Bulletin of the Atomic Scientists

IT IS 5 MINUTES TO MIDNIGHT

Feature

Bulletin of the Atomic Scientists
68(6) 67–78

DOI: 10.1177/0096340212464362
http://thebulletin.sagepub.com

Weighing the risks of climate change mitigation strategies

Evan Mills

Abstract

Most experts agree that the greatest risk associated with climate change is pretending that the problem does not exist, or that it does not require immediate attention and action. That said, the potential pathways for mitigating the effects of greenhouse gas emissions are not created equal in terms of the risks and benefits they entail. Public discourse tends to focus on the most optimistic scenarios for implementing new technologies and to ignore not only the hazards but also the non-climate-related benefits associated with some approaches. Climate mitigation strategies currently undergo economic and engineering analyses, but they are not consistently subjected to rigorous risk assessment and risk management. The author offers the beginnings of a more cohesive decision-support analysis framework. Assessments of various mitigation strategies by the world's largest industry—insurance—are critically important in this process because insurers can provide a dispassionate view and internalize the costs of risk through pricing. Bank financing cannot be mobilized without insurance, and the public sector may be forced to assume many of the risks associated with emerging technologies if insurers opt out. A century of dangerously blending technological enthusiasm with lack of care in assessing the comparative risks of energy and land-use choices ushered in today's climate crisis. Continued inattention threatens to saddle society with new risks from poorly prioritized efforts to solve the climate problem. Procrastination is painting humankind into a corner in which progressively riskier and unproven technologies will be required to mitigate climate change.

Keywords

carbon capture and storage, climate change, climate engineering, energy efficiency, nuclear power, renewable energy, risk management, solar radiation management

Surely no panacea exists for the climate change problem. Many solutions must be deployed in consort—new energy technologies, energy-saving measures, and perhaps even climate engineering schemes—to reduce emissions, remove carbon dioxide from the atmosphere, or to cool the planet by reducing the amount of sunlight that reaches its surface. Developers of such technology and policy solutions traditionally base decisions on engineering and economic models, political considerations, and assumptions about market forces. These are necessary elements of technology

assessment and planning, yet they are not sufficient: Comparative risk must also be part of the calculus.

This is particularly true given the enormous variety of risks presented by climate change response strategies. Many strategies are themselves susceptible to climate impacts, as well as to a host of geopolitical factors. But some climate solutions not only help keep greenhouse gases out of the atmosphere, they also offer positive "co-benefits"—simultaneously mitigating other, unrelated risks or even enhancing a society's capacity to adapt to climate shifts. Ample literature explores the risks of options on a piecemeal basis, but side-by-side comparisons of climate mitigation strategies are rare. The lack of a standardized, integrated framework makes it hard for stakeholders—from policy makers to financiers—to weigh the myriad risks and benefits of climate change mitigation options.

Special interests are usually the loudest advocates for new technologies and are disinclined to explore or reveal downside risks. While specialists are often cognizant of risks, the public discourse is typically uninformed or misinformed about them. In many settings, risks are assumed or implied under "best-case," rather than "likely" or "possible," scenarios. This was the case in Japan, for example, before the Fukushima disaster in 2011: A mythology of "absolute safety" had been promulgated by the nuclear power industry and the government, whose assumptions about the effectiveness of communications during such a catastrophic event proved to be badly flawed (Funabashi and Kitazawa, 2012). The vulnerabilities revealed by the disaster were as much institutional as technical.

Risk perception and assessment

The perception of risk weighs heavily in technology choices. In theory, the risks associated with any climate mitigation strategy can be defined and quantified. But in practice, people generally perceive downside risk as higher than the equivalent upside (for example, people rate the risk of losing money as higher than the prospect of gaining an equivalent sum), and low-probability, high-consequence risks are regarded differently than high-probability, low-consequence ones. Unquantifiable uncertainties (Knight, 1921: 19) can further skew risk perception.

Inadequate risk assessment during technology development, testing, and scale-up can lead to major setbacks. Conversely, some technologies reduce unrelated risks, and yet this point is often lost in the discussion; a classic example of this is the shift from red-hot halogen "torchiere" lights, which were responsible for many fires, to fluorescent replacements that posed no fire hazard (Avery et al., 1998). This shift—championed by insurers—was driven primarily by safety concerns, but it also resulted in lighting energy savings of as much as 75 percent.

The insurance industry—which pays for much of the reconstruction after extreme weather events—is playing an increasingly important role in assessing, pricing, and managing climate risk (Mills, 2005; Vellinga et al., 2001). But beyond this industry, there is a need for more rigorous integration of risk

management in technology assessment, valuation, and public policy.

Examples of macro-level risks that should be considered in climate change technology assessments fall into three broad categories: natural hazards, such as drought, flood, windstorm, wildfire, and earthquake; threats to ecosystems, or human health, including water-quality impairment and ocean acidification; and security concerns, such as terrorism, weapons proliferation, and dependence on foreign energy. Within each of these categories, a particular technology may cause a hazard (such as hydroelectric systems disrupt river ecosystems) or simply increase the vulnerability to a hazard (that is, hydroelectric systems suffer under drought). Conversely, a particular technology may reduce a hazard (for instance, wind energy reduces dependence on foreign fuels) or on vulnerability to a hazard (for example, solar photovoltaic systems are relatively invulnerable to water scarcity).

At the baseline end of the risk spectrum (Mills, 2012) are fossil fuels, which not only contribute to hazards but also are vulnerable to them in almost every category. At the other end of the spectrum is energy efficiency, which neither causes nor is vulnerable to any of the hazards. Energy efficiency, moreover, has the greatest number of co-benefits, such as reducing water demands and energy import dependency. Among the other mitigation options, nuclear power has the greatest vulnerability across the spectrum, followed by climate engineering strategies. Within each broad family of technologies are many variants, each with its own risk factors. For example, space-based solar energy production presents an entirely different risk profile in terms of security than do land-based systems (Wood, 2012).

Climate engineering

The most difficult strategies to assess are climate engineering approaches that are still purely experimental—and, in many cases, nothing more than ideas on paper. Mindlessly engineering the climate by injecting hundreds of gigatons of carbon dioxide into the atmosphere in the last century got us into the greenhouse problem. There is an ongoing spirited debate within the scientific community (*Bulletin*, 2008) about whether climate engineering—this time on purpose—is a necessary element of the solution. Proponents maintain that it is a necessary evil. Opponents, who perceive an element of hubris, argue that climate engineering carries unacceptable risks, treats symptoms and not causes, and could foster a false sense of security among the public (if not policy makers). Moreover, there is no international governance structure for starting or stopping such activities.

Climate engineering includes strategies ranging from removal of carbon dioxide from the atmosphere to solar radiation management. Most of these strategies, if they were to run amok, could amplify rather than lessen climate problems, or create other unforeseen headaches. Some of these proposals can only be fully validated when "tested" at a global scale, and not all of them are readily reversible. Conversely, climate could change abruptly and radically if the interventions were, for whatever reason, halted. Climatologist Alan Robock (2008) has raised concerns

about misuse of weather modification for military and geopolitical purposes.

Climate engineering is positioned as a "last resort insurance policy," although, ironically, private insurers have yet to offer their products to this sector. In the view of the US Government Accountability Office (GAO, 2011): "Climate engineering technologies do not now offer a viable response to global climate change," and significant improvements are decades off. On a Technology Readiness Level scale of 1 to 9, none of the technologies studied by the GAO scored above 3. Far from being a panacea, some of these technologies would in fact offset carbon-dioxide emissions from human activity by only small percentages, while others are potentially 100 percent effective in reducing emissions but estimated to cost billions or even trillions of dollars annually. All of the technologies come with a host of potential and poorly understood risks but very few potential co-benefits (Mills, 2012).

Carbon-dioxide removal

One category of climate engineering focuses on methods for removing carbon dioxide from the atmosphere, which includes industrial carbon capture and storage (CCS), biological methods for sequestering carbon on land, and ocean-based sequestration. Each has its limits.

CCS has the potential to capture and store approximately four-fifths of the emissions associated with fossil-fuel-fired power plants (IPCC, 2005), or to be "carbon-negative" if the feedstock is biofuel. Vulnerabilities occur at various points in the process, from capture to transport to storage. The risks can be immense, particularly if conceptual flaws come to light that simultaneously affect systems deployed around the planet. The strategy is still in testing, and the economics are highly uncertain. Serious concerns have been raised about whether carbon dioxide injected deep underground could leak catastrophically, pollute groundwater, or trigger earthquakes (Zoback and Gorelick, 2012). Deliberate attacks on these installations are certainly conceivable.

Intrinsically vulnerable to water scarcity when used in tandem with water-cooled thermal power plants, the CCS process consumes 10 to 40 percent of a power plant's electrical output (IPCC, 2005), reducing the amount of power that can be exported to the grid. This in turn increases upstream risks associated with fuel supply and energy security.

While the capture and storage of carbon is often framed as an industrial process, biological techniques—such as planting trees, improving agricultural practices, and adding biochar to soil—can also remove carbon from the atmosphere. Most biological methods present a fundamentally lower technical risk profile, and, unlike industrial CCS, have substantial co-benefits. However, these systems may have greater financial risk, resulting from the difficulty of quantifying and communicating the "operation" and performance of non-mechanical systems. Biological strategies are vulnerable to natural hazards. Likely co-benefits include improved soil fertility and runoff management, although the health and safety impacts of biochar production, and its impacts on soil fertility, need more research.

Ocean-based sequestration through artificial fertilization (Kintisch, 2007) is arguably a hybrid of industrial and biological processes. Large quantities of iron introduced into the ocean would spur the growth of algae blooms, which take up carbon dioxide from the atmosphere and then sink, sequestering carbon in deeper waters. Risks include acidification, disruption of food webs, the inadvertent creation of other greenhouse gases (such as methane and nitrous oxide) or of oxygen-starved dead zones in the oceans, and high levels of uncertainty about the efficacy and permanence of storage.

Another hybrid approach is enhanced weathering of rock, which amplifies the natural process of removing carbon dioxide from the air via chemical reactions. This strategy would require significant mining and materials-transportation activities and would be subject to the attendant risks.

The insurance industry's assessment of industrial CCS is of critical importance, as private financing cannot be mobilized without insurance. And without private insurance, the public sector would be compelled to assume the risks. Only a few insurers have brought these products to market (Mills, 2009), and the coverage they have offered excludes a variety of risk factors and any long-term liability.

Meanwhile, because of the failure of some biological sequestration efforts in agriculture and forestry, insurance companies have introduced products and services to assess and transfer the risks of carbon-credit delivery. Given the performance uncertainties and environmental liabilities, insurers are unlikely to assume risks from strategies such as iron fertilization of the oceans.

Solar radiation management

Carbon-dioxide removal methods are just one way of engineering the climate. Another climate-control approach relies on solar radiation management (SRM) techniques such as making clouds or bodies of water brighter with tiny bubbles (Seitz, 2011), deploying space-based reflectors, or continuously injecting millions of tons of particles or gases into the stratosphere each year with fleets of F15 jets. The proposed efforts seem superhuman: for example, deploying five million parasol spacecraft, each five kilometers long and 200 meters wide; or one 420-million-metric-ton, 3,600-kilometer-diameter mirror manufactured in space from asteroids; or 16 trillion spacecraft "fliers," each 0.6 meters in diameter, launched at the rate of 800,000 units every five minutes. The cost of the latter undertaking is estimated at up to $5 trillion to start, plus $13 billion per year indefinitely (GAO, 2011).

One fundamental limitation of this approach is that, by focusing on rejecting incoming solar energy rather than eliminating greenhouse gases, carbon dioxide released to the atmosphere will continue to contribute to ocean acidification.

To offset global warming, some combination of artillery, balloons, or airplanes could loft sunlight-scattering particles into the upper atmosphere (Robock, 2008). The unintended consequences of dimming the skies could include changes in agricultural production or rainfall (Hegerl and Solomon, 2009), changes in evaporation and runoff leading to "dryout," ozone depletion, interference with optical astronomy and satellite imaging, changes in the annual monsoon cycle that is critical

to providing food for much of Earth's population, reductions in the efficacy of solar energy systems, and undesirable feedbacks that have not yet been identified. In some cases, such as cloud whitening, malfunctioning efforts could actually accelerate warming (Romm, 2011). Possible benefits include increased photosynthesis, which would increase the amount of carbon stored in biomass.

Not all SRM requires a leap of faith. Down-to-Earth lightening of surfaces (such as roofs and roads) has been done for centuries in vernacular architecture, but only recently rediscovered as a potent way to cool urban heat islands and even reduce global temperatures (Akbari et al., 2009). Unique co-benefits here are substantial energy savings from reduced air-conditioning use in buildings, and reduction of heat stress for occupants during heat waves. Progressive building codes have begun to adopt the strategy.

Nuclear power

A greater reliance on nuclear power could reduce greenhouse gas emissions, but the tradeoffs are substantial—including the potential for ecosystem disruption from thermal and radiation pollution, mining-related risks, and increased dependency on imported fuel. Nuclear power is arguably the riskiest of all energy supply technologies. Despite decades of effort, the risks associated with waste management and weapons proliferation remain unresolved (Socolow and Glaser, 2009), and these risks are most acute in the places where nuclear power could make the greatest difference but where governments are least capable of preventing corruption and enforcing safeguards.

Nuclear power is itself vulnerable to many of the hazards posed by climate change, particularly because of its dependency on water for cooling. This risk is shared by all steam-driven power plants, but nuclear plants with once-through cooling systems require more water than other power plants: four times that of gas combined-cycle plants (Cooley et al., 2011). When nuclear plants in Europe had to shut down during the heat wave of 2003, France alone lost roughly a reactor-year of power generation, and there have been similar events in the southeastern United States. In 2012, doctoral student Michelle T. H. van Vliet of Wageningen University in The Netherlands and her colleagues demonstrated that the combination of elevated cooling-water temperatures and reduced flows under early to mid-century climate changes will reduce the power output of thermal plants by 4 percent to 19 percent, depending on location and climate scenario, with a three-fold increase in severe outages (van Vliet et al., 2012).

For a multitude of reasons—including production price, government subsidies, and economic priorities—nuclear fuel is often not a domestic resource. Nuclear-powered countries import large shares of fuel from unstable or potentially unstable regions of the world, with the Nuclear Suppliers Group now comprising 46 countries and poised to grow (Hibbs, 2012). About 90 percent of the uranium purchased for commercial nuclear reactors in the United States is imported (EIA, 2010), with Russia and Kazakhstan providing more than one-third of these imports. Africa has also

become a major exporter (Hecht, 2012). Sweden, the world's most nuclear-intensive country (in terms of nuclear electricity consumed per capita) imports 100 percent of its fuel.

Weapons linkages within the nuclear fuel cycle are well-known. Protracted geopolitical conflicts involving Iran and North Korea are only the latest chapter in a multi-decade dilemma (Thapa, 2012). The line between "peaceful" nuclear energy and nuclear weapons remains deeply blurred, and risk management efforts are being relaxed rather than strengthened, as evidenced by Russia's decision in 2008 (contrary to the guidelines of the Nuclear Non-Proliferation Treaty) to export nuclear fuel to India and China's decision in 2011 to export power reactors to Pakistan.

The insurance sector has strictly limited its exposure to nuclear power risks, ceding responsibility for coverage to governments. Insurers' assessments of next-generation plants will be critical to their reception in the financial, as well as the regulatory, communities.

Renewable energy

Renewable energy is a highly diverse ensemble of technologies, each with its own risk profile. They share some common risks, such as the intermittency of the primary resource, and vulnerabilities to natural hazards; and they enjoy the absence of other risks, such as fuel-import dependency.

Solar thermal power production, biofuels, and hydroelectric power are acutely dependent on water supply and thus vulnerable to both drought and flooding. Wind, solar photovoltaic, and industrial-thermal applications, however, do not need water for cooling. Thus, they can avoid a key vulnerability to curtailed output under drought conditions or if water temperatures increase. Recent scenarios in which renewables make a major contribution to the power supply reveal the potential for an 80-percent reduction in water withdrawals for cooling—equivalent to a billion gallons per day—in the US Intermountain West region (Cooley et al., 2011).

Offshore-wind systems pose more severe risks than land-based projects, including challenges of construction and operation in extremely harsh and unpredictable environments. Offshore turbines have exceptionally high repair costs, the prospect of extended operational downtime, and avian mortality concerns.

Insurance companies have closely scrutinized the development of renewable energy, both as a new market and as a strategy for reducing climate-related losses. Insurers looking dispassionately at the risks have come up with pricing and contract terms and have already offered many products and services for renewable energy systems, with a particular focus on products that manage the risk of lost revenue from underperformance due to insufficient solar, wind, or geothermal resources.

Energy efficiency

While perhaps more prosaic than other climate mitigation strategies, improved energy efficiency is widely demonstrated to be among the most promising, well-understood, and cost-effective strategies for reducing greenhouse gas emissions (IPCC, 2007; US Department of Energy, 1997; Williams et al., 2012). Increasing efficiency at the point of

energy use has a fundamentally more benign risk profile than all other climate change mitigation strategies, with application across every sector of every economy on the planet.

Energy efficiency reduces energy import dependence and is thus aligned with enhanced energy security. Efficiency's distributed and low-risk nature make it an unattractive target for terrorists or military gambits (with the exception, perhaps, of Internet-based energy-management systems). Energy efficiency also has more co-benefits than most other strategies, including:

- Buildings with multi-layered window systems and advanced insulation materials are less vulnerable to flood, windstorm, and wildfire.
- High-performance foam insulation materials are not damaged by moisture, as are thermally inferior fiber-based insulations (although foam is of more concern during fires).
- Well-sealed building envelopes result in fewer pressure-induced damages during hurricanes (Parzych and MacPhaul, 2005).
- Energy-efficient roof construction reduces heat loss, resulting in a reduction in rooftop ice dams, which are a major source of insurance claims in northern climates.
- Increasing the reflectivity of roofs reduces air-conditioning needs while curbing photochemical ozone smog (Rosenfeld et al., 1998).
- Strategies as mundane as maintaining adequate tire pressure not only save energy but also increase roadway safety (US Government Accountability Office, 2007).

Energy efficiency often comes hand-in-hand with water efficiency. Energy-efficient clothes washers and dishwashers, for example, save energy in part by saving hot water. Swimming pool covers save enormous amounts of water as well as energy. Electricity savings at the point of end use reduce upstream cooling water needs at the power plant.

The greatest risks in the energy-efficiency category are associated with uncertainties about energy savings or overzealous warranties. Buyers may resort to litigation if efficiency improvements do not save as much energy and money as expected. Lawsuits have been brought against manufacturers of hybrid cars, for example, for not delivering promised fuel economy.

The insurance industry has embraced energy efficiency more than any other mitigation technology, recognizing its risk-reducing co-benefits (Mills, 2006). These range from the roadway risks that are avoided when driving is curtailed in response to mileage-based auto insurance premiums (Bordoff and Noel, 2008), to premium discounts or other incentives that recognize the lowered risk of indoor air-quality problems in green buildings (Mills, 2009).

Managing emerging technology risks in the marketplace

There is an ever-present tension regarding the allocation of climate risks between the public and private sectors. On the one hand, governments may seek reduced involvement in handling the risks associated with emerging technologies. On the other hand, the private sector may be thwarted when government efforts to indemnify parties from

liability, or to subsidize insurance deductibles or premiums, jeopardize the effectiveness of commercial risk-spreading mechanisms (Patton, 2008).

For example, when European governments rolled back financial incentives for offshore-wind programs, insurers observed (Patton, 2010) that turbine owners curtailed maintenance programs, which in turn led to dramatic increases in insured losses that were not predictable and thus not "priced in" to the standing insurance contracts. The ensuing withdrawal of insurance from first-generation offshore-wind projects occurred because of the political risk, not a technology failure. Issues with current-generation offshore-wind insurance now involve more manageable technology-specific risks. Without a robust framework for evaluating and comparing losses, the choice to use or not use this mitigation technology might be made on an erroneous basis. Renewable energy industry players report that political and regulatory risks are equal to technical ones and are second only to financial risk (*The Economist*, 2011).

All emerging technologies, by definition, lack a performance and safety track record. This stands as a legitimate barrier to risk assessment and thus market acceptance (Harrison, 2012). A sober response is to assemble public-domain performance data, incorporate risk considerations into the underlying research and development process, and make loss prevention part of the demonstration and training efforts that routinely accompany public-goods technology development and commercialization programs.

The public sector has paid insufficient attention to these considerations. In the private sector, however, substantial engagement has taken place. An observer (Patton, 2008) from the insurance sector commented that:

> The public dialogue about risks of new technology tends to be superficial—overly simplistic and lacking in specificity. . . . If risk is not appropriately characterized, inappropriate policy solutions result, which ignore relevant market forces, create the potential for long-term dependency, foster economic inefficiency and aggravate the risk of environmental harm—all of which are unsustainable conditions. . . . [I]ll-crafted or overly broad subsidy structures can do more than merely provide price supports; they can unwittingly mask highly risky and/or unsustainable technologies.

As restated at the latest UN climate change conference in Durban, insurance companies—representing the world's largest industry—are willing to assume some of the economic risks of emerging technologies, independently or in partnership with governments (Geneva Association, 2011). Insurers have already made notable efforts to understand and help manage and diversify the risks of climate change mitigation technologies (Mills, 2009). More fundamentally, the price signal sent by insurance—if based on good information—can support markets in making wise technology choices.

Procrastination makes for a riskier (and costlier) future

Conventional assessments of climate change mitigation technologies tend to myopically focus on engineering and economics. Better energy and climate policy decisions can be made when cost–benefit analyses also include comparative risk assessments. Such assessments show that energy efficiency is

not only the least risky of all climate change mitigation strategies, but also has many economic co-benefits. Head-to-head risk comparisons can also make it easier for decision makers to prioritize responses to climate change and minimize regret.

Society is veering toward a risky reliance on unproven and untested climate change solutions in lieu of shovel-ready ones with well-known costs and impacts. Procrastination is moving society into a position of having to make harder choices, potentially more draconian and more costly choices, and to take new risks incurred by a need to act in haste (Socolow, 2011). It is prudent to hold the riskiest and least-proven responses in reserve, in case all else fails. Unfortunately, humankind may be forced to exercise these options, not because of any intrinsic failure of more benign approaches, but rather because of a failure to implement those approaches in a timely fashion. Private insurance and other market-based mechanisms for financing and managing these high-risk technologies will be in short supply, and as a result the costs will fall disproportionately on the public sector.

Acknowledgements

The author thanks Lindene Patton for insightful comments on a draft.

Funding

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

References

Akbari H, Menon S, and Rosenfeld A (2009) Global cooling: Increasing world-wide urban albedos to offset CO_2. *Climatic Change* 94(3–4): 275–286.

Avery D, Mills E, Breighner M, et al. (1998) Campus lighting—lighting efficiency options for student residential living units: A study at Northeastern University, Boston, Massachusetts. Lawrence Berkeley National Laboratory PUB-816. Available at: http://energy.lbl.gov/ea/mills/_archive/EMills-4-2-09/PUBS/arkwright.html.

Bordoff JE and Noel PJ (2008) Pay-as-you-drive auto insurance: A simple way to reduce driving-related harms and increase equity. Brookings Institution Discussion Paper, July. Available at: http://www.brookings.edu/research/papers/2008/07/payd-bordoffnoel.

Bulletin of the Atomic Scientists (2008) Has the time come for geoengineering? Roundtable, May–August. Available at: http://www.thebulletin.org/web-edition/roundtables/has-the-time-come-geoengineering.

Cooley H, Fulton J, and Gleick P (2011) Water for energy: Future water needs for electricity in the Intermountain West. Pacific Institute, November. Available at: http://www.pacinst.org/reports/water_for_energy/.

The Economist (2011) Managing the risk in renewable energy. Economist Intelligence Unit, October. Available at: http://digitalresearch.eiu.com/risksandrenewables/report.

EIA (2010) Uranium purchased by owners and operators of U.S. civilian nuclear power reactors. US Energy Information Administration data for 2009. Available at: http://www.eia.gov/cneaf/nuclear/umar/summarytable1.html.

Funabashi Y and Kitazawa K (2012) Fukushima in review: A complex disaster, a disastrous response. *Bulletin of the Atomic Scientists* 68(2): 9–21.

Geneva Association (2011) *Tackling Climate Risk: An Insurance Contribution to the COP Discussions*. International Association for the Study of Insurance Economics, December. Geneva: The Geneva Association. Available at: http://www.genevaassociation.org/pdf/bookandmonographs/ga2011-tackling_climate_risk.pdf.

Harrison S (2012) Insurers adapt to cover clean energy business: Constant changes create challenges in creating policies. *Business Insurance*, February 26. Available at: http://www.businessinsurance.com/article/20120226/NEWS07/302269996#.

Hecht G (2012) An elemental force: Uranium production in Africa, and what it means to be nuclear. *Bulletin of the Atomic Scientists* 68(2): 22–33.

Hegerl GC and Solomon S (2009) Risks of climate engineering. *Science* 325(5943): 955–966.

Hibbs M (2012) Nuclear energy 2011: A watershed year. *Bulletin of the Atomic Scientists* 68(1): 10–19.

IPCC (2005) *Carbon Dioxide Capture and Storage*. Prepared by Metz B, Davidson O, De Coninck H, et al. (eds). Cambridge: Cambridge University Press.

IPCC (2007) Summary for Policymakers: Contribution of Working Groups I, II, and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Geneva, Switzerland. Available at: http://www.ipcc.ch/publications_and_data/publications_and_data_ reports.shtml#.UFiMGhjR3Jw.

Kintisch E (2007) Should oceanographers pump iron? *Science* 318(5855): 1368–1370. November 30.

Knight FH (1921) *Risk, Uncertainty, and Profit*. Boston, MA and New York: Houghton Mifflin.

Mills E (2005) Insurance in a climate of change. *Science* 308(5737): 1040–1044.

Mills E (2006) Synergisms between climate change mitigation and adaptation: An insurance perspective. *Mitigation and Adaptation Strategies for Global Change* 12(5): 809–842.

Mills E (2009) *From Risk to Opportunity 2008: Insurer Responses to Climate Change*. Boston, MA: Ceres.

Mills E (2012) Qualitative comparison of climate change mitigation strategies: Hazards, vulnerabilities, and co-benefits; and characteristics of selected carbon-dioxide removal and solar radiation management proposals. Available at: http://insurance.lbl.gov/mitigation.

Parzych RB and MacPhaul D (2005) Commissioning the building envelope: Surviving Hurricanes Charley, Frances, and Jeanne. Proceedings of the National Conference on Building Commissioning, May 4–6. PECI. Available at: http://www.peci.org/ncbc/proceedings/2005/16_Parzych_NCBC2005.pdf.

Patton L (2008) Beyond rising sea levels: The importance of the insurance asset in the process of accelerating delivery of new technology to market to combat climate change. *European Business Review*, July/August. Available at: http://www.zurich.com/internet/main/SiteCollection Documents/insight/NewtechnologyPatton.pdf.

Patton L (2010) Using insurance to facilitate adaptation to and mitigation of climate-related risk. Presentation to the Bren School, University of California, Santa Barbara, March 3. Available at: http://www.youtube.com/watch?v=6UFkXgmfiOo.

Robock A (2008) 20 reasons why geoengineering may be a bad idea. *Bulletin of the Atomic Scientists* 64(2): 14–18, 59.

Romm J (2011) Key geoengineering strategy may yield warming, not cooling. *Climate Progress*, April 9. Available at: http://thinkprogress.org/climate/2011/04/10/207866/geoengineering-clould-whitening-warming-not-cooling/.

Rosenfeld AH, Akbari H, Romm JJ, et al. (1998) Cool communities: Strategies for heat island mitigation and smog reduction. *Energy and Buildings* 28(1): 51–62.

Seitz R (2011) Bright water: Hydrosols, water conservation, and climate change. *Climatic Change* 105: 365–381.

Socolow R (2011) Wedges reaffirmed. *Bulletin of the Atomic Scientists*, September 27. Available at: http://thebulletin.org/web-edition/features/wedges-reaffirmed.

Socolow RH and Glaser A (2009) Balancing risks: Nuclear energy & climate change. *Daedalus* (Fall): 31–44. Available at: http://www.princeton.edu/mae/people/faculty/socolow/Daedalus-Socolow-Glaser-Fall-2009-pp-31-44.pdf.

Thapa HB (2012) Climate change, reactors, and bombs. *Bulletin of the Atomic Scientists*, July 26. Available at: http://www.thebulletin.org/web-edition/roundtables/the-nuclear-approach-to-climate-risk.

US Department of Energy (1997) Scenarios of U.S. carbon reductions: Potential impacts of energy-efficient and low-carbon technologies by 2010 and beyond. Prepared by the Interlaboratory Working Group on Energy-efficient and Low-carbon Technologies. Oak Ridge National Laboratory Report No. ORNL/CON-444. Available at: http://industrial-energy.lbl.gov/node/204.

US Government Accountability Office (2007) Underinflated tires in the United States. GAO-07-246R. Available at: http://www.gao.gov/new.items/d07246r.pdf.

US Government Accountability Office (2011) Climate engineering: Technical status, future directions, and potential responses. GAO-11-71. Available at: http://www.gao.gov/products/GAO-11-71.

Van Vliet MTH, Yearsley JR, Ludwig F, et al. (2012) Vulnerability of US and European electricity supply to climate change. *Nature Climate Change* 2: 676–681. Available at: http://www.nature.com/nclimate/journal/v2/n9/full/nclimate1546.html.

Vellinga PV, Mills E, Bower L, et al. (2001) Insurance and other financial services. In: McCarthy JJ, Canziani OF, Leary NA, et al. (eds) *Climate Change 2001: Impacts, Adaptation and Vulnerability*. Cambridge: Cambridge University Press.

Williams JH, DeBenedictis A, Ghanadan R, et al. (2012) The technology path to deep greenhouse

gas emissions cuts by 2050: The pivotal role of electricity. *Science* 335(6064): 53–59.

Wood L (2012) Projecting power: The security implications of space-based solar power. *Bulletin of the Atomic Scientists* 68(1): 70–78.

Zoback MD and Gorelick SM (2012) Earthquake triggering and large-scale geological storage of carbon dioxide. *Proceedings of the National Academy of Sciences* 09(26): 10 164–10168.

Author biography

Evan Mills is a staff scientist at the US Energy Department's Lawrence Berkeley National Laboratory. He served as an author for several Intergovernmental Panel on Climate Change assessments and was a lead author of the 2009 US climate impacts assessment, *Global Climate Change Impacts in the United States*.