price.

The adjustment of the SDR for economic growth uncertainty is modest. For example, if IIA = 2, UDR = 0, g = 2%/year as before but RA = 5, the prudence effect is 0.74%/year and the self-insurance effect is 0.49%/year so the SDR drops from 4 to 3.75% per year and the carbon price rises from \$68 to \$78 per ton of carbon.

4.2 Effects of climatic uncertainties and their correlations with economic outcomes

However, skewed uncertainty about the climate sensitivity has a substantial upward effect on the carbon price especially if the damage ratio is a convex function of temperature. If shocks to the climate sensitivity are more persistent, more volatile, and more skewed, this pushes up the optimal carbon price by more (van den Bremer and van der Ploeg, 2020). In contrast, uncertainty about shocks to the ratio of damages pushes up the carbon price only if the distribution of these shocks is skewed. The effects of these two types of uncertainty on the optimal carbon price can be substantially higher than that of growth uncertainty.

Shocks to the economy, to damages from global warming, and to the climate may be correlated. To illustrate this, assume RA = IIA = 1 so that SDR = RTI and uncertainty about future economic growth does not affect the carbon price. However, if we now have a non-unitary instead of unitary elasticity of marginal damages with respect to consumption, say β, damages are $\mathrm{MDR} \times \mathrm{Temperature}_t \times \mathrm{GDP}_t^{\beta}$ and the social discount rate becomes

(4) $$\mathrm{SDR} = \mathrm{UDR} + (1 - \beta) \times \mathrm{g} - \frac{1}{2}(2 - \beta)(1 - \beta)\sigma^2.$$

There are two additional effects of a “beta” smaller than one: (i) as marginal damages grow at a less rapid rate than world GDP, the present discounted value of marginal damages is smaller and this boosts the SDR (second term in (4)) and lowers the carbon price; (ii) in future states of nature shocks to future damages are now less than perfect correlated with future world GDP, so self-insurance is less and the SDR is pushed down (third term in (4)) and the carbon price is higher. With a growth rate of around 2%/year and an annual volatility of about 3.6%, effect (i) dominates effect (ii).

Dietz et al. (2018) argue that this climate “beta” is close to unity for maturities up to one hundred years. Effectively, the positive effect on this beta of uncertainty about exogenous, emissions-neutral technical change swamps the negative effect on this beta of uncertainty about the climate sensitivity and the damage ratio. Hence, mitigating climate change increases aggregate consumption risk, which calls for a higher discount rate. However, the stream of undiscounted expected benefits also increases in this beta and this dominates the effect on the discount rate, so that on balance the carbon price increases in this beta (cf. effect (ii)).

We can also allow for the effect of correlations between climate sensitivity or damage ratio uncertainty and economic growth uncertainty. There are then two effects: a risk insurance effect and a risk exposure effect to do with growing damages (Lemoine, 2020; van den Bremer and van der Ploeg, 2020). If *RA* exceeds one, the risk insurance effect dominates. If climate sensitivity shocks and economic shocks are negatively correlated, assets returns are low in future states of nature in which temperature is high. This calls for a higher price of carbon. This makes sense for an economy dominated by agricultural producers, heating systems, winter garments, etc. However, if the economy is dominated by industries whose return benefit from higher temperature (e.g. air conditioning, champagne in Sussex), the correlation is positive and thus a lower carbon price is called for. Similarly, if damage ratio shocks and economic shocks are negatively correlated, asset returns are low in future states of nature when the damage ratio is high. This demands a higher carbon price. However, if the economy is set up to make profits from higher temperature (e.g. due to water defence and salvage industry), the correlation is positive. Hence, the carbon price will be lower.

4.3 Effects of gradual resolution of damage ratio uncertainty

Daniel et al. (2019) use a binomial tree with 7 periods of an asset pricing model to show that the optimal carbon price must decline over time. This is in sharp contrast to the key insight derived from the Pigouvian approach (section 3.1) and the carbon budget approach (section 3.2) to climate policy, which both suggest that the carbon price should increase over time. To obtain their result, Daniel et al. (2019) make two key assumptions: (i) a preference for early resolution of uncertainty, which requires that *RA* > *IIA*; and (ii) gradual resolution over time of uncertainty about the ratio of global warming output to economic activity. There is a precautionary motive to price carbon in the face of damage ratio uncertainty. This motive declines over time as the occurrence of damage ratio shocks allow policy makers to learn and to reduce the uncertainty about the global warming ratio. This leads to a tendency for carbon prices to decline over time. Olijslagers et al. (2020) revisits this topic within a continuous-time asset pricing approach and shows that the optimal carbon price consists of two components. The first one is a rising component proportional to GDP since marginal damages are proportional to GDP. The second component is declines with time and depends on uncertainty and the falling volatility of the damage ratio. It turns out that the first component dominates the second component for historical positive rates of economic growth. Only with zero economic growth will the optimal carbon price fall over time.

In regime shift model there is a risk that a tipping point is passed. Higher temperatures bring forward the expected time of a tipping point. The carbon price then internalises the negative effect of global warming on production but also internalise the higher risk of a tipping point. If a tipping point is associated with a sudden reduction in economic output, the carbon price will fall after the tipping point (e,g. van der Ploeg and de Zeeuw, 2018).

4.4 Tipping points, tail risks, and the price of carbon

It has also been shown that the risk of climatic tipping (e.g. melting and collapse of Greenland or West Antarctic Ice Sheet and parts of East Antarctica, melting of the permafrost, boreal forests, melting and breaking up of the Arctic sea ice, reversal of Gulf Stream, destruction of the Amazon rainforest) leads to substantial boosts (say a factor 4 to 8) to the optimal carbon price because global warming increases the risk of tipping and carbon needs to be priced more strongly to internalise this negative adverse effect (e.g. Lemoine and Traeger, 2014, Lontzek et al., 2015; van der Ploeg and de Zeeuw, 2018; Cai and Lontzek, 2019). Some of these tipping points may already be active; and some of them (such as the melting of the Ice Sheets) will take centuries to have their full impact. In addition, it seems likely that one tipping point raises the likelihood of another tipping point setting off. Such domino-effects boost the carbon price and thus more vigorous climate action must be undertaken (Cai et al., 2016; Lemoine and Traeger, 2016).

Like tipping points, tail risk is important. We have already seen that thin-tailed skewed probability density functions for shocks to the climate sensitivity or to the damage ratio give large boosts to the carbon price necessary to internalise deal with global warming externalities and their associated risks. Fat-tailed probability density functions combined with power utility functions give rise to the “dismal” theorem, which states that the optimal carbon price is unbounded and thus that policy makers are prepared to sacrifice all of GDP to curb carbon emissions (Weitzman, 2009, 2011). However, for utility functions with bounded marginal utility, this “dismal” theorem no longer holds. Still, skewed distributions for the climate sensitivity and damage ratio and tipping points call for more stringent climate policies. Pindyck (2011) surveys the effects of fat-tailed and thin-tailed uncertainty on climate policy and warns that cost-benefit analysis of climate policy is very difficult as policy makers cannot even be expected to know the probability distribution of future temperature impacts.

5 Diversification versus climate action

Most of the integrated assessment analysis of the economy and the climate have used models that have only one economic sector to investigate the risk-adjusted carbon price and the optimal transition from carbon-intensive to carbon-free production. Although we have talked about asset pricing in sections 3 and 4, the analysis was concerned with only one economic sector and there were only two assets, i.e. a risk-free bond in fixed supply and one risky financial asset. We now extend this analysis to allow for multiple sectors of the economy and correspondingly multiple risky financial assets. In a deterministic world, policymakers could ensure that all capital is immediately switched from the carbon-intensive to the carbon-free sector. In practice it is not possible or very costly to shift capital from one sector to another sector in which case intertemporal and inter-sectoral adjustment costs would mean that the transition to the carbon-free time takes time. The carbon-intensive sector may even be kept open somewhat longer if it generates a lot of revenue to finance the green transition. In a stochastic world, new considerations come into play as the carbon-intensive sector may be kept open as a hedge depending on the correlations between the various shocks hitting the sectors of the economy. Might it be possible that the need to diversify the portfolio of risky assets frustrates the successful implementation of climate policy?

5.1 Is carbon pricing frustrated by the need to diversify?

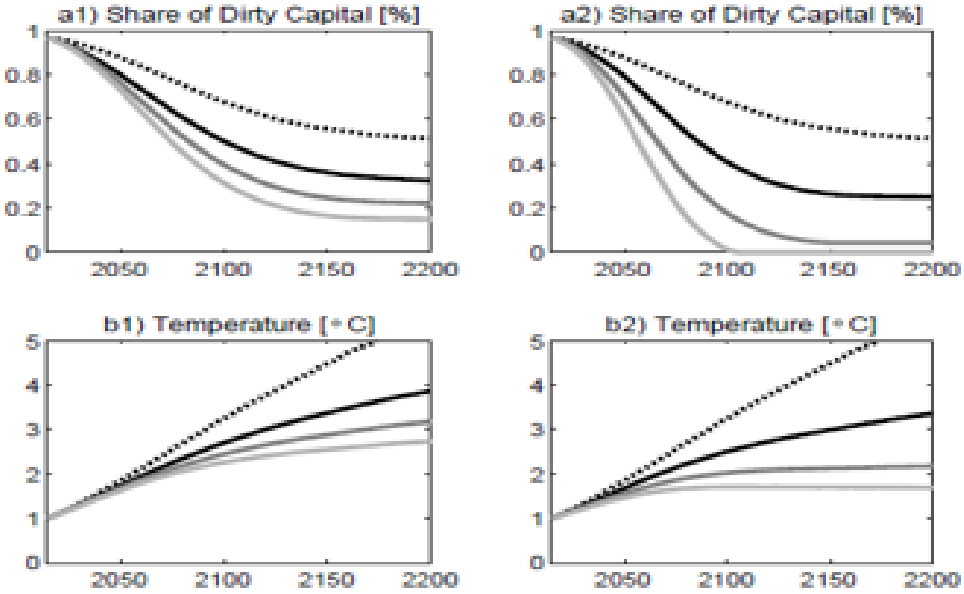
To focus attention on this question, we will throughout assume that there are only two final good sectors of the economy. One is a sector where final goods are produced with fossil fuel (coal, oil, or gas) and the other sector produces final goods using renewable energy only (solar or wind). Dividends are an unleveraged claim on aggregate consumption. We thus move from a one-sector to a two-sector DSGE model and asset pricing with Epstein-Zin preferences to calculate the optimal carbon price, stock market prices, and risk premia of the various assets under a wide range of economic and climate uncertainties and disasters (Hambel et al., 2020). We consider three types of negative externalities associated with global warming: (i) the negative effects of global warming on production in the two sectors (cf. sections 3 and 4); (ii) the negative effect of global warming on the growth rate of the economy (cf. Dell, 2009, 2012) via an increase in the depreciation rate of physical capital in the two sectors; and (iii) the positive effect of global warming on the likelihood of climatic macro disasters (cf. Barro, 2009). These give three reasons to price carbon, which will curb global warming and speed up the decarbonisation of the economy. Investment in each sector respond sluggishly to changes in the Tobin's Q of that sector and reallocation of capital from the dirty to the clean sector is also costly and responds sluggishly to the gap between the dirty and the clean Tobin's Q.

There is a subtle interplay between financial goal to diversify financial assets and the environmental coal to cut carbon emissions. The diversification perspective states that it is optimal to diversify until there is a balance between carbon-intensive and carbon-free, say 50-50 (Cochrane et al., 2007). The environmental perspective demands to run down the stock of carbon-intensive capital completely, but with the modest damages used in DICE it is optimal to keep up and running some of the carbon-intensive capital stock. Effectively, diversification considerations can prevent the dirty capital stock being driven to zero.

To illustrate these insights, Hambel et al. (2020) calibrate this two-sector DSGE asset pricing model to a business-as-usual scenario. Risk aversion is 5.3 but intergenerational inequality aversion is 1. Annual consumption/output volatility is 2%. The reallocation cost parameter is chosen such that global warming is 4 degrees Celsius after 200 years in line with the DICE model. The falling emissions intensity is also calibrated to the DICE outcome. The TCRE is set to 1.8 degrees Celsius for each trillion ton of carbon. The average consumption loss is 20% if a disaster strikes and the annual macroeconomic disaster risk is 3.8%. The size of climatic disaster shocks is 1.5% and has a time-varying annual probability of disaster occurring within a year. This probability increases linearly in temperature; it equals 9.9% and 38.7% at 1 and 4 degrees Celsius, respectively.

Chart 2

Effects of optimal carbon pricing on capital reallocation and temperature



Notes: The dotted lines indicate a hypothetical scenario without global warming damages. The black solid lines standard calibration, whereas the grey and light grey lines show what happens if damage effects are, respectively, 2 and 3 times as high. The left panels apply if temperature affects output negatively and the right panels if temperature increase the incidence of climate-related disasters.

Source: Hambel et al. (2020)

For illustrative purposes, the two columns of Chart 2 show the optimal share of carbon-intensive capital and temperature for the case when there is only an effect of temperature on total factor productivity (column 1) and only an effect on the annual probability of a climate disaster (column two). The dotted lines are relevant when there no damages from global warming in which case there is no benefit from climate action and full diversification occurs (the share of dirty capital stabilises at 50%).

If climate damages do matter, the share of dirty capital is reduced to between 20% and 30%. This happens for both types of adverse effects of global warming (columns one and two) and in both cases temperature is reduced below what it would have been otherwise. Pricing carbon leads to a gradual fall in the share of carbon-intensive capital, more than is required for diversification alone. Diversification and climate action are initially complementary goals, but after a while become conflicting goals and policy makers must counter the positive effects of diversification. Note that if damages to aggregate production become 2 or 3 times as intense, the share of dirty capital and temperature are further reduced but dirty capital is still used in the long run (column one). However, if the incidence rate of climate disasters is doubled or tripled, policy makers no longer feel it worthwhile to keep on using carbon-intensive capital forever (column two). Although we do not show this in the figure, dirty capital will also be driven to zero if all three adverse effects of global warming are switched on together.

Of course, the optimal trajectories will also be affected by correlations between the shocks hitting the dirty and the clean sectors. For example, if shocks to the two sectors are negatively correlated, the diversification motive is amplified so a faster transition to full diversification of assets and decarbonisation of the economy emerge. However, after a while the opposite is the case, and the economy uses a higher share of carbon-intensive capital to benefit from diversification. There is thus less climate action. Conversely, if shocks to the two sectors are positively correlated, the diversification motive is weaker. Hence, in the short run the transition to the green economy is slowed down but it in the longer run it is speeded up and the economy ends up with a lower share of carbon-intensive capital.

5.2 Asset pricing implications of optimal carbon pricing

Asset pricing theory allows one to obtain more general expressions for the risk-adjusted interest rate or risk-free rate than given in expression (3) for the SDR. Hambel et al. (2020) show that this rate consists of the following components. First, impatience is measured by the utility discount rate. A high value of this parameter implies that the economy wants to borrow. As the risk-free asset is in zero net supply, this implies that the risk-free rate must rise to offset this. Second, there is the affluence effect which indicates that the risk-free rate rises if future generations are richer (future growth is high) especially if intergenerational inequality aversion is strong. Third, there is a negative prudence effect which captures the precautionary motive in response to macroeconomic growth uncertainty (cf. equation (3)) and again the risk-free rate must rise to ensure that the risk-free asset stays in net zero supply. Fourth, there is a new negative term to allow for the precautionary motive in response to disaster risk which is larger at higher temperatures for climatic disaster risks (cf. Barro, 2009; Karydas and Xepapadeas, 2019). Finally, there is a new negative temperature diffusion risk effect which captures precautionary saving due to uninsurable, unhedged temperature risk. Again, as the risk-free asset is in zero net supply, the risk-free rate must fall to offset this precautionary saving.

It turns out that the affluence effect (second term) decreases in temperature due to global warming as damages. The affluence effects also decrease in the share of carbon-intensive capital since optimal fossil fuel and thus output declines in the share of dirty capital and the economy reallocates capital at a higher rate and the associated adjustment costs curb growth. Temperature has a tiny effect on the negative precautionary term (third and fourth terms) but the share of carbon-intensive capital has a big non-monotonic effect. The temperature diffusion risk term (fifth term) is almost negligible. Furthermore, the Tobin's Q for both the green and fossil-fuel-based sectors decline in temperature and the book to market ratio increases in temperature, so for given capital stocks market values decline with temperature for both assets. The Tobin's Q of the green asset rises with the share of dirty capital, hence for given capital green asset has a higher market value if the economy is more carbon intensive. The carbon-intensive asset has a lower market value if the economy is more carbon intensive.

The green and carbon-intensive equity premiums are positively related to the clean and dirty shares of capital, respectively. They hardly depend on temperature. If carbon is correctly priced, the green equity premium is higher than the carbon-intensive equity premium. In contrast, Bolton and Kacperzyk (2020ab) find empirically that carbon-intensive assets command a positive risk premium to compensate investors for the risk of carbon pricing being stepped up (see also section 7.1). This confirms that carbon pricing is far from optimal.

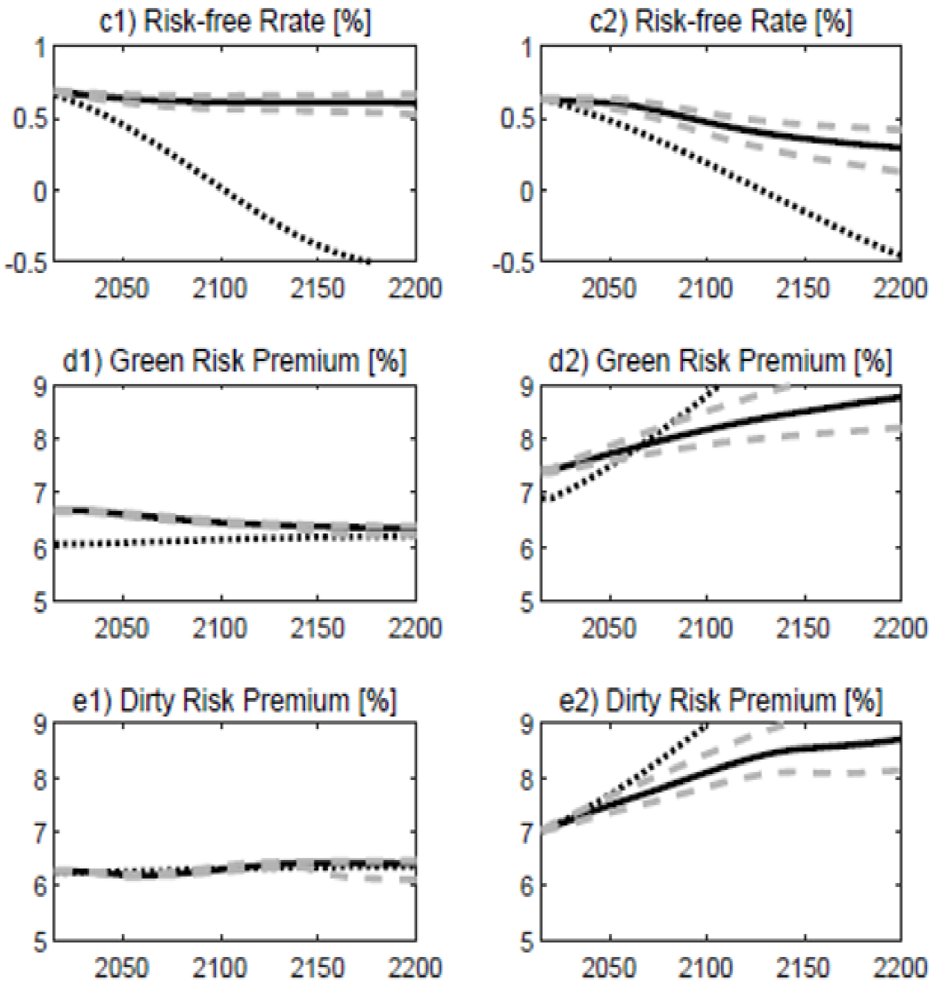
Chart 3 shows asset pricing effects under the optimal and the business-as-usual scenarios. It confirms that the risk-free rate falls much more strongly over time if carbon is not priced. This is due to the precautionary savings motive to cope with the inevitable growing climate damages in the business-as-usual scenario. Comparing the first and the second column of Figure 3, we see that only in case of a negative effect of temperature (the right panels) do we see a significant gradual increase in both the green and the dirty risk premium as temperature rises. This is not so if temperature only curbs total factor productivity (left column).

Note that for temperature affecting the incidence of climate-related disasters, the green and carbon-intensive risk premiums are higher and increasing. This is the result of the additional climate-related disasters generating an extra component in the risk premium. Because the jump intensity increases with temperature, this extra component becomes extra important in the busines-as-usual scenario where asset holders must be compensated for the increasing climate risks. Asset holders need to be compensated much less for this risk when carbon is appropriately priced.

We show that with optimal carbon pricing during with green transition the risk-free rate falls with rising temperature and the risk premia are only significantly affected if the risk of climate disasters increases with temperature (else the effect on risk premia is modest).

Chart 3

Asset pricing implications with and without carbon pricing



Notes: The dotted and solid lines show business-as-usual and mean optimal outcomes, respectively. The dashed lines show the 5% and 95% confidence bounds for the optimal paths. The left panels apply if temperature affects output negatively and the right panels if temperature increase the incidence of climate-related disasters.

Source: Hambel et al. (2020)

The above analysis can be improved in many ways. For example, one might consider the possibility that investors can also diversify their portfolios across different green industries which may weaken the trade-off between diversification and climate action. Also, investors may have non-pecuniary preferences for green companies and may be willing to accept a lower ratio of rewards to variability to speed up the transition towards the green economy. Ethical considerations may play a role when investors hesitate to keep dirty assets as a hedge (e.g. Zerhib, 2000). It is also important to allow for the rising trend in environmental impact investing. For example, Oehmke and Opp (2020) analyse when socially responsible investors impact outcomes by using a social profitability index and enabling a scale increase in clean production. They also make the case that socially responsible and financial investors are complementary. Landier and Lovo (2020) suggest that, if capital markets are subject to search frictions, an ESG fund can increase welfare by internalising environmental externalities despite selfish agents and by taking advantage of the supply chain network. Pastor et al. (2020) point out that in equilibrium green (or ESG) assets have lower expected returns because investors enjoy holding them and because they hedge climate risk. Sustainable investment strategies generate a positive social impact by making firms greener and shifting investment towards green firms. De Angelis et al. (2020) indeed find that, if the fraction of assets managed by green investors doubles, the carbon intensity of companies in portfolios falls by 5% per year.

Karydas and Xepapadeas (2019) perform a very similar exercise by extending Barro (2009) and Wachter (2013) and allowing for Poisson shocks due to climate change with the incidence rate of the shocks increasing in temperature. They calibrate a capital asset pricing model with macro disaster risks (cf. Barro, 2009) and climatic disaster risks to price green and dirty assets. They have one exogenous Lucas green which can be “painted green”, whereas Hambel et al. (2020) have two endogenous Lucas trees in a fully specified DSGE model with two sectors and two risk financial assets (and one safe asset). Their results indicate a positive and increasing risk premium. They point out that the macroeconomic risk seems to work as a hedge against catastrophic climate change in such a way that the aggregate equity premium remains unchanged. They also find that the transition risk of climate policy substantially curbs the share of carbon-intensive assets in the portfolio. We will return to this in the following section. Bansal et al. (2016) have a simpler framework with Poisson shocks due to climate change but not due macroeconomic disasters. They find that global warming induces a positive and increasing risk premium that has almost doubled over the last 80 years and reduces stock market valuations. Their increase in risk premia despite carbon being priced appropriately seems to be due to ignoring macroeconomic risks. They also find that the long-run impact of temperature on growth necessitates a significant increase in the price of carbon.

6 Anticipated tipping of climate policy and risk of stranded assets

A disorderly transition from a fossil-fuel to a carbon-free economy can cause havoc in financial markets. We define various ways in which this can happen and then analyse this more formally.

6.1 Four types of financial market effects of unanticipated changes in climate policy or energy costs

Sudden changes in policy, called policy tipping, can lead to sudden changes in the market valuation of both carbon-intensive and carbon-extensive firm and can lead to the stranding of assets. E.g., the government might suddenly wake up and step up climate action to limit the total amount of cumulative carbon emissions to keep temperature below 2 degrees Celsius and the private sector was previously unaware of that change in policy. Also, a shift in expectations about climate policy (e.g. carbon pricing is moved forward by 10 years but has not yet been implemented) can lead to similar effects. Equivalent to a sudden change in policy is a sudden occurrence of a breakthrough technology in renewable energy (e.g. a sudden drop in the cost of batteries or fusion energy). Such technological breakthroughs threaten the sustainability of the fossil-fuel business model and can lead to stranding of fossil-fuel-based financial assets if they cannot easily be shifted and used productively in the low-carbon or carbon-free economy.[5]

Hence, for asset stranding and sudden changes in market valuation to occur two conditions to be met: first, there must be an unanticipated future change in conditions affecting the profitability of fossil-fuel assets; and second, it must be costly or impossible to shift around the underlying capital stocks in the carbon-intensive industries to productive use elsewhere after the unexpected future change in conditions (van der Ploeg and Rezai,(2020ab). Four types of asset stranding van be distinguished:

First, a big chunk of fossil fuel reserves should be kept in the earth if temperature is to stay below 1.5 or 2 degrees Celsius. This is stranded carbon.

Second, part of the infrastructure and capital invested in the up- and down-stream fossil fuel industry will need to be written off once the economy fully switches to renewable energy. This is stranded physical capital and is relevant when the carbon era ends.

Third, prices of fossil-fuel-based assets in the oil, gas, and coal industry as well as in the steel, cement and other carbon-intensive industries respond long before their industry shuts down and climate policy is stepped up. The valuation of these assets changes once the unanticipated future changes become known.

Fourth, not all policy changes are known with certainty and announcements made by policy makers or innovators today are, of course, subject to uncertainty about whether these changes will occur and if they do when they will occur. If this is so, the initial revaluation blow to carbon-intensive assets at the time of announcement may soften once such uncertainties are removed.

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[5] Caldecott et al. (2016) highlight that asset stranding can be related to broader environmental challenges; e.g. sudden and unanticipated changes in perception of environmental challenges (e.g. realisation of positive feedback loops in the climate system or degradation of soil or water quality), the natural resource landscape (e.g. scarcity of phosphate or shale gas abundance), social norms and consumer behaviour (e.g. Greta Thunberg) and litigation (e.g. carbon liability) and changing statutory interpretations (e.g. fiduciary duty or disclosure requirements).

All these types of asset stranding have undesirable repercussions in financial markets. Most definitions of stranded assets highlight write-offs of the market value of carbon-intensive financial assets when there are downwards revisions in profitability, economic lifetime, or capacity utilisation (e.g. Caldecott, 2017; Caldecott et al., 2018). Asset value can also become negative when assets are subjected to unanticipated or premature write-offs, devaluations, or conversions to liabilities. The damages from global warming can in the future create liabilities for high-carbon emitters (e.g. Covington et al., 2016; Mechler and Schinko, 2016). The definition of a stranded asset as “an asset which loses significant economic value well ahead of its anticipated useful life, as a result of changes in legislation, regulation, market forces, disruptive innovation, societal norms, or environmental shocks” (Generation Foundation, 2013, p. 1) is also useful. Stranded assets are very different from unburnable carbon; the obsolescence of physical capital in the oil, gas, and coal sectors, power generation, and transportation follows very different dynamics that of locking up fossil fuel in the ground.

There is not much empirical evidence on stranded assets yet. However, Atanasova and Schwartz (2019) use a sample of 600 North American oil firms for the years 1999-2018 to show that the growth of oil reserves has a negative effect on firm value, especially for firms with higher extraction costs (even though reserves are an important component of firm value). This effect is due to firms growing undeveloped oil reserves, which implies major investments and longer time before they can be extracted. Furthermore, this negative effect is larger for undeveloped reserves located in countries with stricter climate policies. Hence, markets seem to penalise future investments in underdeveloped reserves growth in countries where there is substantial climate policy risk. We refer to section 7 for more empirical evidence.

6.2 Macroeconomic and financial implications

The unanticipated credible announcement of a future stepping up of climate policy leads to market responses today, devaluing natural and physical capital in fossil-fuel-based industries (cf. Bretschger and Soretz, 2019; Rozenberg et al., 2019; van der Ploeg and Rezai, 2019). With a big chunk of fossil fuel reserves becoming unburnable, there will be falls in the scarcity rents, increasing demand, extraction, emissions, and global warming compared with business as usual. The increase in carbon emissions and acceleration of global warming lead to the green paradox (Sinn, 2008). If politicians use renewable energy subsidies as second-best policy instead of pricing carbon, there will also be higher fossil fuel extraction and acceleration of global warming. While owners of fossil fuel race to burn the last run, investment into the industry ebbs off. Lower returns send investors pursuing higher yields elsewhere, e.g. in the renewable sector. Investors’ concerns about stranding of physical assets in the fossil fuel industry forces them to have skin in the climate game and thus leads to a cut in short-run carbon emissions. This softens the usual green paradox effect (Baldwin et al., 2020).

Second-best policies come with deadweight losses. If carbon pricing is delayed, the delayed carbon price path has to be higher than an immediately implemented carbon price to meet the same cumulative emissions or temperature target and to compensate for the time wasted and the additional emissions due to the green paradox. Since carbon emissions are brought forward, exploitation investment, discoveries and drilling are discouraged. By boosting profitability and preserving shareholder wealth compared to the loss under the immediate tax, owners of fossil wealth have an incentive to delay and hinder policy implementation.

Whether an unanticipated announcement of tightening of climate policy leads to immediate falls in market valuation of natural and physical capital crucially depends on the credibility of this policy. If agents attach a certain probability to this announcement, current or future demand for fossil fuel will fall and the scarcity rent of fossil fuel and price of capital installed in the fossil industry drop. With forward-looking rational expectations, these effects occur immediately as soon as the announcement becomes known. One interpretation of why share prices hardly reacted after the Pairs Agreement is that investors believe that the Paris Agreement are just paper promises. A more realistic approach is to model climate policy as a tipping event, which occurs with a certain probability (van der Ploeg and Rezai, 2019). The probability of policy makers tipping into action may increase as temperature gets closer to the cap to which countries have committed. This transforms the issue of credibility to uncertainty about when stepping up of climate policy will occur. Let us suppose that the market assigns a probability $0 < \pi < 1$ that policy makers change tack at some future date and from then on implement carbon pricing compatible with the internationally agreed upon temperature cap. The market assigns a probability $0 < 1 - \pi < 1$ that policy makers' efforts fail, and business as usual continues. Here, uncertainty involves whether at some future point of time a ceiling on cumulative emissions compatible with the temperature cap is imposed or not. Alternatively, uncertainty could range on the timing of the introduction of a given carbon price path. Both types of tipping events could occur repeatedly.

Uncertainty about the timing and forcefulness of climate policy leads to an additional potential stranding off assets in the transition to a carbon-free economy. Once the tipping event occurred and uncertainty is resolved, agents know that policy will be sustained and that this realisation is equivalent to the case of a policy surprise discussed above. The period before the tip is qualitatively different from the case of an announced and fully anticipated policy. Instead agents take the expected value over both scenarios, given probability π. Changes in the expected policy still impact prices as before, however, now the probability π also determines the extent to which assets are reassessed. This is easy to see when one considers the extreme values of π. With $\pi = 0$ the economy faces business as usual with certainty and with $\pi = 1$ the economy faces climate policy a future date onward with certainty. In reality π will increase gradually at intermediate values, leading to a constant repricing of assets, making it hard to empirically identify asset stranding (e.g. Carattini and Sen, 2019). However, given the self-reinforcing nature of ongoing technological change and unanticipated cost reductions in renewable energies, breakthrough will occur and therefore discrete and significant downward revisions of fossil assets will occur. Given that setting an end date of the fossil fuel era leads to voracious depletion of reserves, uncertainty can have positive implications for the environment. With a positive probability of a continuation of the fossil fuel era (i.e. business as usual), fossil- fuel-based firms are pacing their race to burn the last ton. This reduces green paradox effects in the pre-tip phase and, if the economy ends up with stepped up climate policy, requires less forceful pricing of carbon in later periods (van der Ploeg and Rezai, 2019).

Barnett (2020ab) also shows that an uncertain arrival time of a policy change can generate a run on oil, which leads to falls in the spot price of oil and market valuation of companies, increase in renewable energy use, and higher temperature. These papers consider the Stochastic Discount Factor and asset pricing implications and show the potential occurrence of a carbon bubble. Bretschger and Soretz (2018), van der Ploeg and Rezai (2019), Rozenberg et al. (2020) and Fried et al. (2020) also study the effects of climate policy uncertainty on emissions and stranded assets in the transition to a carbon-free economy. Finally, van der Ploeg (2020) uses a game-theoretic approach to explain the “race to burn the last ton of carbon” and the risk of stranded assets. The mere risk of a cap on global warming at some unknown future data makes oil extraction more voracious and thus accelerates global warming. This is a manifestation of the well-known Green Paradox.

Donadelli et al. (2019) use a two-sector DGSE capital asset pricing model with imperfect substitution between carbon-intensive and carbon-free final goods, but abstract from disaster shocks. The green transition is also driven by carbon taxes and capital reallocation from carbon-intensive to green sectors of the economy in response to changes in the carbon-intensive and green Tobin Q’s. They carefully compare the optimal green transition under an immediate and under a slow transition to optimal carbon prices and then compare the impulse response functions in both scenarios to get a grasp of climate policy risk premia. The positive response in the carbon-free sector’s returns induces positive risk premia and cuts the market value of the green sector and reduces capital reallocation. This corresponds to the risk premium channel of climate policy. A too slow rise to optimal carbon prices (i.e. too low carbon prices) gives rise to positive risk premia and lower market valuations of the carbon-free industries. This is undesirable from a welfare point of view.

7 Empirical evidence of effects of anticipated green transition on asset returns

With 195 countries signing up to the 2015 Paris COP21 climate agreement there is a clear expectation that actions will be undertaken to limit temperature to 2 or even 1.5 degrees Celsius above pre-industrial levels. This might lead to carbon-intensive assets to be subject to a positive and possibly rising carbon risk premium. Furthermore, central banks have been warning about the financial risks associated with climate change (e.g. Carney) and see also the Network of Central Banks and Supervisors for Greening the Financial System (NGFS). Institutional investors are increasingly tracking carbon emissions of listed companies, sometimes banning the most carbon-intensive stocks, and at the same time forming coalitions to engage with companies to cut emissions (e.g. Climate Action Plus 100+). Other Non-governmental organisations have also urged governments to step up the fight against global warming and to honour international agreements. Nevertheless, there remains considerable doubt about whether the internationally agreed upon reduction in carbon emissions takes place and, if so, when they will take place, not only in the United States but in many other countries too. But among commentators and institutional investors too, there is disagreement about how serious the green transition is taken by policy makers. There is a growing literature on the empirical effects of the anticipated effects of the green transition and carbon risk on stock market returns.

7.1 Carbon risk premium on carbon-intensive assets

Bolton and Kacperczsyk (2020a) combine the Trucost EDX data covering carbon emissions of 1,000 listed companies since the fiscal year 2005 and more than 2,900 listed companies in the United States since the fiscal year 2016 with the FactSet returns and balance-sheet data for all listed companies in the United States from 2005 to 2017. They demonstrate empirically using a cross-sectional analysis that more carbon-intensive firms in the United States show indeed higher stock market returns after controlling for size, book to market, momentum, other variables that predict returns, and firm characteristics such as the value of property, plant and equipment and investment over assets. This carbon risk premium is related to the total level of emissions and the year-by-year change in emissions, but not to the emissions intensity. The carbon risk premium is also related to the year-to-year growth in emissions, which suggests that those companies that that succeed in cutting emissions can get away with lower stock market returns. Quantitatively, this study finds significant carbon risk premia. An increase in the level and a change in direct emissions from production (scope 1) by one standard deviation leads to an annualised increase in stock market returns of 1.8% and 3.1%, respectively. For the indirect emissions from consumption of purchased electricity, heat, or steam (i.e. scope 2), these extra annualised returns are 2.9% and 2.2%, respectively. For indirect emissions from the production of purchased materials, product use, waste disposal, outsourced activities, etc. (i.e. scope 3), these additional annualised returns are much higher, namely 4% and 3.8 %, respectively. These carbon risk premia have only materialised in recent years. There is no evidence for them in the 1990s, which suggests that investors did not pay much attention to carbon emissions then.

Since carbon risk premia cannot be explained via unexpected profitability or other risk premia, they conclude that this risk premium is the consequence of investors demanding compensation for the risk to corporations of the government suddenly stepping up climate action at some future moment in time. Hence, this premium is referred to as a carbon risk premium. It stems from climate policy risk, but also from uncertainty about fossil fuel energy prices and from uncertainty about breakthroughs in renewable energy technology. This study also points out that carbon risk may be systemic if climate policies apply across the board or may be introduced in a piece-meal way at the state, industry, or municipal level. If technological improvements in renewable energy apply to particular sectors, the carbon risk would not be systemic either.

Bolton and Kacperczyk (2020a) following Kacperczyk (2009) also find that institutional investors (insurance companies, pension funds and mutual funds) hold a significantly smaller fraction of companies with high scope 1 emission intensity, but do not underweight companies with high level of emissions. Basically, institutional investors appear to be applying exclusionary screens only on basis of scope 1 emissions intensity. If industries with highest emissions (oil, gas, utilities, motor industries) are excluded, the evidence in this study suggests that there is no exclusionary screening at all. All screening is done in just these industries with no divestment in other industries. These findings are in line the emergence of sustainable investment and negative exclusionary screening investment strategies (i.e. excluding “sin” stocks) followed by ESG funds. This is relevant, since negative exclusionary screening is the largest sustainable investment strategy globally. But such a rough exclusionary approach misses the full extent of all emissions at the company level.

Bolton and Kacperczyk (2020b) perform a similar exercise for a cross-section of 14,400 firms in 77 countries and find empirical evidence for both a positive and rising carbon risk premium in the stock market returns of firms with higher carbon emissions. They find that this carbon risk premium for companies with higher carbon emissions occur in all sectors over three continents (Asia, Europe, and North America). Stock market returns are affected by both direct and indirect emissions through the supply chain. They also find evidence that the carbon risk premium has been rising in recent years. They find that there has been widespread divestment based on carbon emissions by institutional investors around the world, but institutional investors tend to focus their divestment on foreign companies. Furthermore, more democratic countries with stronger rule of law tend to have lower carbon risk premia ceteris paribus, perhaps because in those countries climate policy has already been stepped up so that the transition risk is lower. Also, the carbon premium associated with the level of direct emissions is higher in countries with large oil, gas, and coal extracting sectors and in countries more exposed to floods, wild-fires, droughts, etc.

Zerbib (2020) constructs an instrument that captures sustainable investors’ taste for green firms and extends the four-factor model to allow for green investing/ESG and sin stock exclusion. He estimates his model on U.S. date over the period 2000-2018 which yields a green taste and an exclusion effect of 1.5% and 2.5% per year, respectively.

7.2 Is the risk associated with carbon emissions under-priced?

Another hypothesis is that financial markets price carbon inefficiently, and that the risk associated with carbon emissions is under-priced. This is the market inefficiency hypothesis. Global warming may just not be on the radar when pricing stocks. In, Park and Mong (2019) examine 736 firms from 2005-2015 and find empirically that a portfolio that is long in shares of companies with low carbon emissions and short in shares of companies with high returns generates from 2010 onwards abnormally high and positive returns of 3.5% to 5.4% per year. These abnormal returns are not driven by low interest rates after the global financial crisis of 2007/8. This suggests that markets under-price carbon risk (controlling for other risk factors and industry and firm characteristics) to such an extent that green responsible investors (i.e. those who care about mitigating global warming) perform better than non-green investors. Furthermore, it turns out that carbon-efficient firms are “good” in terms of financial characteristics and governance. In contrast to In et al. (2019) and the empirical findings in Garvey et al. (2018), Bolton and Kacperczyk (2020a) find no empirical evidence for an effect of emissions intensity on stock returns which might be because they control for industry, firm characteristics, and known risk factors (in contrast to these two studies).

A recent study by Donadelli et al. (2019) focuses on the fossil fuel industry to circumvent classification issues. Their innovation is to use panel data regression to explain changes in the market to book ratio along trends in climate change awareness during the period 1970-2018 whilst controlling for market-wide value and other trends. Data series for awareness of climate change risks were obtained from Google searches and displayed close similarities with environmental policy stringency. Their empirical findings are that the stock market value of US oil and other fossil-fuel firms has fallen a lot during the last 20 years compared to other firms and, furthermore, that markets have started to price in the climate coefficient (captured by a negative coefficient in the regressions on the climate awareness index).

There is an increasing number of empirical studies investigating the effects of carbon risk on stock market returns. Matsumura et al. (2014) consider S&P500 firms during the period 2006-2008 and find that higher emissions are associated with lower firm values, and that voluntary disclosure mitigates this effect. Chava (2014) finds that firms that derive big returns from sales of coal or gas typically have a higher cost of capital. Ihan et al. (2020) argue that the cost of option protection against downside carbon tail risks is larger for more carbon-intensive firms. This cost becomes larger at times when the public’s attention to climate change spikes, and smaller after the election of President Trump who has been bashing climate policy. Climate policy uncertainty is thus priced in the option market. This study also implies that markets expect significant downward jump in asset prices because of climate change.

Hsu et al. (2020) find that a long-short portfolio made up of firms with high versus low toxic emission intensities with industry generate an average return of 4.42% per year, which remains significant after controlling for risk factors. This pollution premium may potentially be explained by environmental regulations, relatedness to existing systemic risks, investors’ preference for social responsibility, market section sentiment, political connections, and corporate governance. The evidence, however, points to environmental policy uncertainty as the main driver of the pollution premium. These findings also suggest that the carbon risk premium found by Bolton and Kacperczyk (2020ab) seems related to transition policy risk.

Görgen, et al. (2019) use the data from the Carbon Disclosure Project, the ESG statistics and IVA ratings of the MSCI, the ESG ratings of Sustainalytics, and the ESG data of Thompson Reuters to construct a carbon-risk factor. They use this to quantify the carbon risk with a carbon beta for firms controlling for the Fama-French factors. They also demonstrate the implications for various stakeholders. Monasterolo and De Angelis (2019) investigate whether investors demand higher risk premia for carbon-intensive assets and are reducing systemic risk by cutting down on carbon-intensive assets and increasing low-carbon assets in their portfolios after the Paris Cop21 Agreement. They find that investors have started to consider low-carbon assets as an appealing investment opportunity after the agreement but find in contrast to Donadelli et al. (2019) that investors have not penalised carbon-intensive assets yet. Plantinga and Scholtens (2020) examine 7,000 companies over 40 years and find that investment portfolios than exclude fossil-fuel-production companies do not perform worse than unrestricted portfolio. This suggests that divesting from fossil fuel companies does not hurt stock market performance.

7.3 Hedging carbon risk

Andersson et al. (2016) recommend the use of carbon trackers to hedge against carbon risk and found that this is still a fairly cheap way to deal with carbon risk as the returns when climate policy is not stepped up are as good as with normal trackers yet losses are avoided when policy makers implement more ambitious climate policies in the future. Such strategies divest away from carbon-intensive assets and optimise the composition of the low-carbon portfolio to minimise the tracking error with the reference benchmark index. The green trackers that have been constructed in this way have already matched or outperformed their benchmark. The beauty is that on the day that carbon climate policy is stepped up, these trackers outperform the benchmark. Engle et al. (2019) put forward a mimicking-portfolio method to dynamically hedge climate change risk. Innovations in climate change news are extracted using textual analysis of high-dimensional data on newspaper coverage of climate change and a large panel of equity returns is used. Third-party ESG scores of firms are used to model climate risk exposures. The resulting climate hedge portfolios outperform alternative hedging strategies based mostly on industry tilts.

7.4 Effects of global warming and weather on assets and real estate prices

So far, we have examined studies on the effects of climate transition risk on asset returns and asset prices. Other studies have investigated the effects of weather disasters on asset prices. For example, Hong et al. (2019) use the Palmer Drought Severity Index to show that the effects of increasing risk of droughts caused by global warming are not efficiently discounted by prices of food shares. Food share prices seem to underreact to climate change risks. The effects of global warming on real estate prices has also been investigated. Baldauf et al. (2020) use comprehensive transaction data to relate real estate prices to inundation projections of individual homes and measures of belief about climate change. They find weak evidence of real estate prices falling in response to greater flood risk as the sea level rises. Moreover, they find that houses projected to be underwater in believer neighbourhoods sell at a discount rate compared to houses in denier neighbourhoods. Hence, real estate prices reflect heterogeneity in beliefs about long-run climate change risks. Bakkensen and Barrage (2018) conduct a field survey in Rhode Island and find significant heterogeneity and sorting based on flood risk perceptions and amenity values. They suggest that coastal prices currently exceed fundamentals by 10%. If heterogeneity is ignored, this leads to a four-fold underestimate of future coastal home price declines due to sea level rises. Bernstein et al. (2019) show that homes exposed to sea level rise sell for approximate 7% less than to similar unexposed properties equidistant from the beach. This discount has grown over time and is driven by those worried about global warming. Also, there is evidence that pricing of municipal bonds has begun to respond to the risk of severe weather events depending on the climate resilience measures of municipalities (Painter, 2020).

Giglio et al. (2018) estimate the term structure of discount rates for real estate up to the very long horizons that are needed to evaluate investments in climate change abatement.[6] This term structure slopes downwards and reaches 2.6% per annum at horizons beyond a century. They find that real estate is exposed to both consumption risk and climate risk. Using a tractable asset pricing model with climate change modelled as a rare catastrophic event with the probability increasing with economic growth, they allow for economic activity to mean revert following a climate disaster (capturing the ability of the economy to adapt) and thus short-run cash flows are more exposed to climate risk than long-run cash flow not unlike in Daniel et al. (2019). They can thus match the observed housing term structure. This procedure offers insights into the appropriate discount rates to use to evaluate investments that hedge climate disaster risk. The key finding is that the term structure of these discount rates slopes upwards but is bounded above by the risk-free rate (or the long-run discount rates for housing). The important point is that the discount rates to use for climate investments are low at all horizons and much lower than those conventionally used to value these investments and for determining the social cost of carbon. Hence, climate policy will be much more intensive.

8

Macro-financial policies to complement the green transition

Some early contributions on the interactions between fiscal policy and environmental policy employed real business cycle models with no nominal rigidities (e.g. Fischer and Springborn, 2011; Heutel, 2012). A very interesting recent study uses a real general equilibrium model with overlapping generations to show that it is possible to have a climate policy where no generation is worse off and some are better off (Kotlikoff et al., 2020). This requires running up public debt to ensure that the youngest generations get compensated for the sacrifices they make to fight global

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[6] This is related to Giglio et al. (2015), who exploit the price difference between 99 to 999 years leaseholds on residential property in the U.K. and Singapore to back out discount rates below 2.6% for 100-year claims.

warming. There are also many fiscal issues to do with climate policy, especially those to do with financing new green investment or compensating low incomes if carbon taxes turn out to be regressive. There are interesting finance issues to do with the green transition too. For example, firms that are heavily invested in carbon-intensive capital might find it difficult to attract finance for new green investments because just when they need their old capital most in the form of collateral, it drops in value.[7]

Here we are, however, concerned with the interactions between climate, fiscal and monetary policies which typically use New Keynesian general equilibrium models with nominal rigidities and Taylor rules for the nominal interest rate. One question is how the monetary policies of central banks, i.e. the Taylor rules for the nominal interest rate, should respond to global warming within the framework of a New Keynesian DSGE model. Economides and Xepapadeas (2018) study such a DSGE model of a closed economy and find non-trivial implications for the conduct of monetary policy in the euro area. Economides and Xepapadeas (2019) study this problem for a small open economy and find that climate change leads to significant output loss and a dramatic deterioration of competitiveness.

Annicchiarico and Dio Dio (2015) show within such a New Keynesian context that a cap-and-trade policy is more likely to attenuate macroeconomic fluctuations. They also show that the performance of the environmental policy regime in place depends very much on the extent to which prices are staggered. Furthermore, the environmental policy response to shocks depends strongly to how quickly prices adjust and to the monetary policy reaction. Annicchiarico and Dio Dio (2017) show that the optimal response to productivity shocks depends crucially on the instruments that policy makers have available, the intensity of the distortions they must address (i.e. imperfect competition, costly price adjustment and the global warming externality) and the way they interact. Diluiso et al. (2020) discuss how financial regulation and monetary policy can be used to combat global warming and analyse the potential effects on stranded assets. Jaimes (2020) shows in a New Keynesian DSGE model that the negative effects of carbon pricing on output and consumption are reduced if the carbon tax or permit revenue is used to reduce the labour income or consumption tax rate rather than rebating it via lump-sum transfers, especially if wages and price move sluggishly to clear markets.

Böser and Senni (2020) use a New Keynesian DSGE model to study the potential benefit of emissions-based interest rates in the transition to a low-carbon economy and illustrate this for the Euro area. If liquidity costs of banks increase with the carbon intensity of their asset portfolio, banks will favour low-carbon assets and thus makes it easier to finance the green transition. Such a climate-oriented monetary policy helps the decarbonisation of the economy by incentivising green investments. Lessman and Kalkuhl (2020) also consider financial intermediation costs in a dynamic general equilibrium model of climate and the economy.[8] They study how interest rate spreads affect climate policy’s ability to shift capital from carbon-

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[7] More generally, Donovan et al. (2020) discuss transition finance and how to manage funding to carbon-intensive firms.

[8] Schuldt and Lessman (2020) analyse financial market imperfections and green investments in a closed economy.

intensive to green sectors of the economy. They find that with low or moderate interest rate spreads carbon emissions are higher because of lower investment into the capital-intensive green energy sector, but for high spreads emissions falls as lower economic growth curbs emissions. Meeting a temperature cap requires raising carbon prices by a third on account of capital market frictions.

Benmir et al. (2020) use asset pricing to determine the carbon price (as in section 4) when global warming directly affects the marginal utility of consumption and show that the optimal carbon price is pro-cyclical. By cutting the carbon tax in booms and increasing it in recessions risk premium are cut whilst the average risk-free rate is increased, which leads to substantial welfare gains at the macron level. Benmir and Roman (2020) use a New Keynesian DSGE model with a carbon-intensive and a green sector, with balance-sheet constrained financial intermediaries, and with the possibility of a biting zero lower bound on the interest rate. They show that mitigating carbon emissions requires a substantial carbon tax for the Euro area, which leads to significant welfare losses. Furthermore, they consider sectoral time-varying macroprudential weights on loans benefiting green investments, which helps to mitigate welfare costs. They find that a carbon tax improves the benefits of both green and carbon-intensive asset purchases (i.e. quantitative easing). They consider quantitative easing policies that curb the effect of emissions on risk premia. They thus suggest that central banks can have a useful role in the fight against global warming.

Campiglio (2016) argues that carbon pricing is insufficient to fill the gap in low-carbon investments due to the market failure in the process of credit creation and allocation. He therefore makes a case for specific macroprudential financial regulation to boost green investments, especially for emerging economies, and discusses the idea of easing reserve ratios for low-carbon lending. Similarly, McConnell et al. (2020) investigate the case for using central bank collateral as an instrument for curbing carbon emissions. Dafermos et al. (2018) do not use a New Keynesian DSGE model, but a stock-flow-fund ecological macroeconomic model to analyse effects of global warming on financial stability and the effects of green quantitative easing on the economy and global warming. Global warming can increase defaults with adverse effects on bank leverage and can also set in motion a process of asset price deflation. They show that a green quantitative easing programme can curb climate-induced financial instability, where the effectiveness of such a programme depends positively on the responsiveness to changes in bond yields. Monasterolo and Raberto (2018) use a flow-of-funds behavioural model that is stock-flow consistent and is built around a balance sheet approach and Leontief production function. They use it to simulate the effects of green fiscal policies including green technology investments versus green sovereign bonds on green growth, credit market instability, unemployment, income inequality, wealth concentration and the impacts on the real economy. The relative effectiveness of these green policies depends on the fiscal stance of the economy.

9 Disorderly green transitions, the risk of stranded assets, and prudential policy

The Governor of the Bank of England, Mark Carney, was one of the first to warn against the risks posed by global warming for the stability of the financial system and to identify some of the risks to banks, pension funds and insurance companies (Carney, 2015). These climate-related risks tend to be systemic and affect balance sheets throughout the financial sector. There are short-run physical risks caused by drought, wildfires, storms, and other extreme weather events that are more likely as the planet heats up and long-run physical risks caused by sea level rise. As we have seen in sections 4 and 5, the frequency but also the severity of such climate-related disasters tends to increase with global warming. As we have seen in section 6, there are also transition risks following from the uncertainty about if, and when, climate policy is stepped up in the future which can adversely affect market valuations of carbon-intensive firms. Due to high adjustment costs or due to the irreversible nature on investments, assets of such firms are at risk of being stranded. We have seen in section 7 that the market will price those risks in by investors demanding a higher return on carbon-intensive assets. These risk premiums will also help in the efficient reallocation of capital during the green transition.

Another way of putting it is that central banks and financial regulators need to play a prominent role in the low-carbon transition because market imperfections in a second-best world would lead to Green Swans and Climate Minsky Moments as has highlighted in a recent report for the Bank for International Settlements (Bolton et al., 2020). The inability of financial markets to fully price climate risks (see section 7), wide-ranging moral hazard problems in the financial community, and diverging expectations about the introduction of climate policies and impacts means that the informative role of prices is not as good as it should be. In the analysis of carbon pricing under the Pigouvian or the more pragmatic temperature cap approach (see sections 3, 4 and 5) there are no such informational issues. The analysis of climate policy uncertainty or uncertainty about the timing of technology breakthroughs in green energy (see section 6) is an example where asset prices need to take account of this type of uncertainty and thus do not fully reflect the actual changes that are going to happen. This is also reflected in the risk premia on carbon-intensive and green financial assets (see section 7).

But more generally the risk of a disorderly transition to a low-carbon economy can cause abrupt changes in market valuation and increase the risk of stranded assets. Hence, climate policy should be a core interest of financial regulators. In fact, it is their fiduciary responsibility. This is pertinent due to the phenomenon of risk amplification, which arises naturally in financial networks. It is thus important to identify which financial agents are the drivers of impact and of risk amplification and to carefully analyse the endogeneity of risk that might emerge from the interaction between policy makers and investors' expectations and lack of coordination about climate policy. The analysis of economic risks and asset diversification issues (as discussed in sections 4 and 5) should thus be extended to allow for the endogenous risks that might occur and be amplified in financial networks and how this affects the low-carbon transition and pricing of green and carbon-intensive financial assets. It is only by doing this that one can obtain insights into the systemic risks posed by disorderly green transitions.

9.1 Risk amplification in production and financial networks

To understand these issues, economists and scientists have turned to network science and graph theory which has been used to grasp a wide variety of networks varying from cellular networks encoding interactions between genes, proteins and metabolites, neural networks and the functioning of brains, social networks, communication networks, and the power grid of electricity generators and transmission lines, international trade networks, terrorism networks, epidemics, and research networks to the internet (Barabási, 2016). All these networks (or graphs) are coded using nodes (or vertexes) and links (or edges) and can be analysed using the same set of mathematical tools (e.g. degree distributions, adjacency matrices, shortest paths between nodes, random network models, power laws and scale-free networks, percolation theory, cascading). Networks are typically sparse and can be directed or undirected, and the theory helps to understand why certain nodes are more central than others, what determines connectedness and clustering, why hubs are missing, and why some networks are more robust than others. According to Metcalfe's law, the value of a network increases in the square of the number of its nodes albeit it will in practice be less fast due to the sparsity of most networks. Those nodes that have the most links will attract the largest number of new links as time progresses. This growth will determine the eventual structure of the network.

Economists have studied networks to show that microeconomic idiosyncratic shocks in a framework with Cobb-Douglas production functions and intersectoral input-output linkages are not necessarily washed out in general equilibrium but higher-order interconnections may lead to aggregate fluctuations and cascade effects where shocks affect not only immediate downstream consumers but also the rest of the economy (Acemoglu et al., 2012). These propagation effects are strong only if there is significant asymmetry in the role that sectors play as suppliers to each other (i.e. with hubs and star-like or power-law networks); the sparseness of the input-output nature does not affect this effect. Similarly, it has been shown that the idiosyncratic movements of the 100 largest U.S. firms explain one third of variations in output growth (Gabaix, 2011). If one departs from Cobb-Douglas production functions and uses Leontief or CES production functions, networks will display genuine instability with turbulence (Bonart et al., 2014).[9]

Networks can be applied to understand systemic risk and stability in financial networks (Acemoglu et al., 2015). If the size of adverse shocks affecting the financial system is small, a densely connected financial network with a well-diversified pattern of interbank liabilities improves financial stability and resilience. But for large enough shocks, these dense interconnections drive propagation of shocks and make the

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[9] More recently, agent-based models of the financial system with leveraged investors managing risk using a Value-at-Risk (VaR) constraint (e.g. Aymanns and Farmer, 2015). This VaR constraint implies procyclical leverage, which causes irregular leverage cycles. However, if policy ensures that leverage is sufficiently countercyclical and bank risk sufficiently low, endogenous cycles do not occur.

financial system more fragile. Indeed, it has been argued that the “great moderation” was driven by the falling manufacturing share between 1975 and 1985, but that its undoing and the associated rise in macroeconomic volatility is primarily due to the growth of the financial sector (Carvalho and Gabaix, 2013). The surge in the size of finance in the 2000s should thus have served as an early warning signal for more macroeconomic volatility to come. These financial network models can be used to understand bank defaults, deleveraging spirals, and fragility of the financial system.

In recent years, the analysis of propagation of climate risk (versus risk diversification), default, fire sales, common exposures, information asymmetries, collective moral hazard problems, contagion, and financial stability in financial networks has received more attention. This has been used to understand the dynamics of indirect contagion via common asset exposures between banks and funds and to analyse climate stress tests against a background of valuation of interbank claims that takes account of market volatility and endogenous recovery rates (Ronconeri, et al., 2014). The climate stress tests estimate the various channels by which the effects of a late and disorderly alignment to a climate policy scenario operate: (i) losses suffered by banks and funds due to direct exposure (bonds and loans) to climate risks; (ii) ex-ante network (re)valuation of intra-financial claims due to the effects under (i) using a contagion model with endogenous recovery rate plus devaluation of fund assets due to higher risk of bank default; (iii) the reaction of banks and funds to get to initial risk management (i.e. leverage for banks and VaR for funds) with sudden liquidations causing further losses on the balance sheets of banks and funds; and (iv) losses too large to be absorbed by banks and transmitted to external creditors. This allows policy makers to gain insights into which climate policy scenarios and market conditions systemic losses threaten the stability of the financial system.

Another network analysis finds that direct exposure of the Euro area to fossil-fuel-based, utility and energy-intensive sectors is relatively small in monetary terms across equity holdings, bonds and loans, but financial interconnectedness at the macro level significantly affects climate-change-based gains and losses and defaults especially for insurance companies and pension funds (Stolbova and Battiston, 2020). This follows earlier frameworks for climate stress testing and propagation and network effects (Battiston et al., 2017; Stolbova et al., 2018) and on balance-sheet effects in networks (Campiglio et al., 2017), and much of this literature has recently been surveyed (Monasterolo, 2020). These climate stress tests are now applied at the European Central Banks and various national central banks to curb the risk of a disorderly green transition. They reject perfect foresight and typically use adaptive expectations and make use of multiple economic scenarios with unknown probability.

9.2 Idiosyncratic and systemic financial risks from global warming

Financial risks stem from physical risks such as climate and weather-related events, but also from transition risks towards a low-carbon economy (see section 6). The climate-related risk factors show up as credit risks if the physical risks are not insured, market risks if there are abrupt changes in asset prices and market valuation as portfolios are not aligned with expected climate pathways, and operational and reputational risks if severe weather events affects businesses. Jun et al. (2020) report various case studies and methodologies to assess the environmental risks affecting the economies. Volz et al. (2020) highlight seven transmission channels of climate risk for sovereign states: the loss in fossil fuel revenue as a result of stepping up climate action; fiscal impacts of climate-related disasters; fiscal consequences of adaptation and mitigation policies; macroeconomic impacts of climate change on demand and supply; climate-related risks on the financial sector (including the negative feedback loop between financial sector instability and sovereign risk); impacts of global warming on international trade and capital flows; and impacts of climate change on political stability. It is thus clear that not only are investors and industries affected by climate change, but climate change affects sovereign states via each of these channels.

The financial risks propagate and thus affect via networks many sectors of the economy. They can last for long and uncertain periods of time but can be mitigated by actions today. The OECD has also assessed the risks of the low-carbon transition for the financial sector (Boissinot et al., 2016; Jachnik et al., 2019) and so has the European Central Bank with the aid of granular data (Giuzo et al., 2019). The latter study warns for the danger that climate-change-related risks may become systemic for the Euro area, especially if markets are not pricing risks correctly, and argues for the need for a forward-looking framework for risk assessments.[10] Finally, the European Systemic Risk Board has also warned of the systemic risk in transitioning to a low-carbon economy if climate policy occurs too late and too sudden (Gros et al., 2016).

Central banks therefore rightly worry about global warming adversely affecting the stability of the financial system (e.g. Bank of England, 2018; De Nederlandsche Bank, 2018; Battiston et al., 2017; Campiglio et al., 2018; Stolbova et al., 2018). Most of the debate about climate policy has been about carbon pricing, markets for emission permits, green subsidies, and environmental regulation, but only recently the potential role and fiduciary responsibilities of central banks and financial regulators in stemming financial risks from global warming have been highlighted. Financial authorities should not only be concerned with their classical tasks of price stability and macroeconomic stability but also with the goal of climate change (e.g. Campiglio et al., 2018). They should thus guide and stimulate the transition to a green or low-carbon economy and make sure that financial stability is maintained.

Stranded carbon assets are only one small asset class. Fossil fuel companies represent only a fraction of world stock market capitalisation (about 5-7%) and an even smaller fraction of total financial assets (roughly 1-2%). So why should anyone with a well-diversified financial portfolio worry about stranded carbon assets? Wouldn’t fossil fuel companies hedge the risks of a carbon-free world by investing and diversifying into renewable energy sectors? But the top 100 coal and top 100 oil and gas companies keep expanding their exploration and exploitation infrastructure while investing only a tiny fraction of their capital expenditure on low-carbon

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[10] Chenet (2019) also discusses the relationship between planetary health and the global financial system.

technologies. They are therefore prone to sharp selloffs if investors decide to go clean. Counting in reserves held by sovereign states, up to 80% of declared reserves owned by the world's largest fossil fuel companies and their investors may get stranded. About one third of the total value of the FTSE was accounted for by mining and resource companies. The worry is that financial market participants do not share the risks of carbon exposure equally as some pension funds and investment funds have nearly half of their equity portfolios exposed to carbon risk (Battiston et al., 2017).[11]

The mortgage sector was at the root of the global financial crisis of 2007-2008. In a similar way the fossil fuel industry may ignite a financial crisis if the green transition is disorderly and a market panic ensues. Insights about the global financial crisis suggest that high leverage and borrowers' balance sheets expose favouring fire sales to deleverage, lending channels might dry up, thereby causing a general credit crunch and money hoarding, there may be runs on financial institutions – not only on banks, and that there are a strong network effects and a large shadow banking sector (Brunnermeier, 2009). Riding a carbon bubble is rational for all provided these self-reinforcing linkages push prices up and liquidity is forthcoming (cf. the musical chairs analogy of J.M. Keynes). Financial regulators are aware of these risks and there is therefore a strong case for climate stress testing the financial system (e.g. Battiston et al. 2017; ESRB, 2016; Stolbova et al., 2018; Delis et al., 2019).

However, financial systems interlinkages can be very complex multi-layer networks with institutions holding exposures to common assets, hence, the default probability of any institution depends on the default probability of other institutions. This and the fact that small errors on the knowledge of network contracts can induce large errors in the probability of systemic default limits the ability of financial regulators to address systemic risk (e.g. Battiston et al., 2016ab; Campiglio et al., 2018). This might warrant a precautionary approach for central banks and supervisors when dealing with climate-related risks (e.g. Kedward et al., 2020).

9.3 Greening prudential financial policy

The strategies for hedging climate risk that have been suggested by Andersson et al. (2016) and Engle et al. (2009) allow long-term investors to hedge long-term climate risk without sacrificing financial returns (see section 7.3). Since the markets are not pricing in the risk of a policy shift, these trackers have been relatively under-valued. Fear of catastrophic outcomes may lead to rational global pricing of emissions much sooner than the market has built into current prices of stranded assets. The market does not realise that the lacklustre climate policy is irrational as it typically under-estimates catastrophic or fat-tailed risk. A correction is therefore likely to come and

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[11] Semieniuk et al. (2020) review the low-carbon transition risks on the stability of financial systems, paying attention to abrupt asset revaluations, debt default, and bubbles in rapidly rising and declining “sunset” industries and point out that it is essential to examine structural change in the real economy and risks to financial stability together. This review highlights the Schumpeterian view that the crisis stems from the sunrise industries and the importance of innovation for financial distress.

probably sooner than markets expect. Hence, financial markets, and regulators too, should be worried about stranded assets.

Climate policies such as carbon pricing and subsidies for green R&D incentivise the economy to become carbon free. Central banks and financial supervisors realise it is their responsibility to ensure financial stability, improve resilience, and minimise systemic financial impacts of the green transition. They will try to curb the risk of sudden changes in asset valuations and the risk of stranded assets, and the potential sovereign risks that are associated with the green transition. They also increasingly insist on mandatory disclosure of risks following the Task Force on Climate-related Financial Disclosures (TCFD) which can be uses to price in those risks. They also wish to conduct climate stress tests at both the micro and macro-prudential level.

Central banks might also play a role in stimulating green investments, purchasing green assets and developing green corporate quantitative easing programmes that are directed at low-carbon or carbon-free sectors of the economy (e.g. Dafermos et al., 2020) as the health. Biases towards over-representation of carbon-intensive sectors should be avoided in quantitative easing programmes since this amounts to implicit subsidies for those sectors. Financial supervisors might green their prudential policies such as the Basel criteria to reflect the higher risks of carbon-intensive industries relative to green industries, although some central bankers disagree and prefer to take a market-neutral approach by not favouring green policies and thereby carbon-extensive sectors of the economy and avoiding green quantitative easing programmes. Still, a rapidly rising number of central banks and financial supervisors seem to be willing to pursue prudential policies and other policies to help the green transition and avoid the systemic risks associated with carbon bubbles.[12]

Indeed, many of these ideas have been taken up by the Network for Greening the Financial System (NGFS), a growing network of central banks and supervisors established in 2017, which recommends that climate issues are integrated into prudential supervision (NFGS, 2020abcd).[13] This can be done by raising awareness and building capacity for analysing climate-related risks, by using climate stress tests to asses climate risks at the level of individual financial institutions and the financial system, by giving guidance on how to mitigate climate risks, by insisting on disclosures in line with the TCFD recommendations into Pillar 3 of the Basel III banking regulations, and by introducing for example climate-related capital surcharges for the minimum capital requirements under Pillar 1 or special capital requirements for firms exposed to carbon risk under Pillar 2 of the Basel III banking

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[12] D'Orazio and Popoyan (2019) discuss the role of macroprudential policies in fostering green investments and dealing with climate-related risks. See also Schoenmaker and van Tilburg (2016).

[13] The NGFS is backed up by a research network focused on greening the financial system (INSPIRE). The Coalition for Ministers for Climate Action (CAPE) has also more than doubled since its establishment in April 2019, thus committing finance minister to national climate actions and incorporating climate change in their fiscal policies including possibly recycling carbon tax or permit revenues to get broad political support. Fiscal policies be used to curb the risk of stranded assets and set up public investment funds to finance the green transition as government can offer lower interest rates than commercial lenders.

regulations.[14] Disclosure on its own is thus deemed to be insufficient by the NGFS to get rid of climate-related systemic risks and ensure financial stability and resilience for markets may not be very good in pricing in all the climate risks.

10 Concluding remarks

To ensure that global mean temperature stays below 2 or 1.5 degrees Celsius, it is clear what needs to be done: a moratorium on all fossil fuel subsidies and coal production, quick phasing out of diesel- and petrol-based transport, credible commitment to a high and rising path of carbon prices (if necessary on top of the ETS price), and subsidies for green R&D. To convince the general public and get broad support for an ambitious climate policy, it is necessary to recycle part of the carbon tax revenue to make sure that lower incomes are not worse off and to levy border carbon adjustments or give production-based subsidies to those industries that are most threatened by competition from foreign carbon-intensive producers. Each year delay makes realising the Paris agreement climate targets more costly and there is very little time left to act. Businesses, banks, and insurers should realise that the fossil-fuel-based model is of the past and should direct attention at the carbon-free economy of the future. Macro-financial policies should support the green transition. Financial supervisors and banks should support the process by regularly conducting climate stress tests so that transition risks become clear. Of course, financial institutions and industry should be mobilised for the green transition too.[15]

With respect to Covid-19, Churchill rightly said “never waste a good crisis”. Hence, it is important to make sure that new jobs and economic sectors are whenever Covid-19-proof and resilient. By retraining workers from the fossil-fuel-based industries, they can be redeployed into the new green industries. It is crucial not to bailout carbon-intensive firms (steel, airlines, etc.) in the pandemic unless they reform and are viable in the new green economy. Unfortunately, we see too often that governments bail out the “living zombies” of the fossil-fuel era. A survey of 231 central bank and financial ministry officials and other economic experts identified five fiscal recovery packages with high potential on both economic multiplier and climate impact metrics. They are clean physical infrastructure, building efficiency retrofits, investment in education and training, natural capital investment, clean R&D, and for lower- and middle-income countries rural support spending (Hepburn et al., 2020).

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[14] Banks with limited liability and average risk pricing of deposits have excessive leverage, which calls for capital requirements as these make banks safer and are beneficial in the long run albeit that there is a short-run versus long-run trade-off with strength of monetary policy accommodation (e.g. Mendecino et al., 2020). It would be interesting to see how this argument can be extended to allow for *differential* capital requirements. Delis et al. (2020) show that after the Paris Agreement, firms that have been affected by transition risks have been charged higher interest rates from 2015 onwards especially for firms holding more fossil fuel reserves. They also offer evidence that green banks charge marginally higher loan rates to fossil fuel firms. This suggests that differential capital requirements may be called for.

[15] Schoenmaker and Schramade (2019) give an excellent overview and textbook of the principles of sustainable finance and the corresponding challenges for corporate investment to transition to a low-carbon economy without sacrificing returns if possible. This book also analyses the Sustainable Development Goals as a strategy for a greener world and discusses how these can be incorporated by corporate and financial sectors.

Given the large space needed for wind farms and solar panels to make the green transition possible, governments must make spatial planning their top priority and thus ensure that the transition is pandemic- and climate-proof. If climate policy is too easily frustrated by lobbies, one should think of setting up an independent carbon central bank whose prime mandate is to make sure that temperature and cumulative emissions stay below their ceilings.

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