Klaus Keller and Rob Lempert
have given me the title:

Beyond Cost Benefit Analysis

M. Granger Morgan
Head, Department of Engineering
and Public Policy
Carnegie Mellon University
Pittsburgh, PA 15213
412-268-2672
granger.morgan@andrew.cmu.edu

But first…

…indulge me 3-4 minutes on two topics that came up yesterday on which I *have* actually done some real work:

Carbon Capture and Geological Sequestration (CCS)

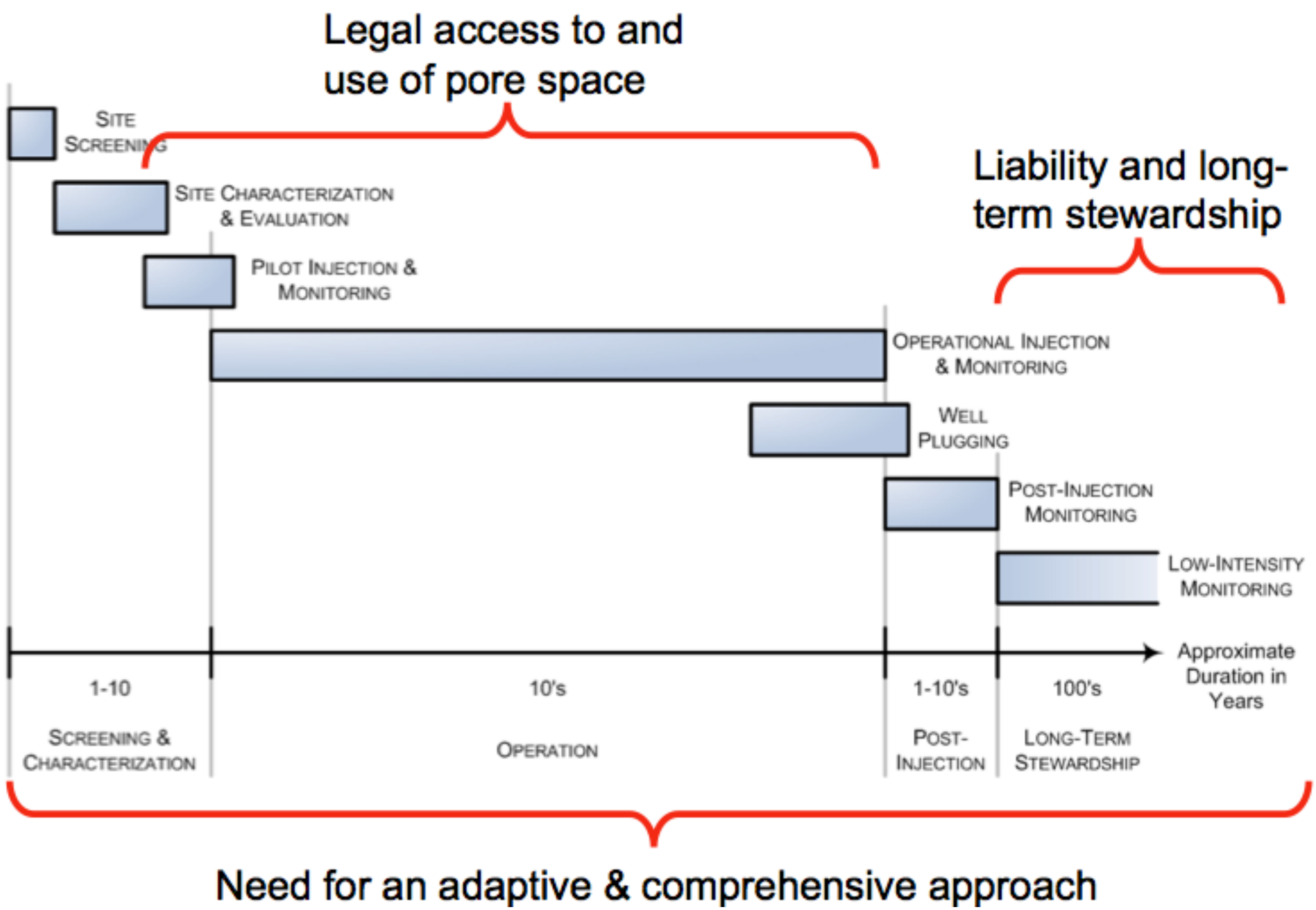
Solar Radiation Management (SRM)

A few years ago…

…we concluded that while the technology for CCS is critically important, so too is developing a U.S. regulatory regime that assures CCS will be done in a manner that is safe, environmentally sound, affordable, compatible with evolving international carbon control regimes (including emissions trading) and socially equitable.

To help make this happen we launched a collaborative effort called the CCSReg Project.

We developed policy briefs to address:

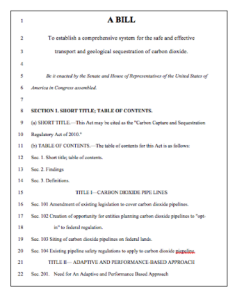


We did extensive briefings…

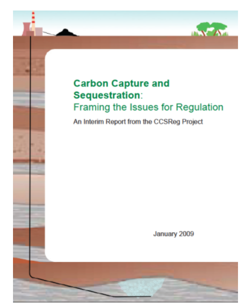
…on Capitol Hill, at EPA, to industry and environmental groups both in the U.S. and internationally. Also organized several workshops and made a variety of conference presentations, all with the dual objectives of getting our ideas out and obtaining critical input.

While we got very favorable reactions, and lots of useful advice, it soon became clear that nobody on the Hill was going to pick up these ideas and convert them to legislative language…

…since we had a couple of experienced lawyers on our team we did it ourselves.



50-pg. draft legislation

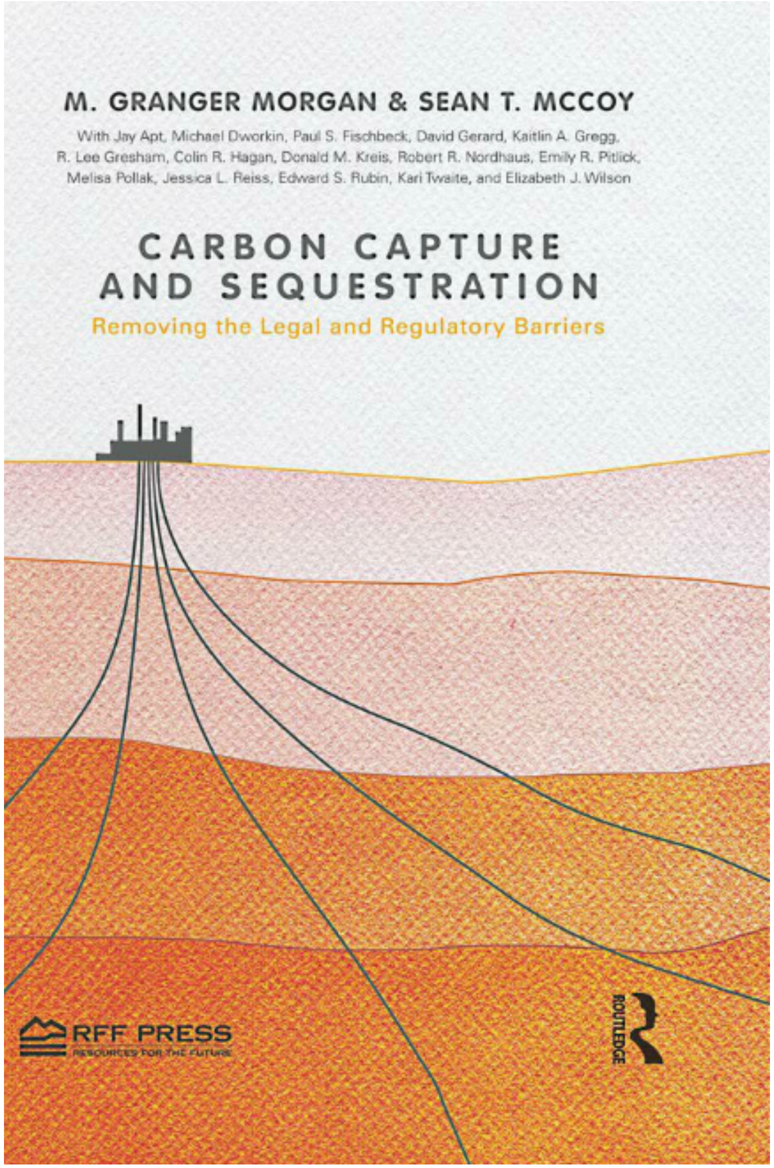


Interim report

Six policy briefs

In June 2012…

…we published a book through RFF Press.



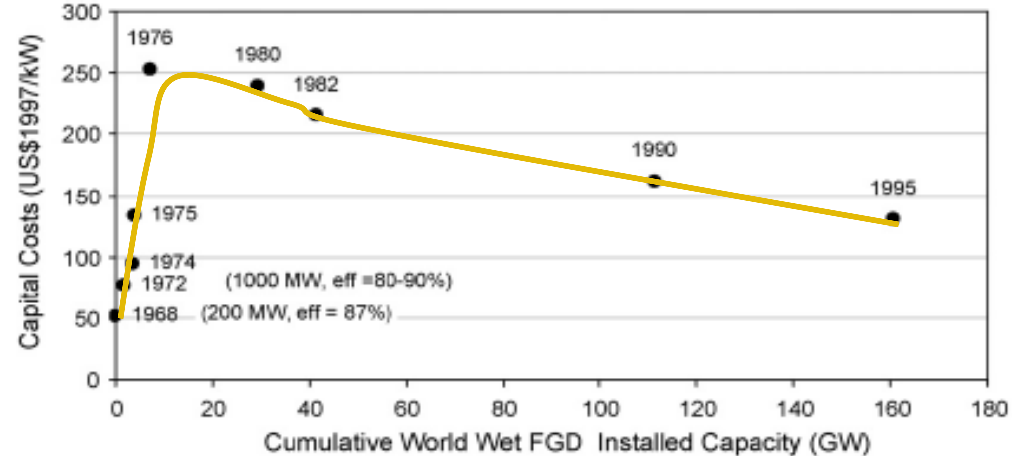
Contents

One figure from Chapter 9

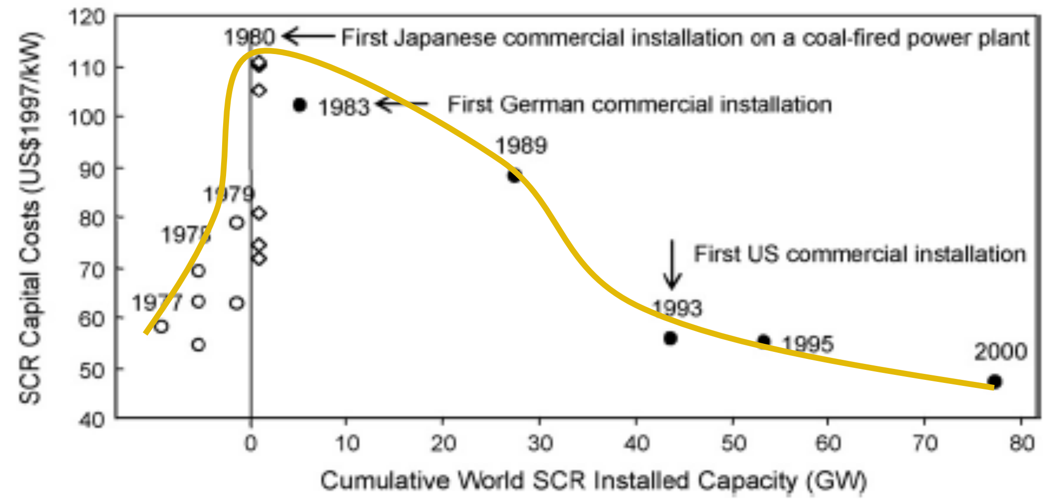
In the case of both SO_2 scrubber technology and in the case of NOx control technology, Ed Rubin finds that costs rose significantly after problems were encountered with the design and performance of the first few plants.

There is every reason to believe that the same will be true for CCS.

SO_2 control



NO_X control

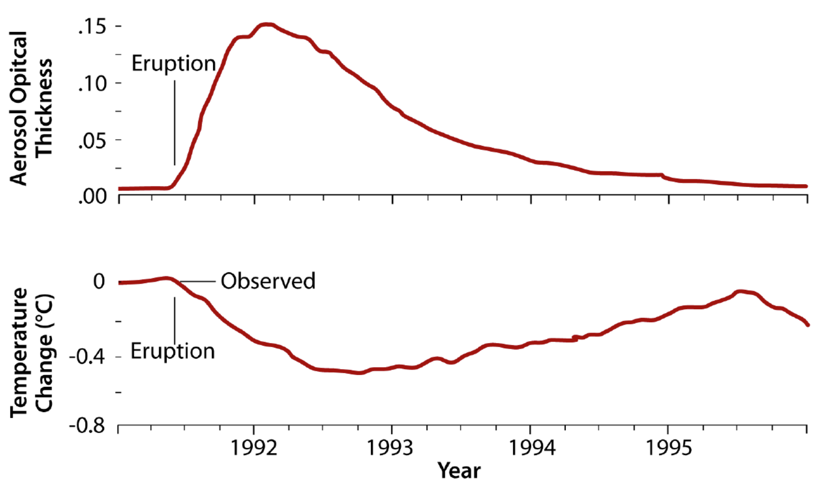


Source: Rubin et al., IJGGC, 2007.

SRM

Experience with large volcanic explosions make it clear that cooling can be very rapid.

The Mt. Pinatubo explosion



We looked at SRM in our first NSF climate center but then moved on…

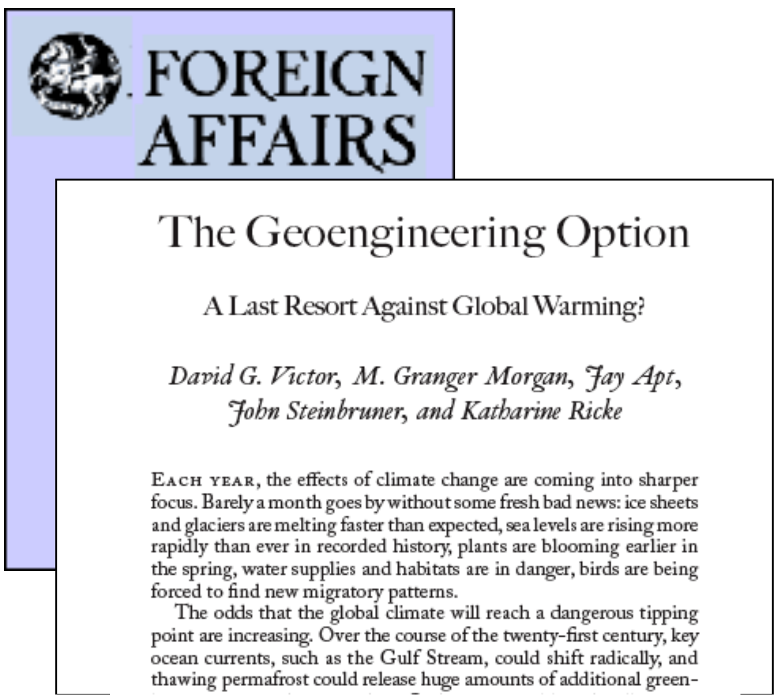
Figure source: NASA and IPCC.

Source: Novim report, 2009, p. 14

The CFR workshop…

Because the diplomatic community was almost completely unaware of SRM, in 2008 I organized a workshop at the Council on Foreign Relations in Washington, DC.

The workshop led to a paper that appeared in the 2009 March/April issue of *Foreign Affairs*.



FOREIGN AFFAIRS

The Geoengineering Option

A Last Resort Against Global Warming?

David G. Victor, M. Granger Morgan, Jay Apt, John Steinbruner, and Katharine Ricke

EACH YEAR, the effects of climate change are coming into sharper focus. Barely a month goes by without some fresh bad news: ice sheets and glaciers are melting faster than expected, sea levels are rising more rapidly than ever in recorded history, plants are blooming earlier in the spring, water supplies and habitats are in danger, birds are being forced to find new migratory patterns.

The odds that the global climate will reach a dangerous tipping point are increasing. Over the course of the twenty-first century, key ocean currents, such as the Gulf Stream, could shift radically, and thawing permafrost could release huge amounts of additional green-

Participants in the 2008 workshop were all from North America.

To extend the conversation to a more international group, we ran a second workshop in April 2009 in Lisbon, Portugal.

Source: Council on Foreign Relations

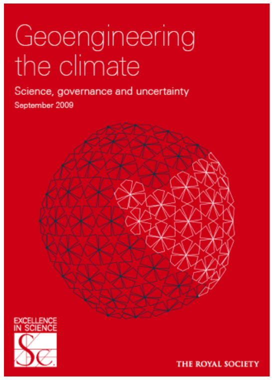
The Lisbon Workshop…

…was hosted by the Ministry of Science, Technology and Higher Education of the Government of Portugal. The two-day workshop was held at the facilities of the Gulbenkian Foundation.

Co-sponsors included: IRGC, CMU-CDMC, U Calgary. Participants came from N. America, EU, China, Russia, and India.

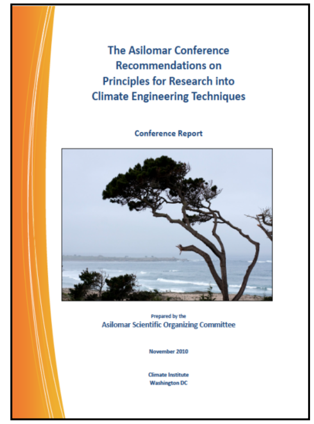
Sources:
Gulbenkian & Qian Yi

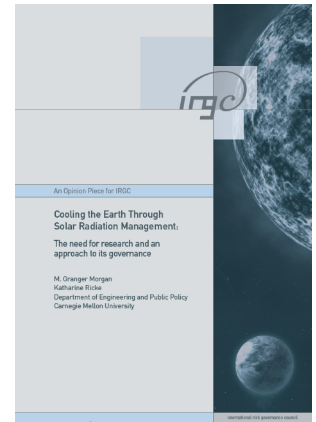
Some subsequent events…



Sep. 2009: The governance section of the Royal Society's report on Geoengineering

March 2010: The discussion of risk governance at the Asilomar conference on geoengineering





Jan 2010

Jan 2011

June 2009: U.S. NRC workshop on geoengineering

Geoengineering Options to Respond to Climate Change:
Steps to Establish a Research Agenda

March 2010: Testimony to a joint session of the U.S. House Science Committee and the Science Committee of the UK Parliament

March 2010: Evening briefing to CFR

November 2010: IRGC opinion piece on governance

August 2010: First multi-university summer study

SRM…(Cont.)

October 2011: BPC report on U.S. research

April 2012: CMU workshop on managing knowledge

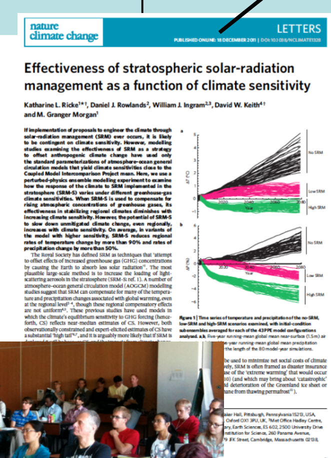
March 2011: SRMGI Kavli Center

June 2011: Lima IPCC expert meeting on geoengineering

May 2012: DC CIT event

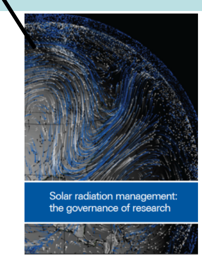
Jan 2011

Jan 2012


nature climate change LETTERS

Effectiveness of stratospheric solar-radiation management as a function of climate sensitivity

Katharine L. Ricke, Daniel J. Rowlands, William J. Ingram, David W. Keith and M. Granger Morgan



January 2011: La Jolla IGBP workshop on ecosystem impacts of geoengineering

Paper now in press at *AMBIO*

August 2011: Second multi-university summer study program for graduate students and other young investigators held at Banff

SRM…(Cont.)

M. GRANGER MORGAN
ROBERT R. NORDHAUS
PAUL GOTTLIEB

Needed: Research Guidelines for Solar Radiation Management

As this approach to geoengineering gains attention, a coordinated plan for research will make it possible to understand how it might work and what dangers it could present.

Emissions of carbon dioxide (CO_2) and other greenhouse gases (GHGs) continue to rise. The effects of climate change are becoming ever more apparent. Yet prospects for reducing global emissions of CO_2 by an order of magnitude, as would be needed to reduce threats of climate change, seem more remote than ever.

When emissions of air pollutants, such as sulfur dioxide and oxides of nitrogen, are reduced, improvements occur in a matter of days or weeks, because the gases quickly disappear from the atmosphere. This is not true for GHGs. Once emitted, they remain in the atmosphere for many decades or centuries. As a result, to stabilize atmospheric concentrations, emissions must be dramatically reduced. Further, there is inertia in the earth-ocean system, so the full effects of the emissions that have already occurred have yet to be felt. If the planet is to avoid serious climate change and its largely adverse consequences, global emissions of GHSs will have to fall by 80 to 90% over the next few decades.

Because the world has already lost so much time, and because it does not appear that serious efforts will be made to reduce emissions in the major economies any time soon, interest has been growing in the possibility that warming might be offset by engineering the planet: a concept called geoengineering. The term solar radiation management (SRM) is used to refer to a number of strategies that might be used to increase the fraction of sunlight reflected back into space by just a couple of percentage points in order to offset the temperature increase caused by rising atmospheric concentrations of CO_2 and other GHGs. Of these strategies, the one that appears to be most affordable and most capable of being quickly implemented involves injecting small reflective particles into the stratosphere.

There is nothing theoretical about whether SRM could cool the planet. Every time a large volcano explodes and injects tons of material into the stratosphere, Earth's average temperature drops. When Mount Pinatubo exploded in

SPRING 2013 37

Jan 2013

FOREIGN AFFAIRS
Published by the Council on Foreign Relations

March 27, 2013
POSTSCRIPT

The Truth About Geoengineering

Science Fiction and Science Fact

David G. Victor, M. Granger Morgan, Jay Apt, John Steinbruner, Katharine Ricke

DAVID G. VICTOR is a professor at the School of International Relations and Pacific Studies and co-director of the School's new Laboratory on International Law and Regulation. M. GRANGER MORGAN is a professor and head of the Department of Engineering and Public Policy at Carnegie Mellon University. JAY APT is a professor and director of the Carnegie Mellon Electricity Industry Center. JOHN D. STEINBRUNER is a professor and director of the Center for International and Security Studies at the University of Maryland. KATHARINE RICKE is a postdoctoral fellow at Carnegie Institution for Science.

Officials prepare to seed clouds near Bangkok, 2007.

Royal Thai Air Force rainmakers hoped to coax rains to clear away thick smoke from forest fires and stubble burning. (Sukree Sukplang /Courtesy Reuters)

The failure to make much progress at the UN Climate Change Conference in Doha, Qatar this winter was yet another reminder that the world might soon face extreme climate shifts. In response, it is becoming increasingly likely that governments will adopt risky strategies, known as "geoengineering," to rapidly cool the planet. Four years ago, in order to raise awareness about geoengineering, we published "The Geoengineering Option [1]" in *Foreign Affairs*. **Almost nobody thought that such tactics -- which included spraying particles into the upper**

CURRENT PROJECTS System | THE NATIONAL ACADEMIES
Advisers to the Nation on Science, Engineering, and Medicine

Committee Membership Information

Project Title:	Geoengineering Climate: Technical Evaluation and Discussion of Impacts
PIN:	DELS-BASC-12-04
Major Unit:	Division of Behavioral and Social Sciences and Education Division on Earth and Life Studies
Sub Unit:	Board on Environmental Change and Society Ocean Studies Board Board on Atmospheric Sciences & Climate
RSO:	Dunlea, Edward
Subject/Focus Area:	Earth Sciences; Engineering and Technology

Committee Membership
Date Posted: 04/25/2013

SRM

David G. Victor, M. Granger Morgan, Jay Apt, John Steinbruner, and Katharine Ricke, "The Geoengineering Option," *Foreign Affairs*, *88*(2), 64-76, March/April 2009.

Katharine Ricke, M. Granger Morgan and Myles R. Allen, "Regional Climate Response to Solar-radiation Management," *Nature Geoscience*, *3*, 537-541, 2010.

David W. Keith, Edward Parson and M. Granger Morgan, "Research on Global Sun Block Needed Now," *Nature*, *463*(28), 426-427, January 2010.

M. Granger Morgan and Katharine Ricke, *Cooling the Earth Through Solar Radiation Management: The need for research and an approach to its governance*, The International Risk Governance Council (IRGC), 24pp., 2010.

Katharine L. Ricke, Daniel J. Rowlands, William J. Ingram, David W. Keith and M. Granger Morgan, "Effectiveness of Stratospheric Solar-Radiation Management as a Function of Climate Sensitivity," *Nature Climate Change*, *2*, 92-96, February 2012.

Lynn M. Russell et al., "Ecosystem Impacts of Geoengineering: A review for developing a science plan," *Ambio: A Journal of the Human Environment*, *41*, 350-369, 2012.

David G. Victor, M. Granger Morgan, Jay Apt, John Steinbruner, and Katharine Ricke, "The Truth About Geoengineering," Postscript, *Foreign Affairs*, 2013 Mar 27.

M. Granger Morgan, Robert R. Nordhaus, Paul Gottlieb, Needed: Resaerch Guidelines for Geoengineering, *Issues in Science and Technology*, Spring 2013, pp 37-44.

BUT…

…I'm supposed to be talking about B-C in the context of sea level rise and other impacts from climate change.

At this point in my presentation at Snowmass I included four photos showing sea level rise that were commissioned by Dan Shrag. He has kindly provided them to me, but I do not feel comfortable sharing machineable copies.

The obvious first question is:

Benefit-Cost Analysis for what? Here are six possibilities:

1. Decisions by potentially affected parties (e.g., Port of Long Beach) about what investments to make to deal with likely future impacts from sea level rise.
2. Choices at the national level between alternative adaptive strategies such as sea walls *versus* coastal retreat.
3. Choices by a nation as to whether and how much emissions abatement to undertake.
4. Choices by a nation as to whether or not to join an international agreement on emissions abatement.
5. Assessment of the "social cost of carbon."
6. Choice of a globally optimum level of emissions abatement.

Example 1:

Decisions by potentially affected parties (e.g., Port of Long Beach) about what investments to make to deal with likely future impacts from sea level rise.

Use of B-C:

It is entirely appropriate to use a B-C formulation when a single decision maker (or a group that has shared values) is trying to decide if the costs of making some investment to mitigate the impacts of possible sea level rise (e.g., changing the dock facilities in Long Beach, CA) are greater or less than the benefits (in the form of reduced damages) that can be expected over the life of the project. Of course, given the high level of uncertainty one may want to use "robust decision making" techniques, but that is not at odds with a B-C formulation.

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I will explain why I say this in a moment, but first let's look at Example 2.

Example 2:

Choices at the national level between alternative adaptive strategies such as sea walls *versus* coastal retreat.

Use of B-C:

Analysis in this case involves several challenging issues:

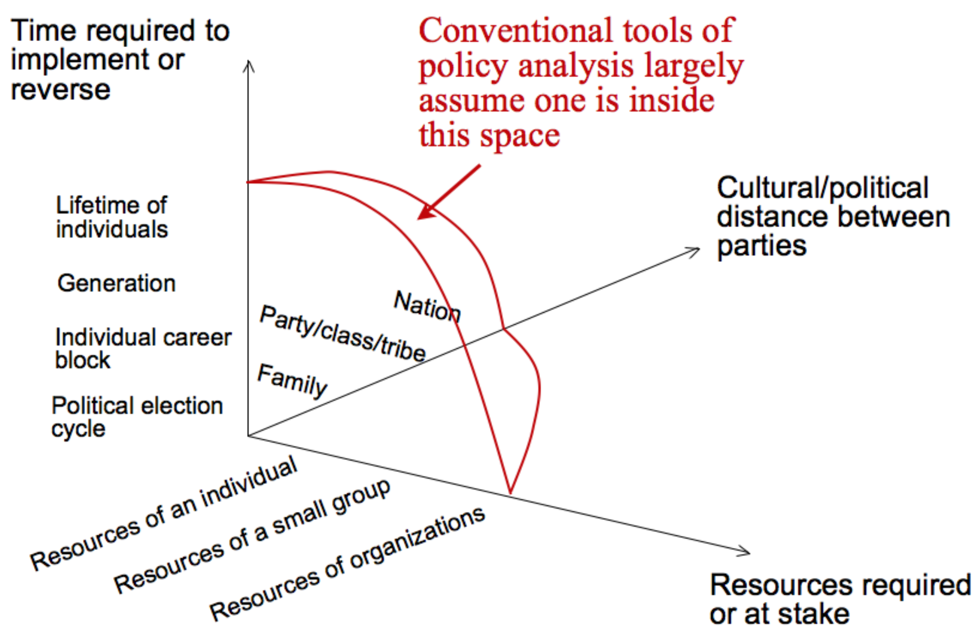
- Building stochastic storm damage models (most early damage will come from storms, not inundation);
- Assessing social values;
- Addressing issues of time preference (it would be desirable to do comparative analysis using several strategies, not just exponential or hyperbolic discounting).

Again, it would probably be desirable to use "robust" methods to search the space of options. However, again I believe this is a case where a nation could appropriately use a B-C formulation to inform its choices.

Why is B-C appropriate…

…as a strategy for Examples 1 and 2?

While the time-scale may be longer than for some B-C calculations, and there are various other analytical complications, both these examples fall squarely in the space in which the underlying assumptions made by conventional tools of policy analysis, including B-C, are valid.



Most conventional tools of policy analysis assume that:

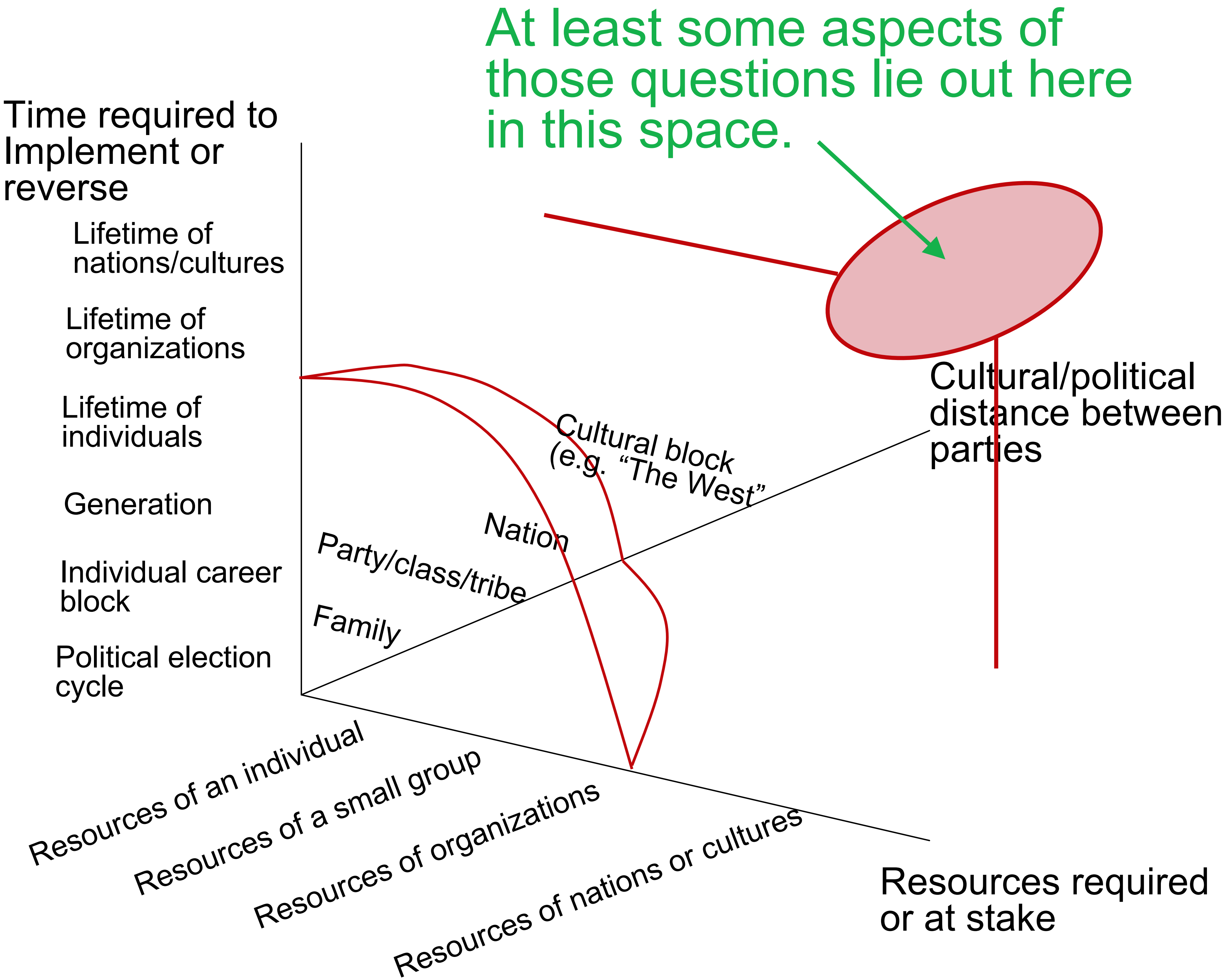
1. there is a single (public-sector) decision maker who faces a single problem (in the context of a single polity);
2. values are known (or knowable), static, and exogenously determined;
3. the decision maker should select a policy by maximizing expected utility;
4. the impacts involved are of manageable size and can be valued at the margin;
5. time preference is accurately described by conventional methods for assessing future costs and benefits;
6. the system under study can reasonably be treated as linear;
7. uncertainty is modest and manageable.

M. Granger Morgan, Milind Kandlikar, James Risbey and Hadi Dowlatabadi, Editorial - "Why Conventional Tools for Policy Analysis Are Often Inadequate for Problems of Global Change," *Climatic Change*, *41*, 271-281, 1999.

Because Examples 3 and 4…

…are more complicated, let me come back to them in a few minutes and next consider examples 5 and 6, where in my view the use of B-C methods is *not* appropriate. To remind you:

5. Assessment of the "social cost of carbon."
6. Choice of a globally optimum level of emissions abatement.


At least some aspects of those questions lie out here in this space.
Time required to Implement or reverse
Lifetime of nations/cultures
Lifetime of organizations
Lifetime of individuals
Generation
Individual career block
Political election cycle
Cultural block (e.g. "The West"
Nation
Party/class/tribe
Family
Cultural/political distance between parties
Resources of an individual
Resources of a small group
Resources of organizations
Resources of nations or cultures
Resources required or at stake

That is because:

1. There is a single (public-sector) decision maker who faces a single problem (in the context of a single polity).

Becomes

1. There is no single decision maker for the entire planet. Rather there are multiple decision makers who face multiple problems (in the context of different polities).

That is because:

2. Values are known (or knowable), static, and exogenously determined.

Becomes

2. Values are diverse across parties, and likely to change over time and across generations (e.g., some may decide they like some of the changes, some may learn that the changes are much worse than expected; I don't want to see a change in the white pine, sugar maple, beach, and birch ecosystem of NH but my great great grandchildren may be very happy with a verdant mix of yellow pine and oak).

That is because:

3. The decision maker should select a policy by maximizing expected utility.

Becomes

3. As noted above, there is no single global decision maker nor is there any single global utility function that all the world accepts that can be maximized.

That is because:

4. The impacts involved are of manageable size and can be valued at the margin.

Becomes

4. Some of the impacts involved will be very large (for at least some parties) and so can not be valued at the margin (consider for example small island states that disappear under water).

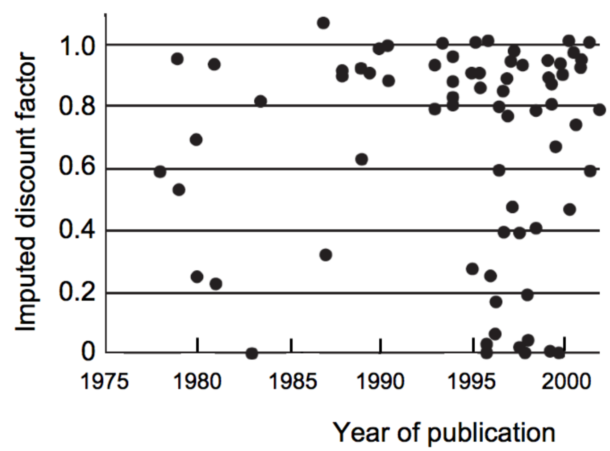
That is because:

5. Time preference is accurately described by conventional methods for assessing future costs and benefits.

Becomes

5. Time preferences are likely to be very different for different parties, and in many cases not exponential or even hyperbolic.

Here, for example, are implicit discount factors from behavioral studies just among U.S. respondents:



Source: Frederick, S., G. Loewenstein, T. O'Donoghue (2002). "Time Discounting and Time Preference: A Critical Review," *Journal of Economic Literature, XL*, pp. 351–401.

That is because:

6. The system under study can be reasonably treated as linear.

Becomes

6. The system under study is obviously highly non-linear and includes various positive and negative feedbacks.

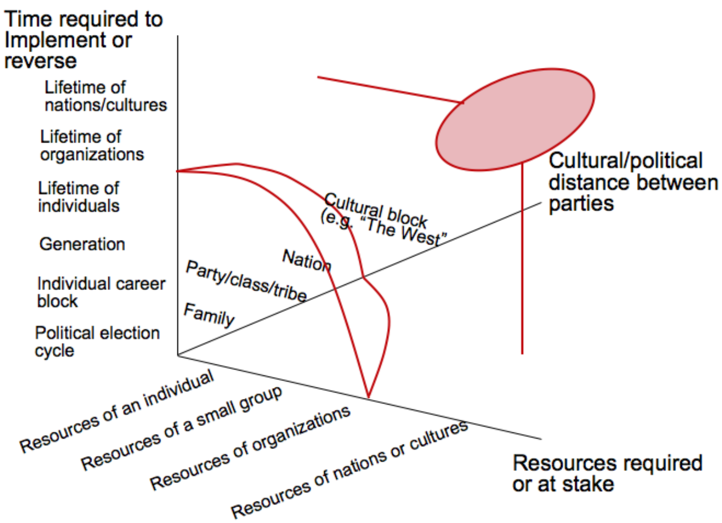
That is because:

7. Uncertainty is modest and manageable.

Becomes

7. Uncertainty is *very* large, and there are both known and almost certainly important unknown unknowns.

Bottom line



Before picking up any of the conventional tools of policy analysis (including B-C) and applying them to a climate problem, one really needs to think carefully about where important parts of the problem lie in this space. If they lie outside the "conventional zone," it is likely that one will need to adopt (or develop) non-conventional analytical methods.

Problem 5.
Assessment of the "social cost of carbon."

Why do we need this?

Answer: Primarily because here in the U.S. some number is needed as agencies decide what carbon abatement investments they should make or how to value the carbon emissions of their projects.

Because of Executive Order 12866, the U.S. recently went through a great deal of numerology in order to get some numbers.

> The purpose of the "social cost of carbon" (SCC) estimates presented here is to allow agencies to incorporate the social benefits of reducing carbon dioxide (CO_2) emissions into cost-benefit analyses of regulatory actions that have small, or "marginal," impacts on cumulative global emissions… (EPA, 2009)

Over the course of 50 pages…

…EPA (2009) performed a variety of reviews and calculations in an effort to cost out things like agricultural productivity, human health, property damages from increased flood risk, and the value of ecosystem services. The report does not cover all the impacts of climate change, nor is it adequately international or come to grips with the possibility that we may end up in a "high tail" of one of the distributions of impacts. However, in my view, Anthoff and Tol (2010) identify the central issue:

> Estimates of the marginal damage costs of carbon dioxide emissions require the aggregation of monetised impacts of climate change over people with different incomes and in different jurisdictions. Implicitly or explicitly, such estimates assume a social welfare function and hence a particular attitude towards equity and justice.

Source: Anthoff, D. and R. S.J. Tol (2010). "On International Equity and National Decision Making on Climate Change," *Journal of Environmental Economics and Management*, *60*(1),14-20.

Problem 6.
Choice of a globally optimum level of emissions abatement.

Why do we need this?

Answer: It is not clear to me that we do. Some would argue we need it in order to decide how much abatement the world should buy. However, even if such an analysis made sense (I'll argue in a moment that it does not), the obvious question is how, and by who, would the result be used?

Problem 6.
Choice of a globally optimum level of emissions abatement.

Why do we need this?

Answer: It is not clear to me that we do. Some would argue we need it in order to decide how much abatement the world should buy. However, even if such an analysis made sense (I'll argue in a moment that it does not), the obvious question is how, and by who, would the result be used?

While it vastly oversimplifies, the following helps to explain my argument.

GHG Management from the top down.

Perform an IA in order to determine the "optimal" level of abatement.

Through international negotiations get a global agreement in place that endorses that level.

Persuade all major emitters to "sign up" and adopt coordinated policies to meet that level.

GHG Management from the bottom up.

Different parts of the world get serious about reducing emission of GHGs at different times.

Each starts doing various things to reduce emissions.

As more get serious, international negotiations begin to work to coordinate the several abatement regimes.

The key thing…

…needed to implement this model is integrated assessment that determines the target.

GHG Management from the top down.

Perform an IA in order to determine the "optimal" level of abatement.

Through international negotiations get a global agreement in place that endorses that level.

Persuade all major emitters to "sign up" and adopt coordinated policies to meet that level.

The key thing…

…needed to implement this model is emission abatement supply curves so that those who choose to get started can do so in the most cost effective way.

GHG Management from the bottom up.

Different parts of the world get serious about reducing emission of GHGs at different times.

Each starts doing various things to reduce emissions.

As more get serious, international negotiations begin to work to coordinate the several abatement regimes.

If and when we manage…

…to begin to get serious control of GHG emissions from major emitting countries, my money is on it happening according to Model 2 (i.e., bottom up).

At that point what will be most needed is clear evidence of what abatement strategies are most cost-effective.

It is for this reason that our latest distributed NSF center is called the Center for Climate and *Energy* Decision Making and is primarily focused on finding ways to decarbonize the energy system.

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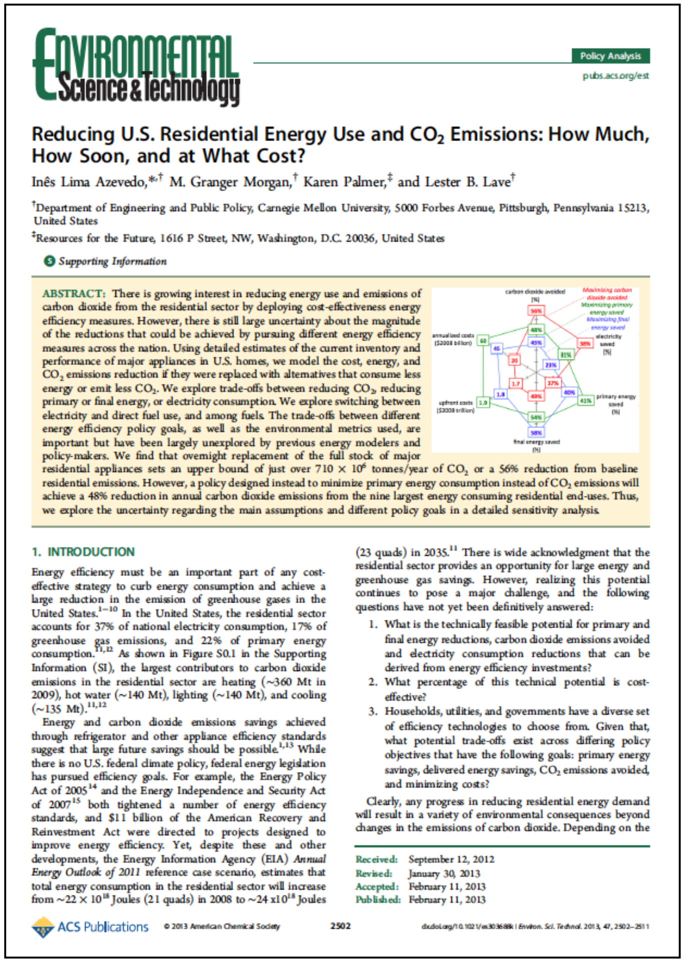
For that we primarily need analysis of cost-effectiveness, not B-C analysis.

Here for example…

…are abatement supply curves for residential electricity.



Environmental Science & Technology
Policy Analysis
pubs.acs.org/est

Reducing U.S. Residential Energy Use and CO_2 Emissions: How Much, How Soon, and at What Cost?

Inês Lima Azevedo,*[†] M. Granger Morgan,[†] Karen Palmer,[‡] and Lester B. Lave[†]

[†]Department of Engineering and Public Policy, Carnegie Mellon University, 5000 Forbes Avenue, Pittsburgh, Pennsylvania 15213, United States

[‡]Resources for the Future, 1616 P Street, NW, Washington, D.C. 20036, United States

Supporting Information

ABSTRACT: There is growing interest in reducing energy use and emissions of carbon dioxide from the residential sector by deploying cost-effectiveness energy efficiency measures. However, there is still large uncertainty about the magnitude of the reductions that could be achieved by pursuing different energy efficiency measures across the nation. Using detailed estimates of the current inventory and performance of major appliances in U.S. homes, we model the cost, energy, and CO_2 emissions reduction if they were replaced with alternatives that consume less energy or emit less CO_2. We explore trade-offs between reducing CO_2, reducing primary or final energy, or electricity consumption. We explore switching between electricity and direct fuel use, and among fuels. The trade-offs between different energy efficiency policy goals, as well as the environmental metrics used, are important but have been largely unexplored by previous energy modelers and policy-makers. We find that overnight replacement of the full stock of major residential appliances sets an upper bound of just over 710×10^6 tonnes/year of CO_2 or a 56% reduction from baseline residential emissions. However, a policy designed instead to minimize primary energy consumption instead of CO_2 emissions will achieve a 48% reduction in annual carbon dioxide emissions from the nine largest energy consuming residential end-uses. Thus, we explore the uncertainty regarding the main assumptions and different policy goals in a detailed sensitivity analysis.

1. INTRODUCTION

Energy efficiency must be an important part of any cost-effective strategy to curb energy consumption and achieve a large reduction in the emission of greenhouse gases in the United States.[1−10] In the United States, the residential sector accounts for 37% of national electricity consumption, 17% of greenhouse gas emissions, and 22% of primary energy consumption.[11,12] As shown in Figure S0.1 in the Supporting Information (SI), the largest contributors to carbon dioxide emissions in the residential sector are heating (~360 Mt in 2009), hot water (~140 Mt), lighting (~140 Mt), and cooling (~135 Mt).[11,12]

Energy and carbon dioxide emissions savings achieved through refrigerator and other appliance efficiency standards suggest that large future savings should be possible.[1,13] While there is no U.S. federal climate policy, federal energy legislation has pursued efficiency goals. For example, the Energy Policy Act of 2005[14] and the Energy Independence and Security Act of 2007[15] both tightened a number of energy efficiency standards, and $11 billion of the American Recovery and Reinvestment Act were directed to projects designed to improve energy efficiency. Yet, despite these and other developments, the Energy Information Agency (EIA) *Annual Energy Outlook of 2011* reference case scenario, estimates that total energy consumption in the residential sector will increase from ~22×10^{18} Joules (21 quads) in 2008 to ~24×10^{18} Joules (23 quads) in 2035.[11] There is wide acknowledgment that the residential sector provides an opportunity for large energy and greenhouse gas savings. However, realizing this potential continues to pose a major challenge, and the following questions have not yet been definitively answered:

1. What is the technically feasible potential for primary and final energy reductions, carbon dioxide emissions avoided and electricity consumption reductions that can be derived from energy efficiency investments?
2. What percentage of this technical potential is cost-effective?
3. Households, utilities, and governments have a diverse set of efficiency technologies to choose from. Given that, what potential trade-offs exist across differing policy objectives that have the following goals: primary energy savings, delivered energy savings, CO_2 emissions avoided, and minimizing costs?

Clearly, any progress in reducing residential energy demand will result in a variety of environmental consequences beyond changes in the emissions of carbon dioxide. Depending on the

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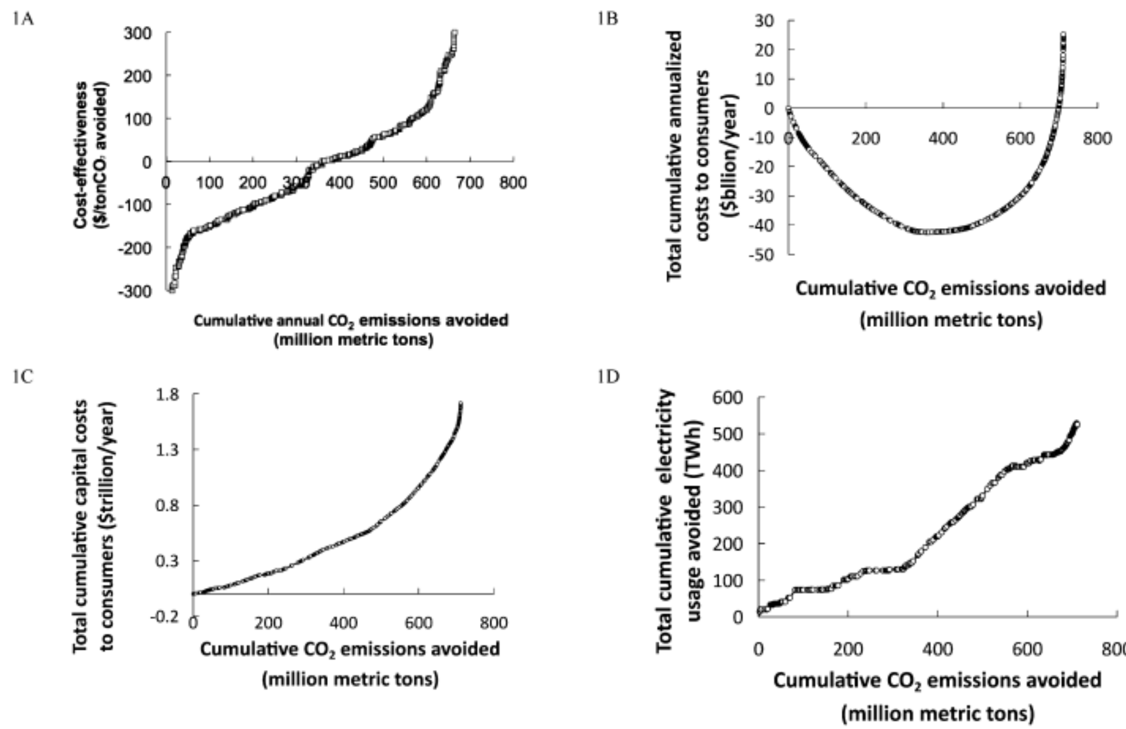
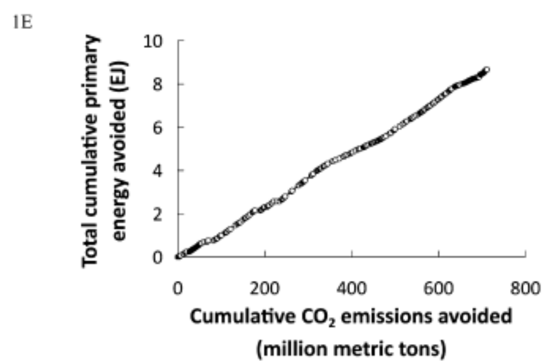
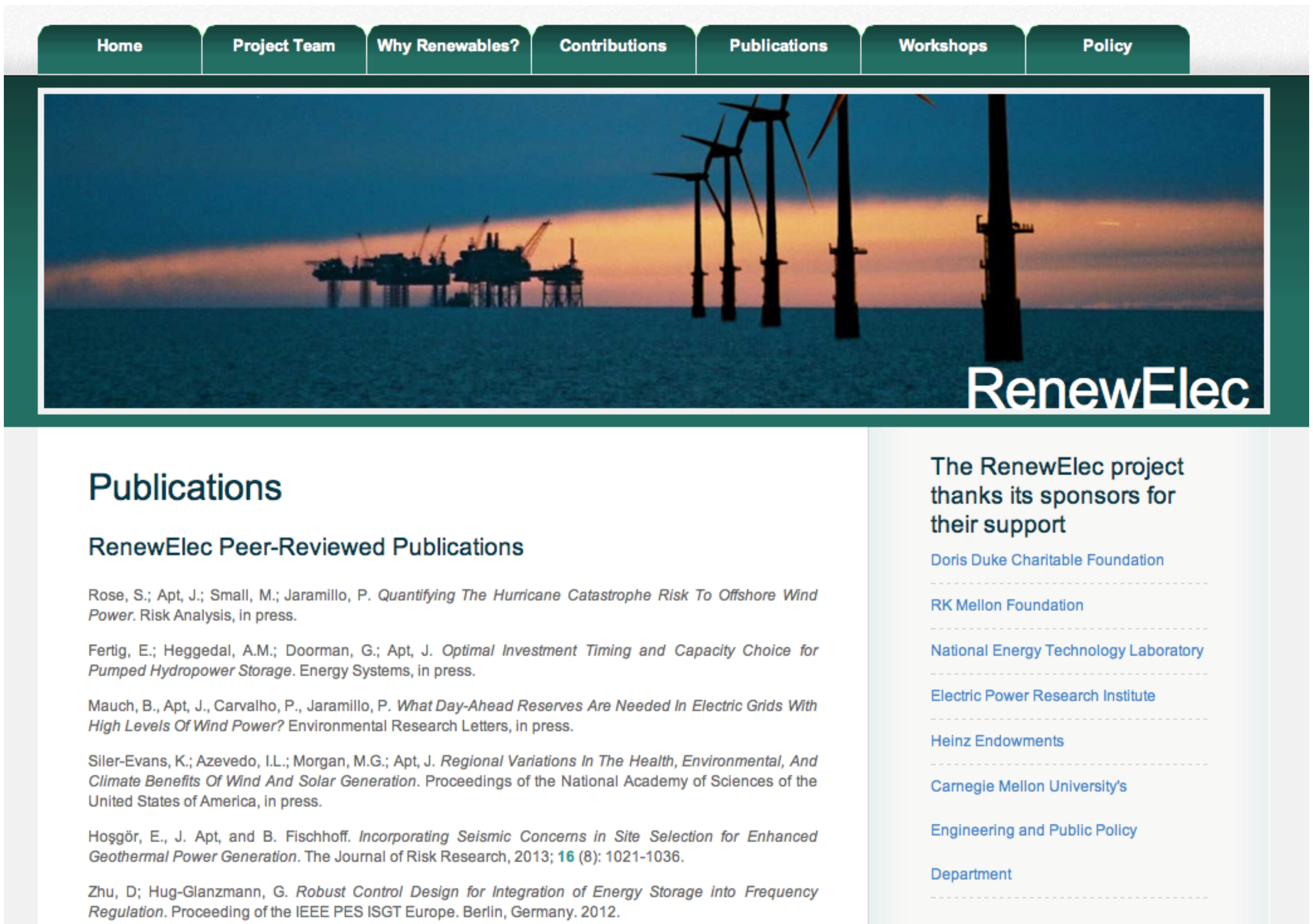




Source: Inês Lima Azevedo, M. Granger Morgan, Karen Palmer and Lester B. Lave, "Reducing U.S. Residential Energy Use and CO2 Emissions: How much, how soon, and at what cost?," *Environmental Science & Technology*, *47*, 2502-2511, 2013.

We’ve been doing lots of work on…

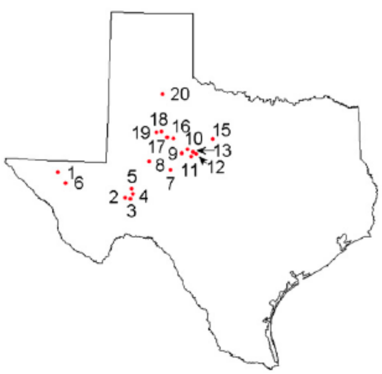
…understanding how to manage variable and intermittent renewables:



Can’t we smooth things out by connecting wind farms together?

The answer turns out to be "only a little."

Jay Apt and his students looked first at the wind farms in Texas (ERCOT).
Then to make sure the results were not specific to just that region they also looked at data (scaled to hub height) from airports all across the mid-west.



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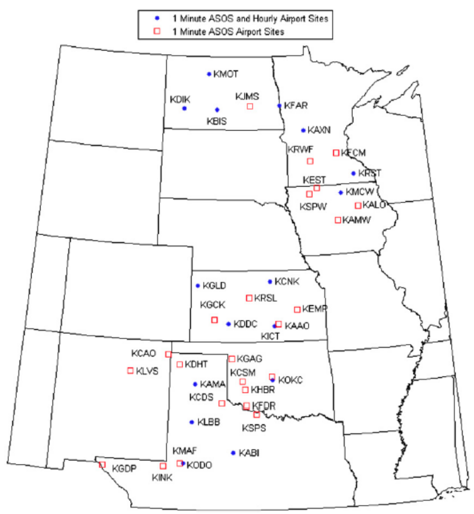

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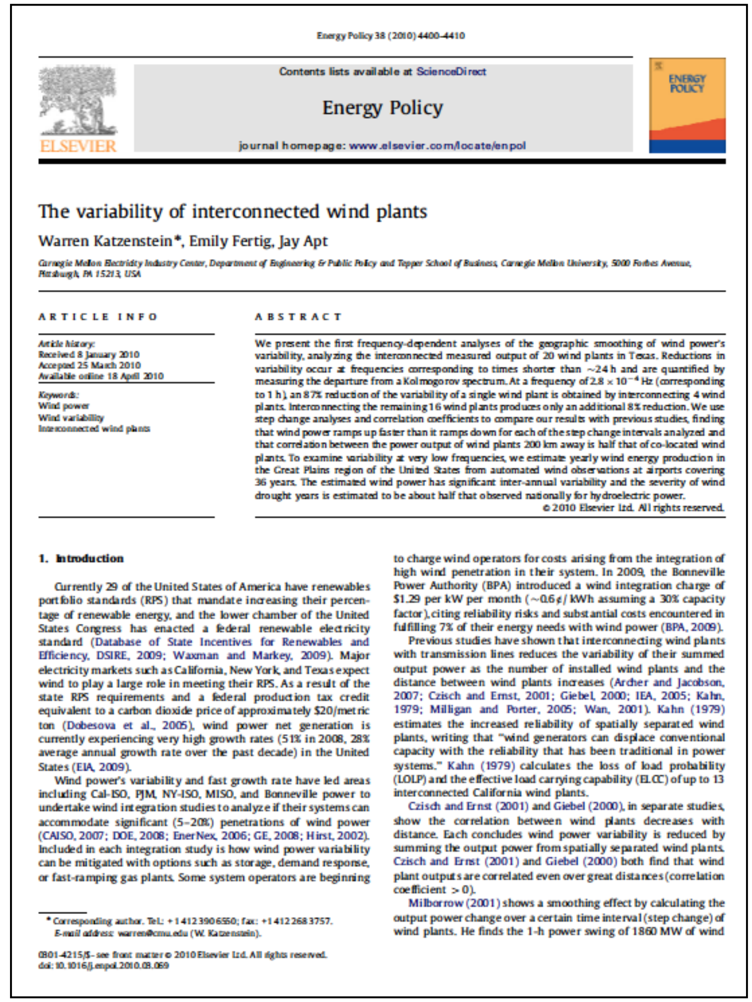

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The variability of interconnected wind plants

Warren Katzenstein*, Emily Fertig, Jay Apt

Carnegie Mellon Electricity Industry Center, Department of Engineering & Public Policy and Tepper School of Business, Carnegie Mellon University, 5000 Forbes Avenue, Pittsburgh, PA 15213, USA

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ABSTRACT

We present the first frequency-dependent analyses of the geographic smoothing of wind power's variability, analyzing the interconnected measured output of 20 wind plants in Texas. Reductions in variability occur at frequencies corresponding to times shorter than ~24 h and are quantified by measuring the departure from a Kolmogorov spectrum. At a frequency of 2.8×10^{-4} Hz (corresponding to 1 h), an 87% reduction of the variability of a single wind plant is obtained by interconnecting 4 wind plants. Interconnecting the remaining 16 wind plants produces only an additional 8% reduction. We use step change analyses and correlation coefficients to compare our results with previous studies, finding that wind power ramps up faster than it ramps down for each of the step change intervals analyzed and that correlation between the power output of wind plants 200 km away is half that of co-located wind plants. To examine variability at very low frequencies, we estimate yearly wind energy production in the Great Plains region of the United States from automated wind observations at airports covering 36 years. The estimated wind power has significant inter-annual variability and the severity of wind drought years is estimated to be about half that observed nationally for hydroelectric power.

1. Introduction

Currently 29 of the United States of America have renewables portfolio standards (RPS) that mandate increasing their percentage of renewable energy, and the lower chamber of the United States Congress has enacted a federal renewable electricity standard (Database of State Incentives for Renewables and Efficiency, DSIRE, 2009; Waxman and Markey, 2009). Major electricity markets such as California, New York, and Texas expect wind to play a large role in meeting their RPS. As a result of the state RPS requirements and a federal production tax credit equivalent to a carbon dioxide price of approximately $20/metric ton (Dobesova et al., 2005), wind power net generation is currently experiencing very high growth rates (51% in 2008, 28% average annual growth rate over the past decade) in the United States (EIA, 2009).

Wind power's variability and fast growth rate have led areas including Cal-ISO, PJM, NY-ISO, MISO, and Bonneville power to undertake wind integration studies to analyze if their systems can accommodate significant (5–20%) penetrations of wind power (CAISO, 2007; DOE, 2008; EnerNex, 2006; GE, 2008; Hirst, 2002). Included in each integration study is how wind power variability can be mitigated with options such as storage, demand response, or fast-ramping gas plants. Some system operators are beginning to charge wind operators for costs arising from the integration of high wind penetration in their system. In 2009, the Bonneville Power Authority (BPA) introduced a wind integration charge of $1.29 per kW per month (~0.6¢/kWh assuming a 30% capacity factor), citing reliability risks and substantial costs encountered in fulfilling 7% of their energy needs with wind power (BPA, 2009).

Previous studies have shown that interconnecting wind plants with transmission lines reduces the variability of their summed output power as the number of installed wind plants and the distance between wind plants increases (Archer and Jacobson, 2007; Czisch and Ernst, 2001; Giebel, 2000; IEA, 2005; Kahn, 1979; Milligan and Porter, 2005; Wan, 2001). Kahn (1979) estimates the increased reliability of spatially separated wind plants, writing that "wind generators can displace conventional capacity with the reliability that has been traditional in power systems." Kahn (1979) calculates the loss of load probability (LOLP) and the effective load carrying capability (ELCC) of up to 13 interconnected California wind plants.

Czisch and Ernst (2001) and Giebel (2000), in separate studies, show the correlation between wind plants decreases with distance. Each concludes wind power variability is reduced by summing the output power from spatially separated wind plants. Czisch and Ernst (2001) and Giebel (2000) both find that wind plant outputs are correlated even over great distances (correlation coefficient > 0).

Milborrow (2001) shows a smoothing effect by calculating the output power change over a certain time interval (step change) of wind plants. He finds the 1-h power swing of 1860 MW of wind

* Corresponding author. Tel.: +1 412 390 6550; fax: +1 412 268 3757.
E-mail address: warren@cmu.edu (W. Katzenstein).

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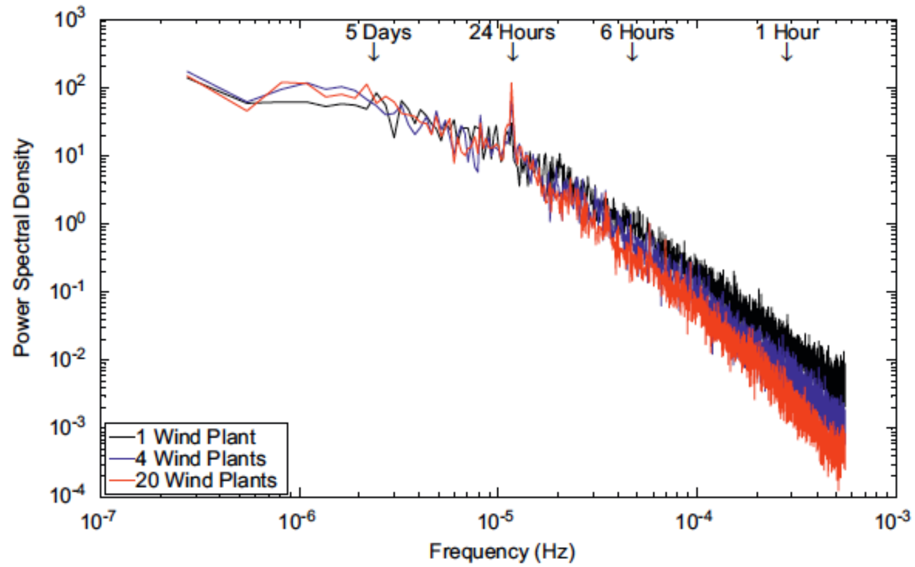
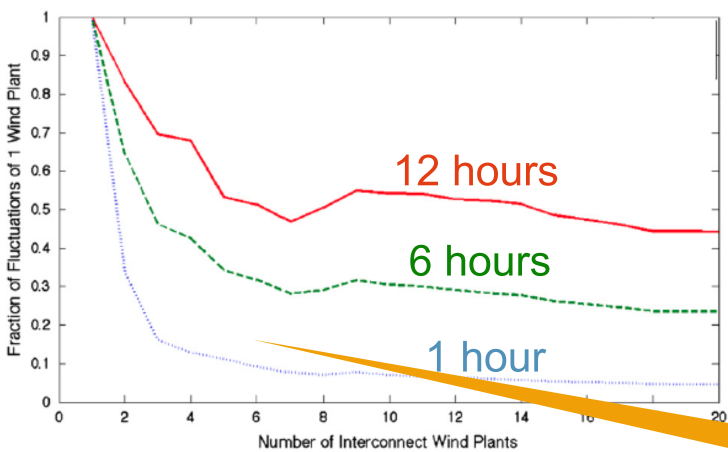
Texas results

The maximum reductions in variability occur at the higher frequencies and diminish as the frequencies decrease until at 24 hours there is no reduction in variability.

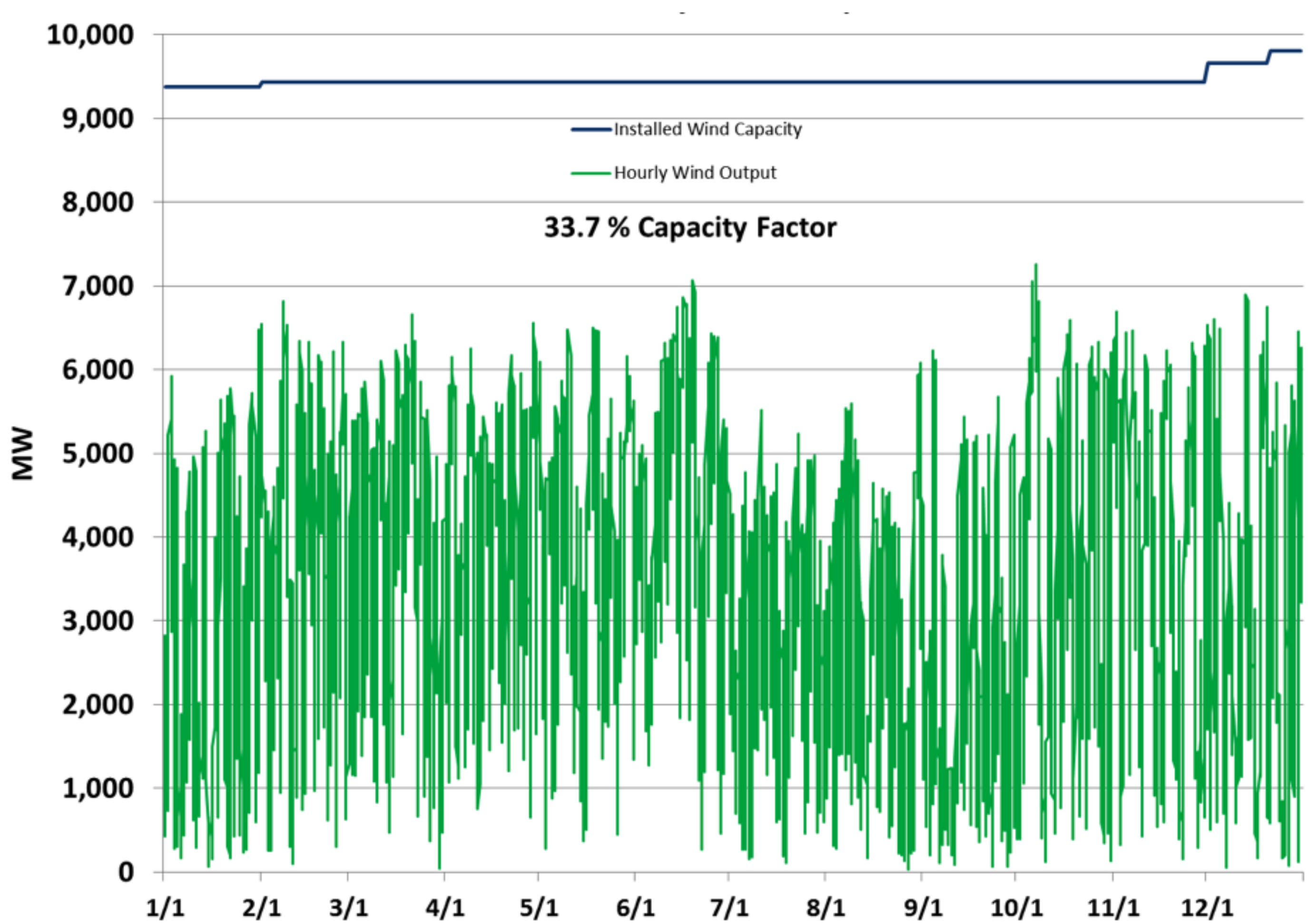




This figure shows that amount of reduction in variability achieved as a function of the number of interconnected wind farms for frequencies corresponding to 1, 6 and 12 hours.

Note that after the first few wind farms are interconnected there is little additional reduction in the fluctuations.

Hourly wind output for *all* of Texas for the year 2011



And, a reminder that because something is viewed as "green"…

…we should not assume its impacts are uniform.

Regional variations in the health, environmental, and climate benefits of wind and solar generation

Kyle Siler-Evans[a], Inês Lima Azevedo[a,1], M. Granger Morgan[a], and Jay Apt[a,b]

[a]Engineering and Public Policy and [b]Tepper School of Business, Carnegie Mellon University, Pittsburgh, PA 15213

Edited by Edward L. Miles, University of Washington, Seattle, WA, and approved May 15, 2013 (received for review December 19, 2012)

When wind or solar energy displace conventional generation, the reduction in emissions varies dramatically across the United States. Although the Southwest has the greatest solar resource, a solar panel in New Jersey displaces significantly more sulfur dioxide, nitrogen oxides, and particulate matter than a panel in Arizona, resulting in 15 times more health and environmental benefits. A wind turbine in West Virginia displaces twice as much carbon dioxide as the same turbine in California. Depending on location, we estimate that the combined health, environmental, and climate benefits from wind or solar range from $10/MWh to $100/MWh, and the sites with the highest energy output do not yield the greatest social benefits in many cases. We estimate that the social benefits from existing wind farms are roughly 60% higher than the cost of the Production Tax Credit, an important federal subsidy for wind energy. However, that same investment could achieve greater health, environmental, and climate benefits if it were differentiated by region.

externalities | renewable electricity | renewable energy policy | air pollution

Wind and solar power provide health, environmental, and climate benefits by displacing conventional generators and therefore reducing emissions of carbon dioxide (CO_2) and criteria air pollutants, which include sulfur dioxide (SO_2), nitrogen oxides (NO_x), and fine particulate matter ($PM_{2.5}$). It is natural to think that the windiest or sunniest sites will yield the best performance. However, the reduction in emissions resulting from wind or solar depends not only on the energy produced but also on the conventional generators displaced, and that varies dramatically depending on location.

Previous research has explored the emissions implications of renewable energy (1–7). The US Department of Energy estimates that achieving 20% wind penetration in the United States would reduce CO_2 emissions by 825 million metric tons by 2030 (1). Valenteno et al. (2) estimate the avoided emissions resulting from wind energy in Illinois, with a focus on the effects of additional cycling of conventional power plants. The study finds that 10% wind penetration would result in a 12% reduction in CO_2 emissions, 13% reduction in NO_x, 8% reduction in SO_2, and an 11% reduction in PM. Lu et al. (3) estimate that the CO_2 reductions resulting from 30% wind penetration in Texas would cost approximately $20 per ton avoided. Kaffine et al. (4) estimate the emissions savings from wind energy for three regions of the United States. The study concludes that "emissions reductions in the Upper Midwest roughly cover government subsidies for wind generation, [while] environmental benefits in Texas and California fall short."

These studies vary greatly in the methods and assumptions used, the regions and pollutants covered, and the metrics reported, all of which prevent meaningful comparisons among studies. This work provides a systematic assessment of wind and solar energy across the United States. We estimate the monetized social benefits resulting from emissions reductions, and we explicitly consider differences in energy production, climate benefits from displaced CO_2 emissions, and health and environmental benefits from displaced SO_2, NO_x, and $PM_{2.5}$. In addition, we compare the social benefits from existing wind farms with the cost of the Production Tax Credit, an important federal subsidy for wind energy.

Results

We evaluate a Vestas V90-3.0-MW wind turbine at more than 33,000 locations and a 1-kW photovoltaic (PV) solar panel at more than 900 locations across the United States. We assume that wind and solar displace the damages from marginal electricity production, which varies regionally and temporally. Damages from CO_2 emissions are monetized using a social cost of $20 per ton of CO_2. Location-specific damages from SO_2, NO_x, and $PM_{2.5}$ emissions are adopted from the Air Pollution Emission Experiments and Policy (APEEP) analysis model, which values mortality from air pollution at $6 million per life lost (often termed the value of a statistical life) (8). For more than 1,400 fossil-fueled power plants, dollar-per-ton damage values for each pollutant are combined with plant-level emissions data to estimate the health, environmental, and climate damages for each hour from 2009 through 2011. Finally, we use regressions of measured hourly emissions and generation data to estimate the reduction in damages that occurs when conventional generators are displaced by wind or solar. To account for regional differences, regressions are performed separately for the 22 subregions defined in the Emissions and Generation Resource Integrated Database (eGRID). eGRID subregions were created by the US Environmental Protection Agency (EPA) using Power Control Areas as a guide. Although not perfect, they provide an estimate for the group of plants serving loads within a region (9).

Results are presented in Fig. 1. For both wind (Fig. 1 *A*–*C*) and solar (Fig. 1 *D*–*F*), we consider three measures of performance: capacity factor, which is the ratio of the annual energy production to the maximum energy production at full-power operation (Fig. 1 *A* and *D*); annual avoided CO_2 emissions (Fig. 1 *B* and *E*); and annual health and environmental benefits from displaced SO_2, NO_x, and $PM_{2.5}$ emissions (Fig. 1 *C* and *F*). For consistency, we provide all results on a per-kilowatt-installed or per-megawatt-hour basis. All monetary values are in 2010 dollars.

Social Benefits of Wind Energy. From an energy standpoint, wind turbines perform best in the Great Plains south through west Texas, where capacity factors can exceed 40%. The wind resource is poor in much of the West and moderate in much of the East. It is also poor in the Southeast, which is excluded from our assessment owing to data limitations (Fig. S1).

We report two metrics for reductions in CO_2 emissions—kilograms of CO_2 avoided annually and the corresponding social benefits, assuming a social cost of $20 per ton of CO_2. Wind turbines are most effective at displacing CO_2 emissions when located in the Midwest, where the wind resource is excellent and

Author contributions: K.S.-E., I.L.A., M.G.M., and J.A. designed research; K.S.-E. performed research; and K.S.-E., I.L.A., M.G.M., and J.A. wrote the paper.

The authors declare no conflict of interest.

This article is a PNAS Direct Submission.

Data deposition: A spreadsheet of the full results reported in this paper for both wind and solar is available at http://cedmcenter.org/tools-for-cedm/marginal-emissions-factors-repository/.

[1]To whom correspondence should be addressed. E-mail: iazevedo@cmu.edu.

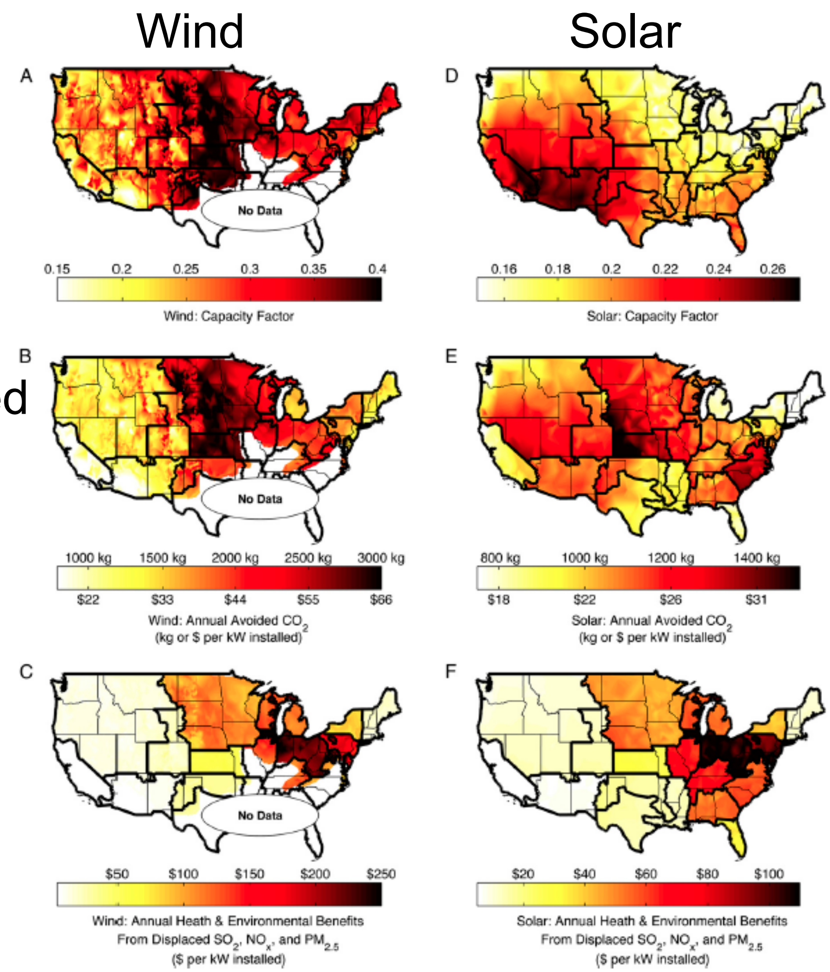
This article contains supporting information online at www.pnas.org/lookup/suppl/doi:10.1073/pnas.1221978110/-/DCSupplemental.

SUSTAINABILITY SCIENCE

Energy:

Displaced CO_2:

Health benefit:



Source: Kyle Siler Evans, Inês Lima Azevedo, M. Granger Morgan, Jay Apt, "Regional variations in the health, environmental and climate benefits of wind and solar generation," *PNAS,* 2013.

Finally, here is work on SMRs

Expert assessments of the cost of light water small modular reactors

Ahmed Abdulla[1], Inês Lima Azevedo, and M. Granger Morgan

Department of Engineering and Public Policy, Carnegie Mellon University, Pittsburgh, PA 15213

Edited by William C. Clark, Harvard University, Cambridge, MA, and approved April 26, 2013 (received for review January 9, 2013)

Analysts and decision makers frequently want estimates of the cost of technologies that have yet to be developed or deployed. Small modular reactors (SMRs), which could become part of a portfolio of carbon-free energy sources, are one such technology. Existing estimates of likely SMR costs rely on problematic top-down approaches or bottom-up assessments that are proprietary. When done properly, expert elicitations can complement these approaches. We developed detailed technical descriptions of two SMR designs and then conduced elicitation interviews in which we obtained probabilistic judgments from 16 experts who are involved in, or have access to, engineering-economic assessments of SMR projects. Here, we report estimates of the overnight cost and construction duration for five reactor-deployment scenarios that involve a large reactor and two light water SMRs. Consistent with the uncertainty introduced by past cost overruns and construction delays, median estimates of the cost of new large plants vary by more than a factor of 2.5. Expert judgments about likely SMR costs display an even wider range. Median estimates for a 45 megawatts-electric (MW_e) SMR range from \$4,000 to \$16,300/kW_e and from \$3,200 to \$7,100/kW_e for a 225-MW_e SMR. Sources of disagreement are highlighted, exposing the thought processes of experts involved with SMR design. There was consensus that SMRs could be built and brought online about 2 y faster than large reactors. Experts identify more affordable unit cost, factory fabrication, and shorter construction schedules as factors that may make light water SMRs economically viable.

nuclear power economics | technology assessment

Individuals, companies and other organizations, as well as governments, must make important decisions in the face of considerable uncertainty. Although we gather what evidence we can—as individuals, we choose where to go to college, who to marry, and whether to have children—we do this all in the face of at least some irreducible uncertainty. Similarly, companies choose to invest in major new technologies, and governments adopt tax and research and development policies, without knowing for certain all the consequences their decisions will have.

Our brains are not well-equipped to make decisions that involve considerable uncertainty. As extensive empirical research has now shown, we make such judgments using a variety of cognitive heuristics that, although they serve us adequately in many day-to-day settings, can result in overconfidence and bias that leads both lay people and experts astray when they address more complex and unusual problems (2, 3). Decision science (4–8) offers a set of strategies for improving how we make important decisions in the face of uncertainty.

In addressing such decisions, one should start with the best scientific, technical, and analytical evidence that is available. However, because such formal evidence often does not capture the full extent of what experts know, in addition to seeking informal expert advice, it is common in decision science to use formal methods to obtain systematic probabilistic judgments from experts who are intimately familiar with the current state of knowledge (9–11). For example, such methods have been used to characterize uncertainty about climate science (12, 13), the impacts of climate change (14–16), and the health impacts of environmental pollutants (17, 18). Of course, the same cognitive limitations that arise when we try to make unaided decisions also arise when experts attempt to provide probabilistic judgments (3). Too often, when seeking expert advice, little or nothing is done to limit overconfidence and reduce bias. Ubiquitous overconfidence (10) and the biases arising from cognitive heuristics, such as availability and anchoring and adjustment (2, 19–21), cannot be completely eliminated. However, well-designed expert elicitations can use a variety of strategies to help improve the quality of expert judgments (9–11).

Expert elicitation about emerging energy technologies that is deeply informed by careful technical analysis is still relatively rare (22). Here, we report the results of applying these methods to one such technology: integral light water small modular nuclear reactors (SMRs).

Why SMRs?

Morgan has argued that if aircraft were made and certified one at a time, in the way nuclear reactors have been built and certified in the U.S., "many travelers would find the level of safety unacceptable and air travel would be much more expensive…pilots and mechanics would have to be specially trained to operate each aircraft…many replacement parts would have to be custom made…[and] every time an aircraft experienced a problem engineers and managers would be unsure how to extrapolate the lessons to other aircraft…" (23). There is no way to mass produce gigawatt-scale reactors in the way that Boeing 747s and Airbus A380s are built. However, by adopting a smaller design, one that could be mass produced in a factory with high levels of quality control, and shipped to the field by road, rail, or barge, the nuclear industry might begin to look more like the aircraft industry. Because individual reactors would be smaller, the unit

Author contributions: A.A., I.L.A., and M.G.M. designed research; A.A., I.L.A., and M.G.M. performed research; A.A., I.L.A., and M.G.M. analyzed data; and A.A., I.L.A., and M.G.M. wrote the paper.

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[1]To whom correspondence should be addressed. E-mail: aya1@cmu.edu.

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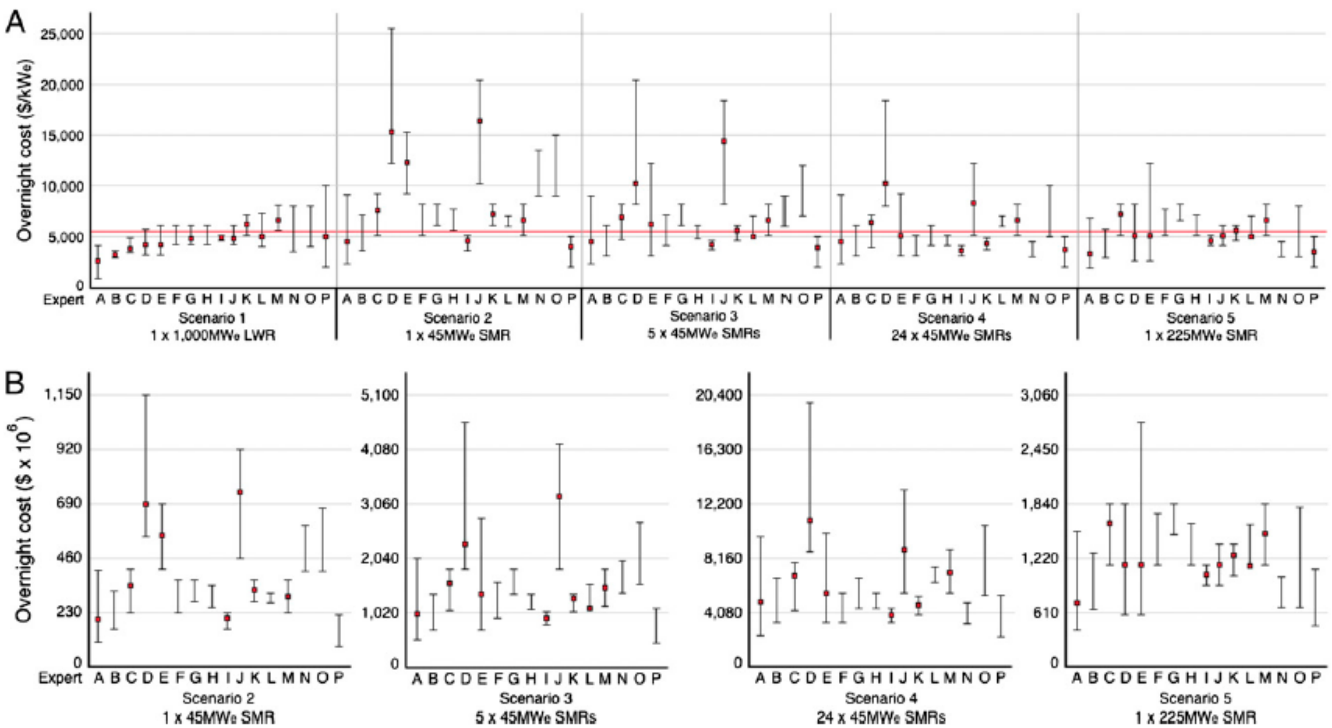


Back to 3 and 4

3. Choices by a nation as to whether and how much emissions abatement to undertake.
4. Choices by a nation as to whether or not to join an international agreement on emissions abatement.

As I have already argued, I do not believe that using B-C or similar methods to assess even the marginal value of the social cost of carbon makes sense.

However, if one framed things in game-theoretic terms (how much will others do, and in light of that, how much should I do), I guess I could imagine an analysis that used B-C ideas, although I am not persuaded it would be worth the time and effort that would be required.

Finally what about…

…including sea level rise in integrated assessment?

As some of you know, in the early 1990s, Hadi Dowlatabadi and I built the ICAM model that treated 2000 variables as uncertain and contained multiple switches that allowed us to explore the implications of alternative model functional forms. With an early version of ICAM…

> …[we found] that the choice of decision rule plays a key role in the selection of mitigation policies, that given a decision rule, uncertainty in key variables can make it difficult or impossible to differentiate between the outcome of alternative policies and that the model parameters that contribute the most uncertainty to outcomes depend on the choice of policy, the discount rate and the geographical region being considered.

Hadi Dowlatabadi and M. Granger Morgan, "A Model Framework for Integrated Studies of the Climate Problem", *Energy Policy*, *21*(3), 209-221, March 1993.

With ICAM 2 and 3, we found that…

- We could get an *enormous* variety of answers depending on the range of plausible assumptions we made about the structure of the model and which regional decision maker one considered.
- Rarely was any policy optimal for all regions.
- Rarely were any results stochastically dominant.

Our work has led us to believe that the first impressions gained from a 'global commoner' model may confuse more than they clarify. At the international level, at least a dozen different nations will make choices which could have significant climate implications. Many of those choices will not be made by single national decision-making authorities, but rather through the individual choices of millions of organizations and individual citizens, and they will be driven by local interests and conditions. This distributed decision making is one of the most fundamental characteristics of the climate problem.

M. Granger Morgan and Hadi Dowlatabadi, "Learning from Integrated Assessment of Climate Change," *Climatic Change*, *34*, 337-368, 1996.

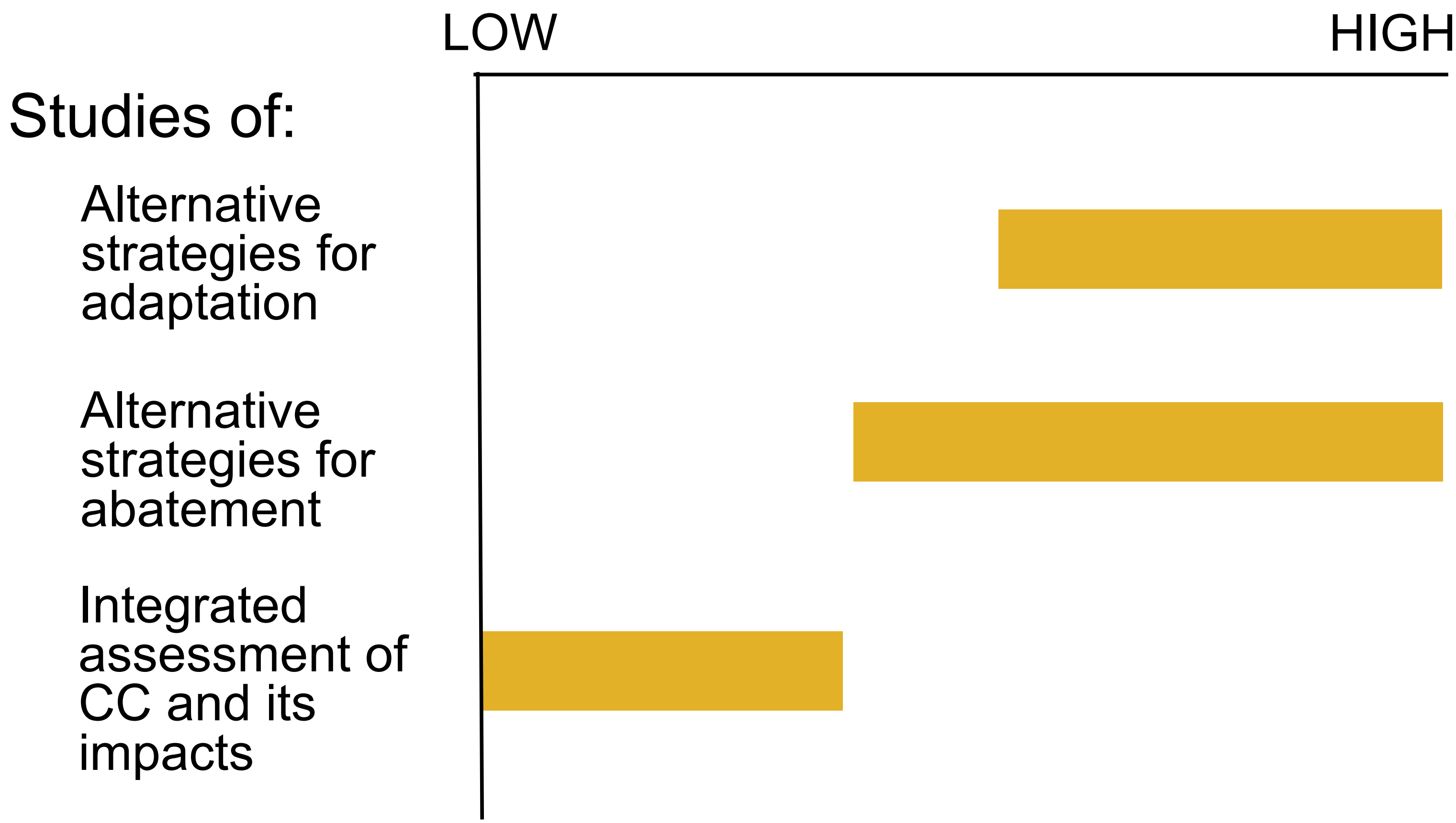
Doing IA was lots of fun…

…and intellectually very stimulating. We developed lots of insights which we wrote about in our papers - although it is not clear they had much impact.

However, because we found we could get a remarkably wide range of answers, because different regions often preferred different policies, and because over time we became increasingly persuaded that progress would occur via Model 2 (bottom up) rather than top down, with the resultant concentrations being an emergent property, not the result of explicit global policy design, we stopped and have moved on to work cost-effective abatement and adaptation.

For me, the key question is…

…who will do something different and consequential, in terms of either slowing climate change or moderating its consequences, as a result of the analyses we do?



End of my talk.

But…

I give the first opportunity to comment to Hadi Dowlatabadi.

The key thing…

…needed to implement this model is integrated assessment that determines the target.

GHG Management from the top down.

Perform an IA in order to determine the "optimal" level of abatement.

Throu international
otiations get a global
greement in place that
es that level.

de all major
s to "sign up" and
coordinated policies
to meet that level.

When Hadi looked at these slides he argued:

"Because this is a non-marginal change problem the IA will be wrong. The driver will be the economics of the system's change and its network effects. In my view, the change will be driven by those who profit, not those who suffer."

GHG Management
from the bottom up.

The key thing…

…needed to implement this model is emission abatement supply curves

sc

Different parts of the world get serious about reducing emission of GHGs at differ t times.

ach starts doing various

o reduce emissions.

e get serious,

onal negotiations

work to coordinate

eral abatement

regimes.

When Hadi looked at these slides he argued:

"I think that this will not be driven by the concerns of GHGs but by energy and economic security. Framing this as climate change will continue because we will have periodic reminders in extreme events, not because we are naïve enough to think that actions will reduce these severe events - if we believed that, retreat would be in place right now."

If and when we manage…

…to begin to get serious control of GHG emissions from major emitting countries, my money is on it happening according to Model 2 (i.e., bottom up).

At that point what will be most needed is clear evidence of what abatement strategies are most cost-effective.

When Hadi looked at these slides he argued:

"This is not something that will fall out of the scenario I described above."

It is for this reason tl center is called the C Decision Making and is primarily focused on finding ways to decarbonize the energy system.

For that we primarily need analysis of cost-effectiveness, not B-C analysis.

End

In developing the ideas discussed in this talk, I have been fortunate to have generous support from the National Science Foundation (SES-9209783; BCS-9218045; SES-034578; SES-0949710 and others), the Electric Power Research Institute, the Gordon and Betty Moore Foundation, the Doris Duke Charitable Foundation, the MacArthur Foundation, the IRGC, Carnegie Mellon University and a number of others. Thanks also to my many colleagues and students, who have worked with me in these projects.