Geoengineering: The good, the MAD, and the sensible

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After the collapse of international climate policy in Copenhagen in December 2009, the tale of geoengineering, promising end-of-the-chimney fixes for anthropogenic global warming, has become increasingly popular (1). This is essentially a tale of two fairies (2): the rather wicked one conjures up solar radiation management (SRM), and the tolerably good one delivers CO_2 removal through schemes like industrial “air capture” (IAC). Unfortunately, a study by House et al. (3) pours lots of cold water on the hot IAC stuff. Most notably, the authors maintain that the total systems costs of IAC (factoring in all pertinent processes, materials, and structures) might well be on the order of $1,000 (US$) per ton CO_2 extracted from the atmosphere. This is tantamount to forecasting a financial tsunami: for making a tangible contribution to global warming [and ocean acidification (4)] reduction, several Gt CO_2 should be “scrubbed” every year in the last third of the 21st century (see below), thus generating a multitrillion-dollar IAC bill.

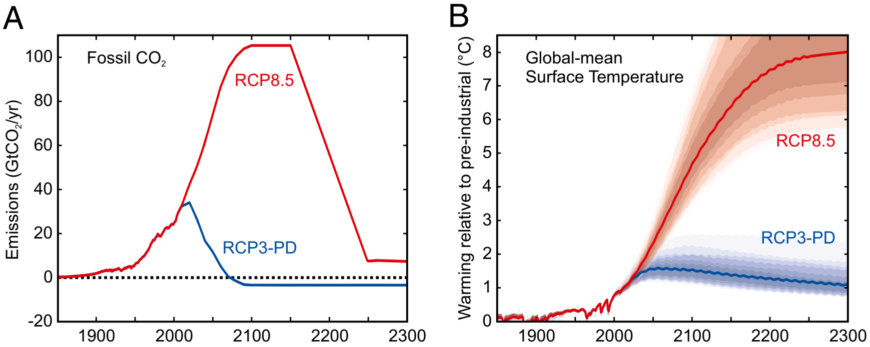

Fig. 1. Thrust Reversal or Reacceleration? Comparison of an emissions scenario compatible with the 2 °C objective (RCP3-PD, blue) and a more-business-than-usual scenario (RCP8.5, red). (*A*) Respective fossil CO_2 release. Note that the annual CO_2 emissions drop to −3.4 Gt by 2100 in the strong mitigation case. (*B*) Resulting likelihood fans for global mean temperature rise. With kind permission from Springer Science + Business Media: Climate Change, The RCP greenhouse gas concentrations and their extensions from 1765 to 2300, 109 (2011) 233, Malte Meinshausen, Figure 6.

House et al. arrive at their important cost estimate by blending existing bits of scientific and technical information into a convincing common-sense analysis. The take-home message is that the energetic and economic challenges of IAC systems design and implementation have probably been underestimated by previous studies promoting that climate-fix option (5–7). The House et al. argument rests on five cognitive pillars, namely (*i*) an evaluation of the pertinent Sherwood-plot approach to dilute streams (8); (*ii*) a realistic thermodynamic efficiency assessment of the processes involved in IAC; (*iii*) a rough quantification of the power costs for IAC, which can achieve significant carbon negativity only by tapping nonfossil energy sources; (*iv*) an analogy assessment of the work required for chemical removal of trace gases from mixed streams, exploiting rich empirical data available for SO_2 and NO_x handling; and (*v*) a careful discussion of the design options for large-scale IAC installations, reconciling competing physical and chemical constraints.

The last aspect is related to the gigantic volumes of air that need to be processed swiftly through the scrubber plants, where the ambient CO_2 contacts appropriate solvents or sorbents. This, in turn, confirms an intuitive skepticism about IAC schemes prevalent among experts with formal training in statistical physics: you need to work hard to beat entropy growth within a given subspace of the universe. So it seems rather odd to first burn fossil fuels (where the ambient carbon was captured, reduced, and concentrated by biogeochemical processes over hundred millions of years), then let the oxidized carbon mix and migrate across the entire atmosphere, and finally distill the CO_2 again molecule by molecule using sophisticated technology. There is no free energy lunch…

This is a most inconvenient truth for climate protection. Fig. 1 highlights the crucial choice that humankind has to make about its collective radiative forcing (9): if CO_2 emissions shrink according to an aggressive worldwide mitigation strategy (“Thrust Reversal”), then there is a good chance of keeping planetary mean surface temperature increase below the 2 °C guardrail (10, 11) as adopted by more than 190 nations in 2010 (12). Note, however, that this strategy not only foresees a complete phase-out of CO_2 emissions by 2070, but also the establishment of *negative* fluxes of CO_2 afterward.

The extreme alternative (“Reacceleration”) is the total shirking of climate responsibility by a world economy fixated on material growth: the plentiful fossil energy resources still in the ground (such as tar sands, shale oil and gas, and—most importantly—coal) are tapped despite the inexorably soaring production costs (13), atmospheric CO_2 concentration approaches the 2,000-ppm level, and global mean temperature rises by up to 8 °C by 2300. Never mind where the civilization jet will eventually crash.

Very few people who accept the insights of state-of-the-art climate science find the Reacceleration scenario and its dire consequences acceptable. However, it is not unlikely that the myopic market forces will drive the extraction process further and further. Therefore, the last best hope may reside in an environmental fix engineered independently of energy systems transformations, namely radiation management that cools down the planet (or, at least, large parts of it). An ample literature on SRM is already available (see especially refs. 14 and 15), in which numerous schemes of varying sophistication (such as placing mirrors in outer space, deploying reflecting aerosols or metal flakes in the atmosphere, manipulating cloud cover, enhancing land albedo, or simply painting roofs white) are explored.

Some of those ideas actually originated in the scientific circles surrounding John von Neumann and Edward Teller in the 1950s (16). These two masterminds openly advocated weather-manipulation ways of winning the Cold War against the Soviet Union. A contemporary giant of science, the Nobel laureate Paul Crutzen, has rekindled the SRM debate in 2006 through an essay on stratospheric sulfur injection (17). However, he has consistently argued then and ever since that such a climate-engineering scheme would be implemented out of despair only, that is, if the

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establishment of any "conventional" climate-protection measure (like a worldwide cap-and-trade system for greenhouse gas emissions) failed. Crutzen, Carlo Rubbia (a Nobel laureate in physics and an eminent energy expert), the climate scientist Alan Robock, and I were members of a recent Pontifical Academy of Sciences panel (18) that also discussed the portfolio of potential SRM schemes. Convincing arguments were raised that radiation manipulation may be a rather bad political idea (see, e.g., ref. 19), whereas research in this field might generate important scientific insights transcending the elusive climate-fix realm (see, e.g., refs. 20 and 21).

On closer inspection, SRM exhibits MAD traits. The latter acronym stands for "mutual assured destruction," that is, the ominous doctrine of the arms race frenzy. If the climate can be influenced rather inexpensively by sending aerosol rockets to the stratosphere, then who decides when and where the buttons are pushed? Certain countries like Russia might actually welcome some warming of their territories. So would they shoot down, say, Indian or Chinese geoengineering missiles launched for stabilizing the Asian monsoon pattern or other tipping elements in the Earth system (22)? One step further up the escalation ladder, the supposed beneficiaries of climate change might deliberately increase their greenhouse gas emissions for overcompensating SRM, and so on. Additionally, the crucial point that temporal failure of artificial insolation reduction would most probably wreak havoc has been made repeatedly (23).

Although a committee recently convened by the Bipartisan Policy Center Panel in Washington, DC seems prepared to relativize some negative aspects of SRM and to call for a substantial research and development program (24), the dilemma of geoengineering does not evaporate: the (moderately) good schemes involving ambient CO_2 capture are not affordable (according to the House et al. assessment summarized above), and the (moderately) affordable schemes involving radiation manipulation are no good, so what are we going to do? The answer seems obvious and utterly sensible, namely intentionally aborting *unintended* geoengineering as resulting from careless fossil fuel use. Following are five arguments in favor of climate mitigation by industrial transformation (25).

First, you need to approach zero before you can go negative. So the decisive phase of the Thrust Reversal scenario of Fig. 1 consists of a resolute phasing-out of CO_2 in the next 5 or so decades. In a consecutive phase, net carbon extraction from the atmosphere should happen. Fortunately, CO_2 capture from concentrated biomass flue gas (26) may do this job more cost-efficiently ($150–400 per ton) than the IAC schemes proposed so far. A precondition for this, however, is the development of appropriate carbon capture and storage (CCS) schemes, which may be needed anyway as a climate-protection bridge between fossil and sustainable energy.

Second, we do know a lot already about energy-efficiency measures (27) and renewable energy systems and infrastructures (13). Technological breakthroughs that are bound to happen with enhanced research and development for IAC will equally likely become available in the former realms through a process of induced innovation (28).

Third, emission reductions will not cost the Earth. According to recent multimodel assessments, mitigation in line with the 2 °C objective would be accompanied by 1–3% aggregated losses of world gross domestic product until the end of the century (13).

Fourth, there are multiple cobenefits of climate protection by systemic decarbonization. Outdoor pollution (such as acid rain) originating from fossil fuel use keeps on destroying invaluable ecosystem services all over the world; indoor air pollution from primitive household fires fed by biomass or coal has just been linked to nearly 2 million deaths per annum (29).

Last, efficiency and renewables will achieve something that geoengineering approaches do not even care to consider: laying the foundations for a sustainable global energy supply system that (*i*) can virtually exist forever, and (*ii*) offers more equitable opportunities for the developing world than the fossil–nuclear complex.

In essence, humankind should avoid betting on the fabrication of a silver bullet for shooting climate change. Our world does not need SRM or IAC in the first place, but rather a novel way of going MAD: "mutual assured decarbonization."

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