The case for mandatory sequestration

Myles R. Allen, David J. Frame and Charles F. Mason

The fact that cumulative carbon dioxide emissions are more important than annual emission rates calls for a fresh approach to climate change mitigation. One option would be a mandatory link between carbon sequestration and fossil fuel extraction.

The risk of dangerous long-term consequences of anthropogenic interference in the climate system is principally determined by the total cumulative emissions of CO_2 into the atmosphere[1–6], and not by the rate of emissions in any given year or political commitment period. Cumulative emissions are particularly important for CO_2. The main other very-long-lived greenhouse gas, nitrous oxide, is projected to have a smaller effect overall, and the impact of shorter-lived gases such as methane depends more on emission rates than cumulative totals. Current estimates suggest we will probably have to limit the total carbon released into the atmosphere as CO_2 to an amount much smaller than remaining fossil carbon reserves. Once this limit is reached, emissions must fall, in effect, to zero: the CO_2 generated by any further use of fossil carbon will need to be sequestered, and any residual emissions balanced by active air capture.

Framing the mitigation challenge in terms of cumulative emissions, or 'stocks', rather than emission rates, or 'flows', may provide a way round one of the fundamental dilemmas of climate policy[7]. Despite assurances to the contrary[8], many protagonists in the climate change mitigation debate fear that the only way to reduce the flow of carbon emissions will be through restrictions on consumption that impede economic development. This is understandable, given historical evidence that emissions have generally only fallen in times of recession[9] and suggestions that climate change provides an opportunity to shift priorities away from 'conventional' growth[10]. Policies focused on emission rates make tension between growth and climate protection seem inevitable, and are difficult to justify scientifically because the physical climate system responds to cumulative emissions, not emission rates.

A more effective framework could focus explicitly on limiting total cumulative emissions: for example, to one trillion tonnes of carbon. This amount has been estimated[3] to give a most likely peak global mean warming of 2 °C above pre-industrial temperatures, with a one-standard-error uncertainty range of 1.6 to 2.6 °C. Other limits have been proposed[4–7], depending on the risk of temperatures exceeding 2 °C. But the need in principle for a cumulative limit near or below one trillion tonnes is generally accepted, over half of which has already been emitted. With current emissions around 10 billion tonnes of carbon per year, and over three trillon tonnes still available in fossil fuel reserves[4,11], emissions need to fall, on average, by over 2% per year from now on to avoid releasing the trillionth tonne. The longer emissions are allowed to rise, the faster they will have to fall thereafter to stay within the same cumulative total.

Conventional approaches to limiting cumulative CO_2 emissions would be either a system of cumulative emission permits[7,12] or a carbon tax designed to discourage further emissions once the cumulative limit is reached. Both approaches face a credibility gap[13]: it is hard to be confident that the pressure to print more emission permits will be resisted when they start to run out in a few decades time. And without concrete data on the costs of very large-scale carbon capture and sequestration[14], it is impossible to be sure that any carbon tax that rises to a high but predetermined level as the

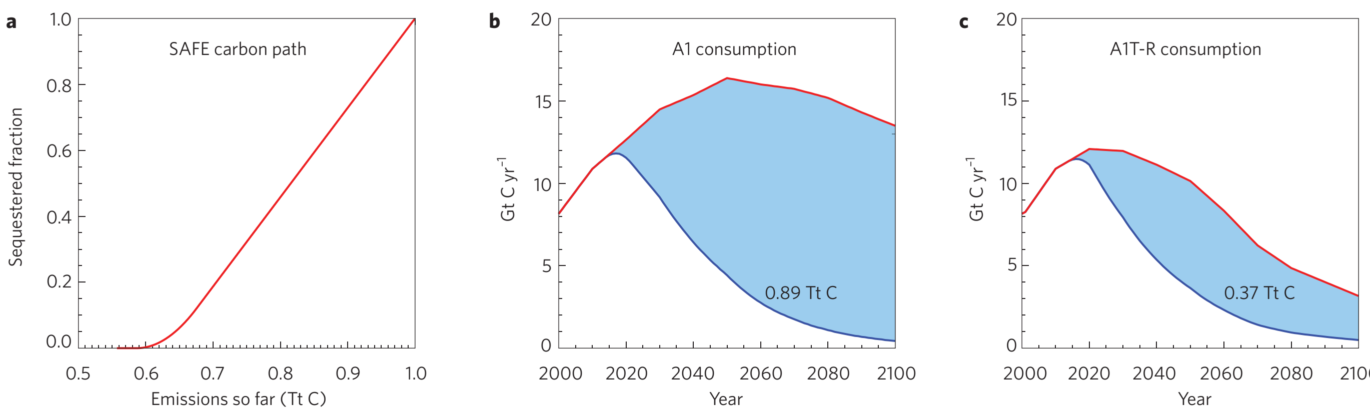

Figure 1 | SAFE carbon futures. **a**, Under a policy that avoids releasing, for example, more than one trillion tonnes of carbon in total, the sequestered adequate fraction of extracted (SAFE) carbon needs to approach 100% as the cumulative carbon emissions approach this total. **b**,**c**, This gives similar atmospheric emissions (blue lines) under very different scenarios for future fossil fuel consumption (red lines), at the price of very different levels of sequestration (blue regions). IPCC scenario A1 (**b**) assumes continued dominance of fossil fuels[15], whereas IPCC scenario A1T-R (**c**) assumes even higher rates of growth in renewable and nuclear energy than IPCC scenario A1T.

cumulative limit is reached will rise fast enough to achieve its goal.

We propose a more direct approach: a mandatory link between carbon sequestration and fossil fuel extraction. Although the costs would be passed on to fossil fuel consumers, just like a carbon tax, such a policy decouples the explicit link between consumption and climate policy, and hence could be more effective, scientifically justifiable and less economically intrusive[7] than short-term targets for emission rates.

The simplest implementation would be to allow the sale and use of fossil carbon only if certified that an adequate fraction of its carbon content has been permanently sequestered. This would bring about a carbon sequestration industry, which would also need to be responsible for (and pass on the cost of) compensating for any leakage from existing reservoirs. Extending the concept of sequestered adequate fraction to non-fossil sources would be more difficult to implement, so we assume here these are controlled with separate measures.

The simplest definition of 'adequate fraction' would be the ratio between cumulative emissions from the time the policy is fully adopted to total outstanding allowable emissions at that time (currently just under half a trillion tonnes of carbon in the above example). As cumulative emissions approach the allowable total, the sequestered adequate fraction of extracted (or SAFE) carbon approaches 100% (Fig. 1a), ensuring that the target total atmospheric carbon budget is not exceeded. Crucially, the sequestration/emissions pathway does not depend on time: if fossil fuel demand increases as the world economy recovers from recession, the fossil fuel supply industry simply needs to raise the fraction of sequestered carbon in line with rising cumulative emissions. Having decided to use SAFE carbon, we would no longer face annual trade-offs between present-day prosperity and long-term planetary well-being.

Fossil fuels will clearly be more expensive under a SAFE carbon regime. How much more expensive cannot be predicted at present, as no large-scale carbon sequestration industry exists. But if the fossil fuel industry decides to defend its share of primary energy supplies (as in the Intergovernmental Panel on Climate Change (IPCC) scenario A1)[15], a formidable 0.89 trillion tonnes of carbon would need to be sequestered by 2100 (Fig. 1b). This amount significantly exceeds current estimates of geological sequestration capacity[11], requiring environmentally acceptable ocean disposal (see Commentary on page 820 of this issue), a cost-effective method of remineralization (see Progress Article on page 837 of this issue), or something entirely new.

These options may sound implausible at present, but if these methods of disposal turn out to be affordable, and socially and environmentally acceptable, then there is no obvious reason why present-day scenario-builders should rule them out. Of course, it is likely that the increased cost of SAFE carbon would reduce fossil fuel consumption (Fig. 1c), but under a SAFE carbon policy, there would be no need to target any particular consumption level. Investors who commit to future use of fossil fuels would bear the risk of not knowing what it will cost to comply with a SAFE carbon regime and hence what future demand for fossil energy will be. But net CO_2 emissions to the atmosphere are almost indistinguishable under two scenarios with very different projections for use of fossil fuels.

The attraction of a SAFE carbon policy is simplicity: it is a single policy, affecting a single industry, delivering a single objective. In contrast to a system of regularly renegotiated emission quotas, this minimizes the need for intervention. Governments would still have a significant role, defining the adequate fraction that needs to be sequestered, certifying reservoirs, monitoring leakage and so forth. Having specified the total target of allowable emissions, they would also have to underwrite the consequences: one trillion tonnes might be deemed tolerable today, but still turn out to be too much. In this case, future taxpayers would have no option but to pump carbon out of the atmosphere again, driving the sequestered fraction over 100% for a time. Uncertainty in the absolute amount of tolerable total emissions means that developing the technical capacity for net negative emissions is a necessary precaution.

A SAFE carbon policy could be introduced with far less market disruption than a comprehensive emission control regime. Initially, a small group of nations or even companies could request its fossil fuel suppliers to supply it with SAFE carbon to establish a market and a price. It would not be necessary for everyone to agree to use SAFE carbon initially for the policy to be effective: the only requirement is that everyone should be using it by the time cumulative emissions reach the acceptable limit. A global certification system would be needed to allow sequestration of CO_2 from power stations in newly industrialized countries to be used in the certification of SAFE carbon elsewhere. This would foster the development of a global sequestration industry and provide a potential incentive for non-participants to start using SAFE carbon if, in the future, this were made a condition of participation in global CO_2 markets.

Demand for SAFE carbon is likely to decline as the sequestered fraction (and hence the price) escalates, but there would be no need to legislate specifically to modify behaviour at either the individual consumer or corporate level. This is a crucial advantage since we are already seeing a significant backlash against the intrusiveness of climate change mitigation measures[16]. Concerns have been raised at the potential level of collectivization of the world economy that might be implied by any effective carbon tax or emissions permit regime[17].

Some might see SAFE carbon as a lost opportunity to use climate mitigation policy to modify consumer behaviour[10] or to reduce global inequalities of wealth[7]. But worthwhile policies should be pursued in their own right. Solving climate change is too important to be held hostage to any other issue. ❐

Myles R. Allen[1], David J. Frame[1,2] and Charles F. Mason[2,3] are in the [1]Department of Physics, University of Oxford, Oxford OX1 3PU, UK, [2]Smith School of Enterprise and the Environment, University of Oxford, Oxford OX1 2BQ, UK, [3]Department of Economics and Finance, University of Wyoming, Laramie, Wyoming 82071, USA.*
**e-mail: myles.allen@physics.ox.ac.uk*

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