Despite these limitations, the study pushes the envelope to show that intermittent renewables plus transmission can eliminate most fossil fuel electricity while matching power demand at lower cost than a fossil-fuel-based grid, even before storage is considered. This finding — alongside previous modelling that suggests the electrification of all sectors combined with the use of low-cost electricity and heat/cold storage, hydrogen and demand response can result in 100% decarbonization of all US energy sectors — provides confidence that the goals of the Paris Agreement are within reach if high percentages of clean, renewable energy can be integrated worldwide. ❐

Mark Z. Jacobson is in the Department of Civil and Environmental Engineering, Stanford University, Stanford, California 94305-4020, USA.
e-mail: jacobson@stanford.edu

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Published online: 25 January 2016

CLIMATE CHANGE ECONOMICS

Reacting to multiple tipping points

When setting carbon prices in a warming world, policymakers must be cognizant of the potential economic and environmental consequences of the risk of multiple, interrelated catastrophes.

Frederick van der Ploeg

The optimal carbon price, whether it is a tax or the price of a permit, must be set to the social cost of carbon[1,2]. This corresponds to the current discounted value of marginal damages to aggregate production, resulting from higher temperatures in the future that are caused by emitting one additional ton of carbon today. This price is higher if society places a higher value on future generations, if current generations are more willing to cut fossil fuel use and sacrifice consumption to limit future warming, and if future generations are richer and society is more risk adverse. This approach to climate policy is concerned with damages around 2–3 °C, but ignores tail risks of catastrophes that rapidly arise at higher temperatures. The optimal carbon price then must be marked up[3], which can double the carbon price[4]. Society also must accumulate precautionary capital to cope when calamity strikes[5]. But what happens when there is more than one tipping point and society has to anticipate the potential damage caused by multiple catastrophes? This issue is addressed by two studies now published in *Nature Climate Change*[6,7].

IAN JOUGHIN, UNIVERSITY OF WASHINGTON

In the first study, Derek Lemoine and Christian Traeger[6] consider three tipping points in a simplified version of the integrated assessment model DICE-2007 (discussed in ref. 1): (i) a sudden increase in the climate sensitivity from 3 °C to 5 °C due to melting of the permafrost or retreating land ice sheets (implying that a doubling of carbon stock would lead to a rise in temperature of 5 °C instead of 3 °C); (ii) sudden halving of the rate of atmospheric CO_2 removal; and (iii) sudden increase in severity of production damages, say, due to weakening of the Atlantic conveyor belt. Policymakers use Bayesian learning of the unknown thresholds for each of these irreversible tips. Ignoring catastrophes requires a carbon price of US$6 per ton of CO_2 (tCO_2), whereas allowing for all three catastrophes pushes up the price to US$11 per tCO_2, with the biggest contribution coming from the third tipping point leading to a sudden increase in production damages. As a result of the extra mitigation efforts, peak temperature would be brought down from 4 °C to 3 °C. The optimal carbon price adjustment is 50% higher than simply adding the effects of the individual tipping points, but this adjustment by more than three quarters in 2050. This effect is especially strong for the temperature and damage tipping points. The domino effect arises because crossing the threshold for the temperature tip or the carbon sink threshold boosts the risk of crossing the threshold for the damage tip, but not vice versa. Delaying carbon pricing is 60% more costly than in the scenario without tipping points.

In the second study, Yongyang Cai, Timothy Lenton and Thomas Lontzek[7] analyse a 16- instead of 4-dimensional version of DICE-2007. This study separates the coefficient of relative risk aversion from the coefficient of relative intergenerational inequality aversion (that is, 3.07 and 0.67, whereas the values for DICE-2007 are both 1.45), and uses experts to calibrate the likelihood of each of five tipping points (reorganization of the Atlantic conveyor belt, disintegration of the Greenland Ice Sheet, collapse of the West Antarctic Ice Sheet, dieback of the Amazon rainforest and a more persistent El Niño regime) and how it depends on the state of the others[7]. It adds realism by allowing for slow and differential impacts of each catastrophe. Nevertheless, much bigger effects of tipping points are found: the optimal carbon price increases from US$15 to $116 per tCO_2. It is optimal to shut down carbon emissions by mid-century and cap temperature rise at 1.4 °C instead of 3 °C by 2100 in the baseline. In that case, there is only an 11% chance of crossing one or more tipping points by 2100 compared with a 46% chance in the baseline. A big part of the reason for the eightfold — rather than double — increase of the carbon price is due to using high relative risk aversion and low intergenerational inequality aversion coefficients. There are both positive and negative effects on the risk of crossing other tipping points after a tip, which is why the net effect is a modest increase in the expected optimal price of carbon from US$109 to $116 per tCO_2. However, some interactions in specific sample paths can have big effects on the expected price. The collapse of ice sheets might have already been crossed, increasing the risk of reorganization of the Atlantic conveyor belts, but this should nevertheless lead to intensified efforts to curb carbon emissions to cut the risk of other tipping points.

The more imminent risk of catastrophes at higher temperatures offers a better narrative than the usual approach that only considers costs at moderate degrees of temperature rise. It might encourage policymakers to finally take significant action to curb global warming. Such a change of discourse should also stimulate institutional investors to decarbonize their portfolios and avoid tail risks of climate catastrophes. Hedging strategies generate low-carbon portfolios that achieve the same return as the benchmark if there is no stepping up of climate policy but outperform the benchmark as soon as CO_2 is properly priced[8].

Future research is important. First, we need to know what can and should be done in terms of adaptation to prepare for potential calamities. This will probably involve precautionary saving, but also large-scale investment in water defences and other projects that weaken the impact of catastrophes. Second, research is needed to estimate the insurance society is willing to pay to limit the impact of catastrophes. One study finds that society is willing to pay a permanent tax of 7% if revenues are used to limit catastrophic losses to less than 15%[9]. Third, one needs to allow for substitution between renewable energy and fossil fuel and for green technical progress on optimal climate policy. Fourth, one must allow for anticipation effects resulting from future scarcity of fossil fuel on climate policy. Delayed policies lead to faster extraction of oil and gas before it becomes more expensive, thus increasing global warming and the risk of tipping (the so-called green paradox). Finally, climate catastrophes interact with non-climate catastrophes such as mega-virus pandemics, nuclear terrorists, bioterrorists, earthquakes or an asteroid hitting Earth. Cost–benefit analysis yields strange results as it is no longer necessarily optimal to prioritize averting the catastrophe with the largest benefit-cost ratio[10]. Policies associated with different catastrophes are therefore inextricably intertwined. ❐

Frederick van der Ploeg is at the Oxford Centre for the Analysis of Resource Rich Economies, Department of Economics, Manor Road Building, Manor Road, Oxford OX1 3UQ, UK.
e-mail: rick.vanderploeg@economics.ox.ac.uk

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Published online: 21 March 2016

EXTREME PRECIPITATION

Increases all round

Globally, extreme rainfall is expected to increase with warming, but regional changes over land have been less certain. Now research shows that this intense precipitation has increased across both the wetter and the drier parts of the continents, and will continue to do so as global warming continues.

William Ingram

People, crops and cities cannot survive long without fresh water, which almost entirely originates from rain. But one can have too much of a good thing — our habit of living by sources of fresh water may be convenient, but it also increases the risk of flooding. Global average precipitation is expected to increase moderately with global warming[1,2], but nobody lives in the global average. It is extreme rain in a particular catchment that can have devastating consequences, so changes on smaller space- and timescales are important for planning and adaptation. Over the ocean, we expect the overall geographical pattern to follow a 'wet gets wetter, dry gets dryer' trend[2]. This means that net evaporation will increase where it already exceeds precipitation, whereas net precipitation will increase where it dominates at present. But over the continents, where most of the world's population lives, it has been less clear to what extent this trend applies[2]. Writing in *Nature Climate Change*, Markus Donat and colleagues[3] show that observations and models agree in showing that extreme rain