The Annual Proceedings of

# The Wealth and Well-Being of Nations

2017-2018

## Volume X: Energy and the Wealth of Nations

Michael Greenstone

Warren Bruce Palmer, Editor

# The Miller Upton Program at Beloit College

The Wealth and Well-Being of Nations was established to honor Miller Upton, Beloit College's sixth president. This annual forum provides our students and the wider community the opportunity to engage with some of the leading intellectual figures of our time. The forum is complemented by a suite of programs that enhance student and faculty engagement in the ideas and institutions that lay at the foundation of free and prosperous societies.

## Senior Seminar on The Wealth and Well-Being of Nations:

Each year, seniors in the Department of Economics participate in a semester-long course that is built around the ideas and influence of that year's Upton Scholar. By the time the Upton Scholar arrives in October, students will have read several of his or her books and research by other scholars that has been influenced by these writings. This advanced preparation provides students the rare opportunity to engage with a leading intellectual figure on a substantive and scholarly level.

## Endowed Student Internship Awards:

A portion of the Miller Upton Memorial Endowments supports exceptional students pursuing high-impact internship experiences. Students are encouraged to pursue internships with for-profit firms and non-profit research organizations dedicated to advancing the wealth and well-being of nations.

## Student Research Colloquium and Speaker Series:

The department has initiated a research colloquium that gives students the opportunity to read and discuss seminal articles aimed at deepening their understanding of the market process. Students also develop original analysis that applies economic ideas to novel contexts. Colloquium participants receive close mentoring as they craft an article with the eventual goal of publication in a newspaper, magazine, or academic journal. The themes of the research colloquium and annual forum are supported with a speaker series featuring the next generation of scholars working on questions central to our understanding of the nature and causes of wealth and well-being.

## Annual Proceedings of The Wealth and Well-Being of Nations:

The keynote address presented by the Upton Scholar is an important contribution to the public discourse on the nature and causes of wealth and well-being. Further, the annual forum includes presentations by noted scholars who expand upon or challenge the work of the Upton Scholar. These presentations are assembled in the *Annual Proceedings of the Wealth and Well-Being of Nations*, which serves as an important intellectual resource for students, alumni, and leaders within higher education.

# The Annual Proceedings of the Wealth and Well-Being of Nations

## 2017-2018

### Volume X

Warren Bruce Palmer
Editor

Jennifer Kodl
Managing Editor

The Annual Proceedings of the Wealth and Well-Being of Nations, 2017-2018.



Printed in the United States of America

ISBN: 978-0-578-20660-8

# Contents

# Contributors

**Warren Bruce Palmer** is the Elbert H. Neese, Jr. Professor of Economics, Beloit College.

**Michael Greenstone, the 2017 Miller Upton Scholar**, is the Milton Friedman Professor in Economics, the College, and the Harris School, as well as the Director of the Becker Friedman Institute and the interdisciplinary Energy Policy Institute at the University of Chicago. He previously served as the Chief Economist for President Obama's Council of Economic Advisers, where he co-led the development of the United States Government's social cost of carbon, and on the Secretary of Energy's Advisory Board.

**Andrew Revkin**, who has written on climate change and sustainability for more than 30 years, is the Strategic Adviser for Environmental and Science Journalism at the National Geographic Society and author of four books on climate and environmental sustainability.

**Eric D. Isaacs** is President of the Carnegie Institution for Science.

**Anukriti Hittle** is Policy Research Specialist, Social Sciences Research Institute, University of Hawaii and former East-West Center Visiting Scholar.

**Rema Hanna** is the Jeffrey Cheah Professor of South-East Asia Studies at the Harvard Kennedy School and Co-Director of the Evidence for Policy Design (EPoD) research program at the Center for International Development, Harvard University.

**B. Kelsey Jack** is James L. Paddock Assistant Professor of Economics, Tufts University.

**Jermaine Moulton** is Assistant Professor, Department of Economics, Beloit College.

# Introduction

**Warren Bruce Palmer**[1]

For the fourth and final time, I have the pleasure to introduce the *Annual Proceedings of the Wealth and Well-Being of Nations,* a selection of papers presented at the 2017 Miller Upton Forum.

Held each fall, the Miller Upton Forum, a multi-component event, features one of the world's most influential thinkers on the ideas and institutions necessary for advancing the freedom, wealth, and well-being of the nations and peoples of the world. Each year's Miller Upton Scholar is joined on campus by a group of other thinkers and practitioners who engage us in a week of enlightening classroom discussions, panel discussions, and one-on-one conversations, capped off by the Miller Upton Scholar's keynote address -- The June B. Martin'40 and Edgar W. Martin Memorial Lecture. Each fall the Economics Senior Seminar, required of all majors in the Department of Economics, is built around the theme of that year's Forum. The seminar students intensively study the work of the Miller Upton Scholar and are well-prepared to engage with the Scholar and other speakers during the week of the Forum.

The Miller Upton Programs and the Miller Upton Forum are named in honor of Miller Upton, the sixth President of Beloit College, and are inspired by Miller's unflagging dedication to the ideals of a liberal society: political freedom, the rule of law, and peace and prosperity through the voluntary exchange of goods and ideas.

As the Elbert H. Neese, Jr. Professor of Economics, it has been my pleasant duty for four years to design and organize the Miller Upton Forum and to teach the Senior Seminar. For my final Miller Upton Forum, I chose a theme that has been central to my own intellectual career: "Energy and the Wealth of Nations".

At the 2016 Miller Upton Forum, Deirdre McCloskey, the 9th Miller Upton Scholar, discussed what she calls the Great Enrichment -- that burst of unprecedented development in the last 200 years that has allowed so many to escape from

1 Warren Bruce Palmer is the Elbert H. Neese, Jr. Professor of Economics, Beloit College.

lives of terrible poverty and ignorance. As Professor McCloskey said, we should wish and work for the continued advance of the Great Enrichment to include everyone in the world.

The commercial production and application of energy has been a crucial component of the Great Enrichment. I like to tell my students that “Energy Makes Giants of Us All” and illustrate the point with pictures of cars, planes, thermostats, refrigerators and laptop computers. The average person in the U.S. lives a life inconceivable just a short time ago, and it is modern, commercial energy that powers such lives and transforms our personal environments.

However, the claim that “Energy Makes Giants of Us All” is not yet true for large swathes of humanity. More than one billion people lack access to reliable electricity, and more than 3 billion people still cook with biomass stoves that create terrible air pollution in their homes. What the poor of the world need is inexpensive, reliable commercial energy to cook their meals, to light and heat their homes and schools, to power their villages and towns, to energize their businesses and to give them all the benefits of commercial energy that people in developed nations take for granted. Moreover, the claim that “Energy Makes Giants of Us All” must be tempered by recognizing the high costs imposed by the Great Enrichment’s reliance on fossil fuels. While the world needs to extend energy services to developing nations, the world also needs less pollution and less $CO_2$ from burning fossil fuels.

Ending poverty, reducing pollution and limiting climate change are three of the greatest challenges facing humanity today and all three are intimately connected to our production and use of modern commercial energy.

To address this triple challenge, at the suggestion of Robert N. Stavins, the 2014 Miller Upton Scholar, we recruited Michael Greenstone, one of the world's most innovative environmental economists, to serve as the 2017 Miller Upton Scholar.

## *Michael Greenstone, Tenth Miller Upton Scholar*

We were delighted that Professor Greenstone could accept our offer as he is a most sought after public speaker with a full agenda as a researcher and director of multiple programs. He is the Milton Friedman Professor in Economics, the College, and the Harris School, University of Chicago. He is the Director of the Becker Friedman Institute for Research in Economics, University of Chicago, one of the world's premier economic think tanks whose slogan is "frontier research, global impact" and whose goal is to improve the world through evidence-based research with real-world impact.[2] He is the Director of The Energy Policy Institute at the University of Chicago (EPIC), whose goal is to research solutions to the global energy challenge that was the topic of this year's Miller Upton Forum. He is also the Director of the Energy & Environment Lab at the University of Chicago Urban Labs that "partners with civic and community leaders to identify, rigorously evaluate, and help scale programs and policies that reduce pollution, conserve limited natural resources, and improve environmental outcomes, while ensuring access to reliable and affordable energy."[3] Previously, Prof. Greenstone served as the Chief Economist for President Obama's Council of Economic Advisers, and was the 3M Professor of Environmental Economics at MIT.

Professor Greenstone's research is having a profound impact on people's lives around the world. His research in China on life expectancy and particulate pollution[4] has influenced China's recent efforts to rapidly reduce pollution.[5] In India, his varied research addresses the impact of climate change on mortality, economic incentives to improve environmental regulation, the impact of redesigned cookstoves and of improved toilets. In the U.S. he co-led the Federal government program to estimate the social cost of carbon and has researched energy efficiency programs, the impact of air pollution on economic outcomes and the economic impact of climate change.

During his three-day residency at Beloit College as the Miller Upton Scholar, Prof. Greenstone was very busy: he delivered a Faculty Forum presentation on the social cost of carbon, one of his key efforts on the Council of Economic Advisers; spoke to five Beloit College classes; participated in three dinner meetings with faculty, staff and students; participated in two panel discussions and then delivered the June B. Martin'40 and Edgar W. Martin Memorial Lecture.

In his talk and in his paper in this volume, Prof. Greenstone addresses what

2 https://bfi.uchicago.edu/sites/default/files/file_uploads/UCH-004_BFI_Brochure_v05.7_Spreads_web.pdf

3 https://urbanlabs.uchicago.edu/labs/energy-environment

4 For latest published version of this research, see Ebenstein, Avraham, Maoyong Fan, Michael Greenstone, Guojun He and Maigeng Zhou. 2017. "New evidence on the impact of sustained exposure to air pollution on life expectancy from China's Huai River Policy" *Proceedings of the National Academy of Sciences*, Sep 2017.

5 "Four Years After Declaring War on Pollution, China Is Winning" Michael Greenstone, *New York Times*, March 12, 2018

he calls the global energy challenge which "requires finding a balance between preventing disruptive climate change, managing the pollution and health problems associated with energy consumption, while also increasing access to the inexpensive and reliable energy that is so critical for growth." He then discussed seven facts that explain why it is so difficult to solve the global energy challenge, reviewing his research and the research of others on these topics. He concluded by discussing ways to solve the global energy challenge, with the first step being embedding both air pollution and carbon damages in energy prices.

In addition to Prof. Greenstone's paper, this volume includes papers by five other speakers who participated in two panel discussions: "Scaling Low-Carbon Energy for the Developing and Developed World" on Thursday, 10/26/2017 and "Energy and the Wealth of Nations" on Friday, 10/27/2017. Also included in this volume is a paper by Beloit College Professor Jermaine Moulton delivered to the Senior Seminar.

Andrew Revkin, one of the nation's top environmental journalists, spoke in both panel discussions, and his paper in the Proceedings draws on both of his talks. Revkin's blog entry on Bill Gates' Clean Energy Innovation Agenda[6] inspired the selection of the topic for this year's Miller Upton Forum. Revkin recently became strategic adviser for environmental and science journalism at the National Geographic Society. Previously he was the senior reporter for climate and related issues at ProPublica, which he joined after 21 years of writing for *The New York Times*, most recently through his Dot Earth blog for the Opinion section, and six years teaching at Pace University. Revkin has won most of the top awards in science journalism, along with a Guggenheim Fellowship. In his paper, "Innovation on Three Fronts in Pursuit of Energy and Climate Progress," Revkin notes the need for technological innovations in energy generation and utilization – what Bill Gates called "energy miracles" in his original TED Talk[7] that prompted Revkin's blog entry -- and the need for policy innovations that encourage the development and adoption of new technologies and use of existing technologies in ways that meet the global energy challenge. To achieve these two forms of innovation, Revkin argues that we need a third type of innovation: innovation in his area of expertise, communi-

6 https://dotearth.blogs.nytimes.com/2016/02/23/bill-gates-the-impatient-optimist-lays-out-his-clean-energy-innovation-agenda

7 https://www.ted.com/talks/bill_gates/transcript

cation environments, with which we discuss the global energy challenge and that "tolerate common but differentiated approaches to progress."

Eric D. Isaacs'79, the Executive Vice President for Research, Innovation and National Laboratories and the Robert A. Millikan Distinguished Service Professor in Physics at the University of Chicago, reluctantly accepts the term "energy miracle" in his paper "Scaling Low-Carbon Energy for the Developing and Developed World." Isaacs, director of the United States Department of Energy's Argonne National Laboratory, 2009-2014, knows well the amount of hard, scientific work that "energy miracles" require, and his paper celebrates some of the energy innovations since he graduated from Beloit College in 1979. For example, he notes that the capacity of the world's largest wind turbine today is 3,500 times that of the most advanced wind turbine in 1979 and that installed capacity of wind turbines in the U.S. is expanding rapidly. His paper describes similar advances in solar power technologies. These intermittent, renewable energy sources need low-cost storage technologies in order to replace fossil fuels, and his paper summarizes recent advances in "revolutionary new battery technologies." These low carbon energy technologies are expanding around the world, promoting electrification particularly in developing nations. The recent widespread adoption of these technologies helped flatten the growth in $CO_2$ emissions even as world GDP grew, Issacs says. However, much more innovation is needed to shift the world to a future of abundant, low-carbon energy. Isaacs argues that what is needed is an integrated, multidisciplinary approach to innovation to shorten the innovation pipeline. Such rapid innovation requires scientists, engineers, economists, and policymakers working collaboratively to develop and deploy low or no-carbon energy systems at the scale needed to head off the worst of climate change.

In her article, "The Promise of Paris and Lessons from Paradise: Hawaii's Contributions to US Pledges under the Paris Agreement," Anukriti Hittle'86 examines lessons that Hawaii can teach about the transition to clean energy. Hittle, Policy Research Specialist, Social Sciences Research Institute, University of Hawaii and former East-West Center Visiting Scholar, summarizes Hawaii's current dependence on petroleum and its ambitious efforts to reduce this dependence with the most aggressive goals for reducing $CO_2$ emissions of any U.S. state. Hittle argues that sub-national commitments to climate change mitigation are as important as national commitments, particularly when changes in national leadership weaken a nation's previous commitments. Hawaii is making striking progress, shifting electricity generation from petroleum to renewable energy, setting a legal deadline of a 100% renewable energy system, while progress on shifting ground and air transport to renewables has been much slower. Nevertheless, Hawaii, part of the 15 state Climate Alliance created to maintain the Paris Agreement, is more than doing its part to achieve U.S. pledges in the agreement. Hittle concludes by calling on other member states to compete with Hawaii to ratchet up their ambition to de-carbonize their energy systems.

Rema Hanna, the Jeffrey Cheah Professor of South-East Asia Studies at the Harvard Kennedy School, discusses the importance of studying environmental economics in developing nations in her article, "Environmental Economics, Developing Nations and Michael Greenstone." Her paper describes the key role that Michael Greenstone played in her graduate studies and the key role he has played in focusing attention on environmental economics in developing nations. Her paper summarizes five reasons why such attention is important: pollution levels are much higher in developing nations than in developed ones; the non-linear effects of pollution mean that the health impacts of this higher pollution are even greater in developing nations; populations in developing nations likely know less about the extent of pollution; people in developing nations lack the resources to adapt to pollution; finally, people in developing nations also must deal with an additional source of pollution from the biomass stoves in their homes. Hanna then presents a case study of cook stoves in India, explaining the importance of large-scale, long-term studies to determine what policies are effective in achieving environmental improvements in developing nations.

B. Kelsey Jack, the James L. Paddock Assistant Professor of Economics, Tufts University, also has co-authored papers with Michael Greenstone. In her paper, she discusses the challenges that developing nations face in adapting to and mitigating climate change. She also makes the case why such challenges are different for developing nations than for developed nations: climate change impedes economic development; poorer nations have fewer resources to adapt to climate change; and, poor nations getting richer will typically increase $CO_2$ emissions and thus cause more climate change. Her paper summarizes recent research that explores the unique challenges climate change presents to developing nations. For example, mortality in developing nations rises much more in response to rising temperatures than does mortality in developed nations because developed nations intensively use air conditioning. People in developing nations quickly begin buying air conditioners when their incomes rise, but increased use of air conditioners leads to demand for more electricity, much of which has been generated from fossil fuels. Jack says that these challenges require the development of new strategies that decrease negative feedbacks to resolve the conflict between adaptation and mitigation that developing nations currently face.

Jermaine Moulton, Assistant Professor of Economics, Beloit College, presented his paper contained in this volume to the students of the Senior Seminar in Economics. In his paper, "Revisiting Shadow Prices and Environmental Efficiency of $SO_2$ and $NO_x$ Emissions by Coal-Burning Power Plants," Moulton examines the cost of reducing $SO_2$ and $NO_x$ to target levels. He estimates the average shadow prices – the pollution cost from an additional unit of pollution -- and compares these prices to actual tradeable permit market prices for 131 power plants with data from 2001-2012. His results show technical progress by firms in efficiently reducing emissions of both pollutants.

## *Acknowledgements and Thanks*

On behalf of the Department of Economics and Beloit College let me reiterate my thanks to Jennifer Kodl, Program Coordinator of the Miller Upton Programs and Managing Editor of this volume. Jennifer Kodl has been the logistical master-mind that has made the Miller Upton Forum an outstanding success for the past ten years.

The Miller Upton Forum also could not achieve its current level of success without the stellar leadership of Bob Elder, Chair of the Department of Economics, Beloit College and without the active support of each member of the Department of Economics: Diep Phan, Shatanjaya Dasgupta, Laura Grube, Jermaine Moulton, and Darlington Sabasi. Brian Morello, Director of the Center for Entrepreneurship in Liberal Education at Beloit (CELEB), also played a key role during Upton Week. Let me also thank the members of this year's Economics Senior Seminar who eagerly embraced the opportunity to study the works of Michael Greenstone and who so ably represented Beloit College in their interactions with all participants in this year's Forum. Finally, continued thanks are due to the many alumni, friends, and charitable foundations who have supported the Miller Upton Programs. Their initial support launched the Upton Programs, and their continued support enables the Department of

Economics to invite to campus the world's top scholars and practitioners who are committed to understanding and promoting the sources of the wealth and well-being of nations.

Finally, let me conclude my leadership of the Miller Upton Forum by thanking Rona Finman, who has been a constant source of support.

# The Global Energy Challenge: Will We Ever Stop Using Fossil Fuels

**Michael Greenstone**[1]

Thank you for inviting me to give the keynote talk on Energy and the Wealth and Well-Being of Nations at this year's Miller Upton Forum. We all instinctively know that there are important connections between modern economic growth and energy, and tonight I will explore some of those connections.

Consider the picture below. It illustrates what I like to call the global energy challenge, which may also be given the intentionally provocative subtitle, "Will we ever stop using fossil fuels?" (Covert, Greenstone, Knittel, 2016)

Figure 1 is a scene in Beijing. It's the middle of the day. Our friend on the bike is moving quickly. The cars are moving quickly, and the picture depicts the three legs of the stool of the global energy challenge.

Figure 1 *(Photo Credit: How Hwee Young /Epa/REX/Shutterstock)*

The photo is full of the motion and action that is going on in Beijing and in China. Every visitor to China in the last couple decades has seen that China is

1 Michael Greenstone, the 2017 Miller Upton Scholar, is the Milton Friedman Professor in Economics, the College, and the Harris School, as well as the Director of the Becker Friedman Institute and the interdisciplinary Energy Policy Institute at the University of Chicago. He previously served as the Chief Economist for President Obama's Council of Economic Advisers, where he co-led the development of the United States Government's social cost of carbon, and on the Secretary of Energy's Advisory Board.

definitely a country on the move. Its vitality appears in its ultra-modern airports as soon as you get off the plane and at street-level, as in the picture here, with its newly built streets and highways now filled with cars and trucks. Even as recently as the early 1990s, China's city streets were primarily filled with bicycles. What has happened in China in the last 25 years or so -- all of that recent economic growth -- has to be one of the greatest achievements in human history, bringing literally hundreds of millions of people out of absolute poverty. This growth would have been impossible without access to inexpensive and reliable energy -- the first leg of the stool that I call the global energy challenge: how can we ensure that people around the world have access to the reliable, affordable energy needed for economic growth and human development without putting the environment, climate or security at risk?

The second leg of the global energy challenge is also immediately apparent in the picture: it is the middle of the day in Beijing, but the sun cannot be seen because of air pollution. The same energy powering all this economic growth is largely coming from fossil fuels that are producing all the pollution that is hiding the sun. It is no secret that air pollution is bad in Beijing. Our bike rider is very aware of it: he is wearing a mask, goggles, and gloves. The second leg of the energy challenge is reducing the pollution associated with energy production and consumption. People around the world dislike air pollution not just because it reduces visibility, but also because it imposes great health costs on them.

The third leg of the global energy challenge is not visible in the picture, the growing levels of $CO_2$, but it is there and it is also caused by the same fossil fuels powering economic growth and causing the visible air pollution. The invisible, growing levels of $CO_2$ increase the probability of disruptive climate change.

These three facets of the global energy challenge make it crucially important for study. Solving the global energy challenge requires finding a balance between preventing disruptive climate change, managing the pollution and health problems associated with energy consumption, while also increasing access to the inexpensive and reliable energy that is so critical for growth. It is not hard to think of solutions or policies that solve one or two of these problems. It is very difficult to think of policies that solve all three problems at once. Inevitably, solving the global energy challenge involves trade-offs based on people's income levels, on their morals and on their social customs. And it is in that grey space of tradeoffs where I think much of the world's most interesting problems live.

## *Seven Facts that Explain the Difficult Balance between Energy and Growth*

Seven facts explain or illustrate the global energy challenge and the difficult balance between energy and growth.

### *Fact 1: Energy is critical for modern economic growth.*

Anyone who works with data knows that data are often incredibly disappointing. Too often data poorly matches the questions we want to ask. However, data do not disappoint our efforts to understand the connections between modern economic growth and energy. There is a very clear relationship -- we really do not have instances of economies achieving high levels of living standards without high levels of energy consumption. That is a key fact of the global energy challenge.

### *Fact 2: Energy access is a major problem.*

Figure 2 illustrates the second key fact of the global energy challenge: energy access is a major problem; per capita energy consumption in developing economies remains significantly lower than developed world levels. Actually, this is one of these cases where when you start to look at the numbers, it is a little hard to stop thinking about the numbers. Consider that Canadians consume about 15,500 kilowatt hours of electricity per person per year. In the United States, annual per capita electricity consumption is about 13,000 kwh. Now examine the world's two most populous countries. Annual per capita electricity consumption in China is about a quarter of the U.S. level. In India, annual per capita electricity consumption is much lower, less than 10 percent of the U.S. level. Even within India, large disparities exist. The last row of this table depicts the Indian state of Bihar where I do a lot of research. Bihar's population is now probably 120 million people, almost one-third of US population. Bihar's per capita energy consumption is 122 kilowatt hours per year, less than 1 percent of the U.S. level; not even enough to light a single 60-watt light bulb for six hours per day. Residents of Bihar are not satisfied with this low level of electricity consumption. They want the life-improving amenities made possible by higher levels of electricity consumption and economic growth. Bihar's per capita electricity consumption must grow

100-fold to reach the US level. According to the International Energy Agency (IEA 2017), globally nearly 1.1 billion people lack access to reliable electricity – 239 million in India alone. To raise living standards around the world requires large increases in energy consumption.

Figure 2: Per Capita Electricity Consumption and Population

| Country | Population (Millions) | kWh per Capita |
| --- | --- | --- |
| Canada | 36 | 15,542 |
| U.S. | 321 | 12,985 |
| China | 1,364 | 3,762 |
| Mexico | 125 | 2,057 |
| India | 1,295 | 765 |
| Bihar | 104 | 122 |

*(Source: World Bank https://data.worldbank.org/indicator/eg.use.elec.kh.pc)*

## *Fact 3: Energy demand will grow rapidly in developing countries.*

The third fact of the global energy challenge is not surprising: energy demand is projected to grow rapidly in developing countries, much less so in developed countries. Total energy consumption per capita has basically been flat in the United States and Canada for about 40 years. Per capita energy consumption in China was flat for a long time under the planned economy and then, following the start of economic reforms, per capita energy consumption began to grow as economic growth took off. India's per capita energy consumption will accelerate as India's economic growth catches up with China's. What are the standard projections for the next several decades? There will be basically no growth in energy consumption in the developed countries, the OECD countries, and really quite strong and robust growth, almost a doubling, between now and 2035 in developing countries. Hundreds of millions more people will move into the middle class in China, India and other developing nations between now and 2035 with profound implications for energy demand. Global energy demand is set to grow by one-third between now and 2035. Fully 100 percent of expected growth will occur in emerging market economies, especially in Asia. China and India are expected to account for more than half of the growth in global energy demand between today and 2035.

That is fine: energy is critical for growth, and any basic sense of fairness and concern for the welfare of the world's poorer citizens says that everyone should aspire to the improved living standards enjoyed by the developed world. What will be the source that will meet the world's rising demand for inexpensive, reliable energy?

## *Fact 4: Fossil fuels are expected to meet much of the growth in energy demand.*

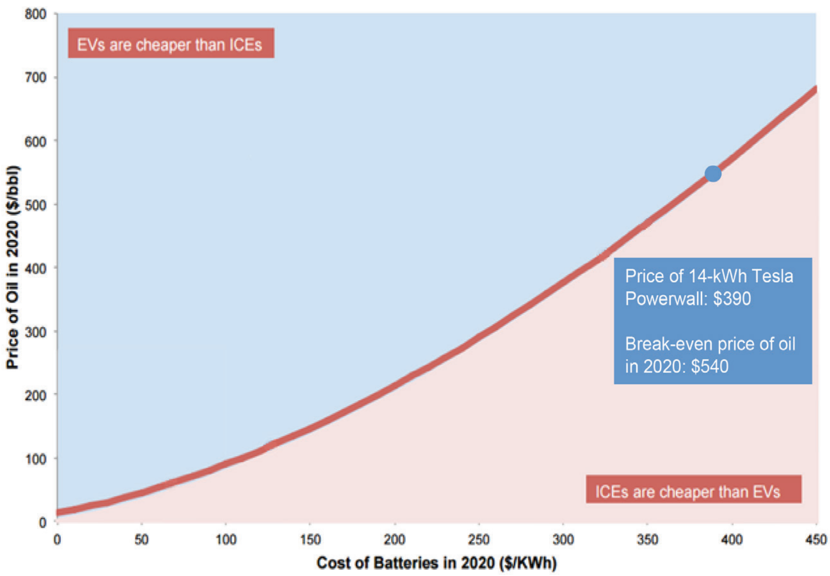
All of the standard models, all of the standard projections, predict that much of the world's rising demand for energy will come from fossil fuels. This is a striking prediction given optimistic news articles about changes in the energy system. Much is written about the high growth rates of installed wind and solar capacity and the rapid growth in wind and solar energy, but standard models based on available data do not support such optimism. Based on policies in place and committed at the end of 2016, the International Energy Agency expects fossil fuels to supply 74 percent of world primary energy in 2040, compared to 81 percent in 2014. While renewables are the fastest growing resource, coal, oil and natural gas together will still account for more than half of all growth in energy supply through 2040.

Why is that? Although burning fossil fuels has negative, unintended, undesirable consequences of air pollution and increased $CO_2$, fossil fuels are, nevertheless, quite remarkable inventions and are quite capable of producing energy at very low out-of-pocket cost. Conventional fossil fuels and technologies are the most cost-effective sources of energy today and continue to attract significant investment as a result. An existing coal plant in the U.S. can probably produce a kilowatt hour of electricity for about three cents. Production at a new natural gas plant in the U.S., with the recent decreases in natural gas prices probably costs

5.5 cents. A new coal plant with all the environmental controls required in the U.S. would probably produce at 8 cents. The cost of low carbon or low pollution sources, such as nuclear or renewables, is maybe two or three times as much. It is not accidental that fossil fuels are projected to be the primary energy source given currently constructed energy markets, whose economics push people to choose a fossil fuel.

The low cost of fossil fuels is true both in the power sector and also true in the transportation sector, despite all of the excitement over electric cars and trucks (EVs). Consider Figure 3 which compares the cost of vehicles with internal combustion engines (ICEs) powered by liquid fuels, such as gasoline and diesel, to the cost of electric vehicles whose 'fuel'—electricity -- is stored in large batteries. The choice between vehicles powered by ICE vs EV depends to a large extent on the cost of crude oil versus the cost of EV batteries, as Figure 3 illustrates. The figure is a little complicated, so let me explain it. The horizontal axis shows the cost of batteries per kwh of stored electricity and the vertical axis shows the price of crude oil. The calculations used to construct this figure actually compare the lifetime costs of owning and operating an electric vehicle to the lifetime costs of owning and operating an internal combustion engine vehicle. The equal cost line on the graph shows the oil and car battery prices where internal combustion engines and battery-powered cars have the same lifetime operating costs. For any cost combination below the line, ICE vehicles are cheaper and for any cost combination above the line EVs are cheaper. Now, I am just going to highlight a couple of points along the equal cost line. Currently, the Tesla power wall, a battery pack for home solar installations composed of batteries also used in Tesla electric vehicles, costs $390 per kilowatt hour excluding installation costs. What price of crude oil would make owning an ICE vehicle equal to this battery cost? As the equal cost line in Figure 8 shows, the answer is $540 per barrel of oil. Currently, the price of oil is much less than $100 per barrel, so today electric cars are a long way from competing with cars powered by gasoline or diesel. The U.S. Department of Energy projects that EV battery prices might decline to $264/kwh by 2020, which would be a pretty sharp decline from current prices. Even at this lower battery price, crude oil would have to cost more than $310 per barrel for EVs to be cheaper than ICEs. If battery prices came down to $125/kwh, the break-even price of crude oil would be about $115. Currently the price of oil in 2020 is projected to be $50 per barrel, which means batteries would have to cost $60/kwh for EVs to compete with ICEs. The only point to take away from this is that in both the transportation sector and the power sector, fossil fuels are relatively very inexpensive given the economics of energy markets as currently constructed, a key point I will come back to later. It is not surprising that the world's heavy reliance on fossil fuels is currently projected to continue.

Figure 3: Breakeven NPV of Owning an ICE vs an EV with 250 Miles of Range




*(Source: Covert, Greenstone, Knittel, 2016; Copyright American Economic Association; reproduced with permission of the Journal of Economic Perspectives.)*

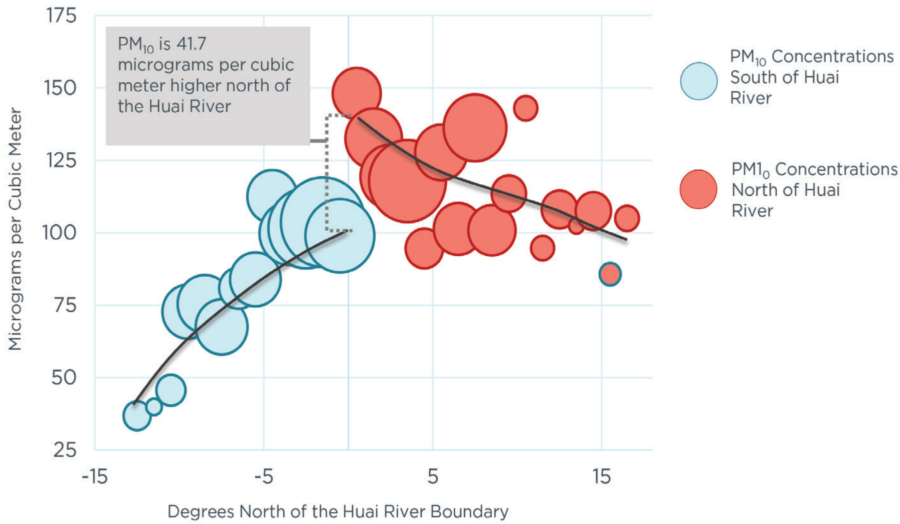
It's not just that fossil fuels are cheap. They are also incredibly abundant. There are many different ways to illustrate this, but one of my favorites is the ratio of fossil fuel reserves to production, year by year. In 1980, the world had about 35 years of production available and had we not discovered any more oil, what would be true in 2015? We would be out of oil, right? Thirty-seven years ago in 1980 the world had only 35 years of estimated oil reserves. What is striking is that even though the world increased the rate of oil consumption after 1980, today the reserve/production ratio is 55: in other words, the world could sustain current levels of oil consumption for 55 years without discovering any more oil. How is it possible that the rate of oil consumption has gone up, yet the world has more even more oil than in 1980? Well, it is possible because all the various oil and gas companies are really, really good at what they do. They are continually innovating, and they are continually finding inexpensive ways to access fossil fuels. So the world is nowhere near running out of fossil fuels. This is true for crude oil. It is also true for natural gas and coal. The main point is that fossil fuels are both abundant and inexpensive.

### *Fact 5: Fossil fuels increase pollution that shortens lives.*

If fossil fuels are cheap and abundant, why worry about their expanded use? The problem is that fossil fuels come bundled, if they are not controlled, with pollution that shortens lives. I am going to briefly describe a paper (Ebenstein, etal. 2017) that I and my co-authors published a few weeks ago that estimates the impact on life expectancy of sustained exposure to air pollution. Estimating this impact is not easy since no one deliberately wants to run a randomized control trial of exposure to ambient air pollution over people's lifetimes. Instead we looked for a natural experiment from which we could estimate the effect of long-run exposure to air pollution on life expectancy. Our paper exploits a very arbitrary, perhaps even capricious, policy that China implemented in its planned economy period, 1950 – 1980, that mimics many of the features of a randomized control trial. In particular, during this period, to control the costs of winter heating, Chinese leaders drew a line formed by the Huai River and the Qinling Mountains across the country. Between November 15 and March 15 every year, the government provided free coal to run small boilers for winter heating to people living north of the line and not to people living south of the line .[2] Importantly, another policy also highly restricted migration so that where people lived determined whether or not they were exposed to high levels of air pollution. These two policies on winter heating and internal migration created what amounts to a natural experiment. Comparing people who lived just north of the line to those who lived just south of the line, our paper asked if people in the two different areas were exposed to different levels of air pollution and if so, how did the difference in exposure affect life expectancy. The paper essentially boils down to two pictures.

2 Indeed, the legacy of that policy lives on. I recently lectured at a university in Chengdu, Sichuan which is south of the line but which has cold winters. All the students were wearing winter coats.

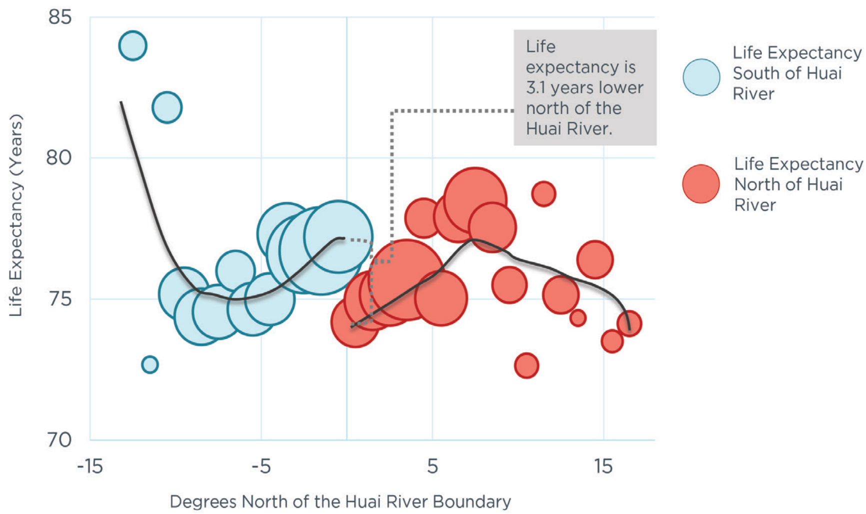
Figure 4: $PM_{10}$ Concentrations North and South of the Huai River




*(Source: Ebenstein et al. 2017)*

In the first picture, Figure 4, the vertical line between the red and the blue circles is the Huai River line, and then as you move to the right or left, each circle represents the pollution concentration in one degree latitude bins. The circles are proportional to the number of people who live in each locale. The figure shows a significant jump in the level of pollution in the coal-burning areas north of the river. Pollution is about 40 percent higher north of the river relative to south of the river. We tested to see if such a jump in pollution occurred at any other line and found that the river really is the dividing line between higher and lower air pollution. Thus the heating policy caused a large difference in the air people breathed, depending on whether they lived north or south of the river.

Figure 5: Life Expectancy North and South of the Huai River




*(Source: Ebenstein et al. 2017)*

The second picture, Figure 5, answers the question: is there a change in life expectancy right at the river's edge? Here too is another example of data conforming, showing a very sharp decline in life expectancy that occurs right to the north. The data from China shows that cause of death and elevated rates of mortality leading to these lower levels of life expectancy are all running through cardiorespiratory causes of death, which helps build the case for the decreased life expectancy being plausibly related to air pollution.

Let me zoom out of this paper on China and ask, how does particulate pollution around the world affect life expectancy? I and some of my colleagues at the University of Chicago created an Air Quality of Life Index[3] that shows the gain in life expectancy that is feasible if each part of the world moved into compliance with the World Health Organization standards for the smallest particulate pollution, PM 2.5, which causes the greatest damage to health. Air pollution problem is largely a developing country problem. Much of China suffers 3 – 5 years loss of life expectancy and remember, this is multiplied by the 1.4 billion people who live in China. India has similar loss of life expectancy. The United States looks very different than China and India and much different than it did in the 1970's.

3 For more on the Air Quality of Life Index, see https://aqli.epic.uchicago.edu/ .

There has been remarkable progress on air pollution in the United States although there are still some areas, such as Chicago and Los Angeles with modest declines in life expectancy due to air pollution.  Decreased life expectancy is just one of the undesirable features of fossil fuels.

## *Fact 6: Fossil Fuels are Causing Climate Change and the Consequences are Complicated*

Another undesirable feature of fossil fuels is that their combustion is causing climate change. The consequences are complicated so I will try to explain that as we go along here.  Let us use degrees Fahrenheit to measure temperature because I and most of the audience are more familiar with this measure than degrees Celsius. The average Indian citizen has maybe 60 days a year where the average daily temperature is between 79 and 81 degrees Fahrenheit, and then there are a couple days where it is greater than 90° F, which is very hot since this is the average of daily high and low temperature. That is the current distribution.  What would it look like in 2100 if we did not have any global climate policy?  There would be an enormous piling up of days at the very hot ranges of temperatures.  The number of days greater than 90 would go from a couple of days to 10 or 15 per year.  The next few categories have similar, if not larger increases.  This is a more useful way to understand the impact of climate change than simply saying there will be a two degree change in average global temperatures.  The relationship between human well-being and temperature is really dependent on what happens at temperature extremes.  Many of the bad outcomes such as  elevated rates in mortality and crop failures come from these very hot days.

Let me summarize a working paper (Burgess, et al. 2014) that projects the impacts of climate change on mortality.  The paper's main conclusion is that a developed nation such as the United States will suffer much less from higher temperatures than a developing nation, such as India. In the US,  hot days seem to cause small increases in mortality. In India the impact of an extra day in the greater than 95° F range is to increase the annual mortality rate about 25 times larger than in the United States. Developing nations such as India that appear poised to increase fossil fuel consumption are in a tough position with respect to air pollution and are also quite vulnerable to climate change.  The projected path for India is a terrible way to live.  People in India very much want their economy to move to the U.S. path, which is just a much easier lifestyle.  Developing nations' desire to attain the comfortable U.S. lifestyle is driving their desire for economic growth and for much more energy, which makes apparent the trade-offs inherent in the global energy challenge. It is not that India is not aware that using a lot more energy will increase the likelihood of disruptive climate change. It is that they have a very painful trade-off between underdevelopment today and improved living standards in the future. The entire world, in one way or another, is going to be affected by the energy choices that India, China and other developing countries make as they continue to grow.

So let us consider current and projected cumulative greenhouse gas emissions. Up to the present, the United States has produced about 18 percent of greenhouse gas emissions since the industrial revolution began; India has produced about four percent, and China has emitted about 12 percent. Given current projected economic growth and business as usual, by 2100 the U.S.'s cumulative share of greenhouse gas emissions declines to about 12 percent of total emissions, while China's share increases to about 25 percent and India's share to about 9 percent. What this means is that to address climate change, in one way or another, there has to be a reduction in $CO_2$ emissions relative to what is projected in the very countries that are desperate for more energy. Yet when facing energy markets as currently constructed, these countries are going to feel like the fossil fuels are the way to go.

Suppose we really did burn all available fossil fuels. The carbon dioxide released would raise average global temperatures by 16 degrees Fahrenheit. Recall my earlier point that we are not running out of fossil fuels any time soon. The world possesses practically unlimited fossil fuel resources, and advancements in technology will make the majority of this resource base accessible over the coming decades. At some level, the whole world is going to be dependent on the energy choices made in developing nations.

## *Fact 7: The Paris Agreement is Expected to Help…Some*

Burning all fossil fuels yields a grim prediction for climate change. The good news is that the Paris Agreement is expected to help avoid the worst possible outcome. Policymakers around the world made ambitious commitments to reduce greenhouse gas emissions at the December 2015 Paris Climate Negotiations. Even though these commitments are not adequate to avoid serious climate damages over the coming century, at least they move the world away from the worst-case scenario: the climate models say the global temperature rise by 2100 from fully exploiting fossil fuels would be about a 4.5° C or 8° F temperature increase, and if fossil fuel development continues unabated, global temperatures would continue to rise after 2100. If the world aggressively reduced carbon emissions, the best-case scenario limits the increase in global temperature to about 2° C or 3.5° F by 2100. The temperature path made possible by the Paris Agreement is between the worst-case and best-case scenarios. The Paris Agreement is voluntary, and there are many issues with it. The Paris Agreement only goes out to 2030 but it starts to move the world away from the worst-case scenario and at least sets the stage for a slower rise in temperatures, even though with the Paris Agreement temperatures will continue to rise after 2100.

## *Feasible Solutions*

Now, with these seven facts, let's talk about why I think, actually, there are completely feasible economic solutions to the global energy challenge. We can debate how politically feasible these solution are -- politicians do not always follow what economists recommend -- but there are certainly economically possible solutions. In some respects, the global energy challenge is actually a boring economics problem. Understanding and solving the global energy challenge does not require rocket science. The first step in solving the global energy challenge is just to price energy at its full social cost. The reason there is all that $CO_2$ and all that air pollution is that people around the world do not face fossil fuel prices associated with the damages that come from producing and using fossil fuels. Government policies distort energy prices and, more often than not, distort energy prices in the wrong direction. Fossil fuels are cheaper than they should be, so one obvious solution is to price energy at its full cost. Doing so has a great potential to disrupt energy markets in a way that would both unleash innovation and would also cause people to make different choices.

Recall my discussion of the out-of-pocket costs of generating electricity. Coal and natural gas power plants produce electricity at the lowest out-of-pocket cost. What happens to the costs of generating electricity if power plants paid the costs created by emitting carbon and other pollutants? Let's consider the levelized costs of generating electricity with new power plants, including all internal and external costs. Levelized costs incorporate all construction and operation costs. Internal costs are the generating utility's out-of-pocket costs to build and operate a new electric power plant. External costs are all of the environmental costs that the market does not currently require the utility to pay, but are real costs of pollution and climate change from building and operating a new power plant. Note that even hydro, wind and solar have such costs because renewables are very intermittent and the calculations include supplementing their output with natural gas backup. That's why a carbon charge would also increase the cost of those technologies.

A combined cycle natural gas plant delivers the cheapest energy. Its out-of pocket cost is 5.3 cents per kwh, and its total levelized cost with all environmental costs included is 8.4 cents per kwh. In contrast, new coal plants are a bad deal, generating electricity at the highest cost, including all internal and external costs. The out-of-pocket cost of new coal plants is 8 cents per kwh, but the external costs from air pollution and greenhouse gas emissions emitted by the coal plants add an additional 9.4 cents per kwh for a levelized cost of 17.4 cents per kwh. If the price of coal-fired electricity included all of its costs, coal would be way, way out of the market. The levelized cost for a nuclear plant would be 10.5 cents, which shows why utilities in the U.S. are not building nuclear plants; their out-of-pocket costs are much higher than new coal or combined cycle natural gas plants, even though their total cost is lower than coal. Renewables cost more than new combined cycle natural gas plants, but are much cheaper than new coal-fired plants. The total cost of wind power is 11.3 cents per kwh and solar is 12.1 cents per kwh – much lower than the total cost of coal-fired electricity.

These calculations depend on answering a key question: What is the right price for external costs caused by burning fossil fuels? That is an exciting research question. The economic cost of an additional ton of $CO_2$ emissions is often called the social cost of carbon. Up until October 2017, the U.S. social cost of carbon was set at $42 per ton. Estimating this value is crucial for choosing sensible climate change policies; it gives us a bright line for the policies that are actually beneficial for society and the policies that are undesirable or net negative. For example, if the social cost of carbon is truly $42 and we are implementing a policy that costs $600 a ton, that is a bad deal. It costs more than the benefits it is providing. For example, it costs about $600 per ton of $CO_2$ abated by appliance upgrade programs (Davis et al. 2014), and it costs about $200 per ton of $CO_2$ abated by residential weatherization programs (Fowlie et al. 2017). These costs vastly exceed the estimated benefits of $42 per ton.

There are parts of the world that do have carbon markets that generate market prices for carbon. The share of global emissions subject to carbon pricing is now up to about 13 percent. All of these market prices are lower than $42 per ton. Effectively, we are doing mental jiu-jitsu, choosing programs such as appliance rebates that cost $600 to reduce $CO_2$ emissions by one ton when instead we could choose programs that cost $10 or $15 per ton of $CO_2$ reduction. There is a lot of room for expanding carbon pricing programs in the 87 percent of the world where it is not priced and many parts of the world where it is priced too low. The average price should be equal to what research reveals the social cost of carbon to be.

Estimating the social cost of carbon depends on estimating the future damages caused by future climate change. There has been great dissatisfaction with current models for estimating these damages. I am helping to lead a group with three colleagues called the Climate Impact Lab[4] that is estimating the future damages based on observations of real world relationships between climate and human well-being in a variety of sectors. For example, we are estimating the relationship between mortality and temperature by location and age group. Our initial work in using data from around the world has found that the damages associated just for increased mortality from higher temperatures, not from any of the other sectors, are about as large as total damages in the three existing damage functions. Let me say that again and try to say it in English. We are finding that the projected costs of climate change just on mortality, never mind all the other ways in which climate change might affect human well-being, are about as great as the total costs from the three main existing models. We are working to apply this detailed approach for other sectors, such as agricultural production, crime and labor productivity and energy management. This new empirical approach appears to be suggesting we have been systematically understating the cost of climate change. I do not think there is a plausible social cost of carbon that is ever going to make us think $600 per ton is a good idea, but it is very possible that the social cost of carbon should be greater than $42.

There are many elements in solving the global energy challenge, but the first step in solving the problem is to embed in energy prices both the air pollution and the carbon damages. This should be done all over the world and that will allow everyone around the world to make better choices. We do not escape the costs by not putting pollution and carbon costs in the price of the energy. We just pay for these costs in a different way and in a less effective way with shorter lives and

4 For detailed results from the Climate Impact Lab, see https://www.impactlab.org/.

disruptive climate change.

Let me just close by recalling our picture of the guy on the bike which very well illustrates the global energy challenge: how do we increase the supply of inexpensive and reliable energy that gets the guy off the bike while controlling the pollution released by fossil fuels and avoiding vastly increasing the probability of disruptive climate change? That is the global energy challenge, and solving it is key to maintaining and increasing the wealth and well-being of nations.

## *References*


Barreca, Alan, Karen Clay, Olivier Deschenes, Michael Greenstone, and Joseph S Shapiro. 2016. "Adapting to Climate Change: The Remarkable Decline in the US Temperature Mortality Relationship over the Twentieth Century," *Journal of Political Economy*, 124 (1), 105–159.

*BP Energy Outlook* https://www.bp.com/en/global/corporate/energy-economics/energy-outlook.html

*BP Statistical Review of World Energy* https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html

Burgess, Robin, Olivier Deschenes, Dave Donaldson, and Michael Greenstone. 2014. "The Unequal Effects of Weather and Climate Change: Evidence from Mortality in India" unpublished working paper.

Covert, Thomas, Michael Greenstone and Christopher R. Knittel. 2016. "Will We Ever Stop Using Fossil Fuels?" *Journal of Economic Perspectives* VOL. 30, NO. 1.

Davis, Lucas W, Alan Fuchs, and Paul Gertler. 2014. "Cash for Coolers: Evaluating a Large-Scale Appliance Replacement Program in Mexico," *American Economic Journal: Economic Policy*, 2014, 6 (4), 207–238

Deschenes, Olivier and Michael Greenstone. 2011. "Climate Change, Mortality, and Adaptation: Evidence from Annual Fluctuations in Weather in the US", *American Economic Journal: Applied Economics*, 2011, 3(4): 152-85.

Duflo, Esther, Michael Greenstone, Rohini Pande and Nicholas Ryan. 2013. "Truth-Telling by Third-Party Auditors and the Response of Polluting Firms: Experimental Evidence from India" *Quarterly Journal of Economics*, 2013, 128(4):1499-1545.

Ebenstein, Avraham, Maoyong Fan, Michael Greenstone, Guojun He and Maigeng Zhou. 2017. "New evidence on the impact of sustained exposure to air pollution on life expectancy from China's Huai River Policy" *Proceedings of the National Academy of Sciences* Sep 2017.

Fowlie, Meredith, Michael Greenstone and Catherine Wolfram. 2018. "Do Energy Efficiency Investments Deliver? Evidence from the Weatherization Assistance Program". *Quarterly Journal of Economics.*

Greenstone, Michael, and Rema Hanna. 2014. "Environmental Regulation, Air and Water Pollution, and Infant Mortality in India." American Economic Review 104 (10): 3038–72.

Greenstone, Michael and Ted Gayer. Quasi-Experimental and Experimental Approaches to Environmental Economics, *Journal of Environmental Economics and Management*, 2009, 57(1): 21-44.

Hanna, Rema, Esther Duflo, and Michael Greenstone, "Up in Smoke: The Influence of Household Behavior on the Long-Run Impact of Improved Cooking Stoves", *American Economic Journal: Economic Policy*, 2016, 8 (1): 80-114.

International Energy Agency (IEA 2016) *World Energy Outlook 2016* https://www.iea.org/newsroom/news/2016/november/world-energy-outlook-2016.html

International Energy Agency (IEA 2017) *Energy Access Outlook 2017: From Poverty to Prosperity* https://www.iea.org/publications/freepublications/publication/WEO2017SpecialReport_EnergyAccessOutlook.pdf

Ito, Koichiro, "Asymmetric Incentives in Subsidies: Evidence from a Large-Scale Electricity Rebate Program" *American Economic Journal: Economic Policy*, Vol. 7, No. 3, August 2015.

# Innovation on Three Fronts in Pursuit of Energy and Climate Progress

**Andrew Revkin**[1]

I was honored last year to learn that the central theme of discussions at Beloit College's tenth Miller Upton Forum, "Modern Energy and the Wealth of Nations," was inspired by my 2016 conversation with Bill Gates. In a 45-minute discussion in Seattle for my *New York Times* blog, Dot Earth,[2] Gates and I explored his strategies for spreading access to abundant, cheap energy and the wellbeing it enables while cutting environmental and climate impacts from the still-dominant source – fossil fuels. His investments were centered on filling a longstanding gap in research and development aimed at big-scale breakthroughs.

In our chat, Gates had laid out the logic behind his focus on leapfrog advances even as others were pursuing policies aimed at expanding the use of today's renewable energy technologies. He argued that only abundant zero-carbon energy that was affordable in developing countries could do the trick, and by his calculation, even for renewable energy, big jumps were needed.

"India is paradigmatic," Gates told me, challenging critics. "They have to electrify. That's why children don't die. They need to be able to refrigerate their food and heat and cool.... The United States could afford for energy to cost a lot more than it does today. Europe can afford for energy to cost a lot more. Japan can afford for it to cost a lot more. But the future $CO_2$ emitters are not going to pay some meaningful premium, nor are they going to give up total reliability. Their hospitals want energy; their factories want energy all the time."

1 Andrew Revkin, who has written on climate change and sustainability for more than 30 years, is the Strategic Adviser for Environmental and Science Journalism at the National Geographic Society and author of four books on climate and environmental sustainability.

2 http://j.mp/dotgates

Gates is part of a long lineage of advocates for intensified pursuit of breakthrough technologies as the solution to humanity's energy and climate challenges. In essence, he and those in this camp argue that modern energy *is* the wealth of nations.

An earlier champion of energy breakthroughs was the chemistry Nobel Laureate Richard Smalley. Starting in 2003, Smalley, even as he fought leukemia that would take his life, became an evangelist for energy innovation after he ran the numbers and realized that the single factor that could help solve the world's top 10 problems – from global security threats to education to health to global warming and more – was universal access to clean energy.

This cuts against the "small is beautiful" theme that has underpinned much of environmentalism until recently. But at least one ecologist, Daniel B. Botkin, found evolutionary logic in pursuit of energy abundance. In a 2007 essay, Energy and Civilization,[3] Botkin, seeking a solar revolution, said abundant energy is necessary for civilization itself, even democracy:

"One widespread view is that we must all scale back our energy use and learn to use as little energy as possible - in effect, go on a long-term, even permanent, energy diet," Botkin wrote. "As we know all too well, people are not good about sticking to prolonged diets. And in any case, as an ecologist who has done research for years about how animals and plants and ecosystems garner energy, I see the problem differently. Life with a minimum amount of energy is a life on the margin."

The 2017 Miller Upton Scholar, Dr. Michael Greenstone, the Milton Friedman Professor in Economics at the University of Chicago, echoed the energy imperative of these thinkers and doers and, in his lecture and talks on campus, pushed for innovation.

But Greenstone's focus is on innovation in *policy*, more than laboratories, as a driver of technological and social energy transitions. In his keynote lecture and comments, he described methods that could most objectively reveal – and integrate into the economy -- the costs and benefits of a range of regulations or programs. Too often these days, he said, the external costs of fossil fuels remain unaccounted for and even when governments pursue energy efficiency or low-carbon choices, those that are most politically convenient or that feel most "green" turn out to be of limited value.

3 https://www.danielbbotkin.com/2007/03/19/energy-and-civilization/

For several years, I'd been reporting on Greenstone's scholarship and analysis at both ends of the global energy spectrum – from his work with colleagues assessing efforts to cut smoky pollution from cooking on wood or dung in more than 100 million Indian households to his stint in the Obama administration setting a "social cost of carbon." This metric is designed to estimate how much it would be worth today – in dollars per ton of United States emissions of heat-trapping carbon dioxide – to reduce risks of costly climate change impacts in future decades.

The title of Greenstone's June and Edgar Martin Memorial Lecture on the global energy challenge in the context of climate change set a refreshingly interrogatory tone appropriate for a momentous problem that, despite years of proclamations and prescriptions, has no easy solution. "Will We Ever Stop Using Fossil Fuels?" he asked.

Reflecting the sobering nature of a challenge other scholars have labeled "super wicked"[4] for its deep complexity, he offered roadmaps more than answers. While laying out his proposals for making energy and climate policies more efficient, he was refreshingly humble in acknowledging he was not sure how to make meaningful progress when politics, from Indiana to India, is driven far more by local and real-time worries than long-term and uncertain risks.

As if to challenge his own approach, Greenstone echoed Gates in stressing how the huge divide in global energy access between countries like the United States and India requires profoundly different considerations in shaping paths to energized societies and a stable climate. An Indian state in which Greenstone had worked, Bihar, has electricity consumption at 130 kilowatt-hours per person per year, while the average American consumes 13,000 kilowatt-hours per year. When American and European leaders admonished India not to fully exploit its vast coal beds for the sake of global climate stability during negotiations around the Paris Agreement on climate change, it's no wonder that call was resisted, with India demanding the lion's share of "carbon space" left in the atmosphere.[5]

In my comments at Beloit, I noted that all paths toward progress on energy and emissions that I've assessed in thirty years of reporting on climate change come with big questions and run up against tough realities – particularly the daunting scales of producing terawatts of clean energy while cutting gigatons of

4 http://j.mp/superwicked

5 http://www.thehindu.com/sci-tech/energy-and-environment/cop21-vacate-carbon-space-india-tells-west/article7960631.ece

heat-trapping gases even as our species heads toward a population of 9 or 10 billion people in the next 30 years, all seeking decent lives.

In that context, I argued that the 2015 Paris Agreement was a great success for the same reasons it was a total failure. The success was in creating an architecture soft enough to convince leaders of nearly 200 countries to agree on a common framework and process for building a safer global relationship with the climate system. The success LAY in CRAFTING Paris AS the first step in what was acknowledged to be a century-long journey. That followed two decades of failed treaty negotiations that aimed at a contract-style pact with hard targets and timetables and punitive measures for those who faltered.

The failure, of course, lies in what I called the "reality gap," particularly past 2030, between even best-case forecasts for emissions reductions and the path scientists had calculated had a good chance of avoiding dangerous climate disruption. Only completely untested technologies, at a scale unimaginable given the lack of research investment, could fill the gap.

So where does this leave us? What is the role of policy, either through regulation or economic signals? What is the role of invigorated basic science and long-shot investments like those of Bill Gates? What is the role of political activism like that pursued by young people through divestment campaigns or the 350.org movement. What is missing?

Of course, the answer is there is no answer, if the expectation is for some solution that can fill the climate reality gap either through a top-down instrument or bottom-up breakthroughs. Facing an emergent source of profound but uncertain risks like climate change, the best answer lies in working to establish constructive dynamics more than some specific policy. Constructive ferment, constrained with some objective methods to set baselines (like those Greenstone is trying to create), can create a solution-seeking environment that can evolve as knowledge builds, or is rebuilt.

This means a third area of innovation is required – particularly in these times of social "filter bubbles" that cause us to cluster instead of achieving the dream of those who named the World Wide Web, creating an open system for universal sharing and shaping of ideas, observations and insights.

That's been my focus in the last decade, first in my blogging at *The New York Times* and then at Pace University, where I launched a course called Blogging a Better Planet -- and it's my focus even more now that I've moved early this year to the nonprofit side of National Geographic, the 130-year-old Society that, through recent restructuring, is able to greatly expand its grants and support for global communication innovations aimed at achieving a balanced relationship between people and the planet and biological wonders that are increasingly in our sway.

As I've written before, a pivotal moment for me came around 2013, as those fighting for climate progress seemed more riven than ever over how to proceed. I did some Web searching for the terms "response . . . diversity . . . environment" to see if anyone had explored how or whether environmental campaigns might tolerate common but differentiated approaches to progress.

My Google search turned up a remarkable 2003 paper on the sources of ecosystem resilience by Thomas Elmqvist of Stockholm University and others.[6] It included this line:

> The diversity of responses to environmental change among species contributing to the same ecosystem function, which we call response diversity, is critical to resilience. Response diversity is particularly important for ecosystem renewal and reorganization following change.

As I read it, I pondered whether the following slight tweak might also be true:

The diversity of responses to environmental change among *people* contributing to the same *social* function, which we call response diversity, is critical to resilience. Response diversity is particularly important for *social* renewal and reorganization following change.

Can the environmental movement find room for diverse strategies?

I hope so. It's utterly human to have varied responses to change and challenges—in this case, humanity's intertwined energy and climate challenges. I see great value, for example, in the work of students and academic colleagues pursuing divestment from fossil fuel companies. To me, there's particular merit in examining investments and divestment as a path to putting ossified terms and norms under fresh scrutiny. Is a school's endowment more than its financial investments? Is fiduciary responsibility limited to preserving those assets measured only in dollars and cents? Are trustees of a company, university, or planet responsible only for sustaining values measured that way?

But I also see the value in engaging with—dare I say it, even working for or investing in—big companies as a way to test the possibility of building a different

6 https://esajournals.onlinelibrary.wiley.com/doi/10.1890/1540-9295%282003%29001%5B0488%3ARDECAR%5D2.0.CO%3B2

culture from the inside out.

Rather than looking at either strategy as right or wrong, I see both as part of a broadening commitment to a new and durable human relationship with both energy and climate.

One thing that this approach requires is a willingness to accept, even embrace, failure and compromise.

A helpful metaphor came to me in a conversation about a decade ago with Joel E. Cohen, a demographer and development expert affiliated with Columbia and Rockefeller University. He said that after the sprint of the last couple of centuries, humans would do well to seek a transition to a more comfortable long-distance pace more suited to adulthood than adolescence.

Walking, he reminded me, is basically "a controlled forward fall." It is a means of locomotion by which one moves steadily ahead, adjusting to bumps or hurdles, even trips and collisions, shifting course as needed but always making progress toward the desired destination.

Essentially, societies need to find a way to fall forward without falling down.

The prismatic complexity of climate change is what makes it so challenging to address, but this also means everyone can have a role in charting a smoother human journey. I've come to see the diversity of human temperaments and societal models and environmental circumstances and skills as kind of perfect for the task at hand. We need edge pushers and group huggers, faith and science, and—more than anything—dialogue and effort to find room for agreement even when there are substantial differences.

At the level of nations and cultures, a diversity of approaches is also inevitable, and that's why the recent shift in climate diplomacy away from a binding top-down model to a flexible but credible and inclusive agreement, although long seen as a failure (including by me in early stories), is a perfectly human version of success.

It's notable that Pope Francis stressed the need for diversity and dialogue in his 2015 historic encyclical on equity, climate change, and environmental care.[7]

He didn't hesitate to express his personal displeasure with consumptive capitalism, but despite being the ultimate top-down leader of a top-down institution—he is *il Papa*, after all—Francis said that dialogue and compromise between

---

7 http://w2.vatican.va/content/francesco/en/encyclicals/documents/papa-francesco_20150524_enciclica-laudato-si.html

worldviews are key to whatever comes next.

Like a parent confronted by squabbling kids, he was essentially saying, “Work it out.”

Creating communication environments in which we can work it out is at least as grand a challenge as finding the next battery breakthrough or designing a carbon price that can work in America’s great, but flawed, democratic system.

That’s my part of this challenge. Find yours.

## *References*


Barreca, Alan, Karen Clay, Olivier Deschenes, Michael Greenstone, and Joseph S Shapiro. 2016. "Adapting to Climate Change: The Remarkable Decline in the US Temperature Mortality Relationship over the Twentieth Century," *Journal of Political Economy*, 124 (1), 105–159.

*BP Energy Outlook* https://www.bp.com/en/global/corporate/energy-economics/energy-outlook.html

BP Statistical Review of World Energy https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html

Burgess, Robin, Olivier Deschenes, Dave Donaldson, and Michael Greenstone. 2014. "The Unequal Effects of Weather and Climate Change: Evidence from Mortality in India" unpublished working paper.

Covert, Thomas, Michael Greenstone and Christopher R. Knittel. 2016. "Will We Ever Stop Using Fossil Fuels?" *Journal of Economic Perspectives* VOL. 30, NO. 1.

Davis, Lucas W, Alan Fuchs, and Paul Gertler. 2014. "Cash for Coolers: Evaluating a Large-Scale Appliance Replacement Program in Mexico," *American Economic Journal: Economic Policy*, 2014, 6 (4), 207–238

Deschenes, Olivier and Michael Greenstone. 2011. "Climate Change, Mortality, and Adaptation: Evidence from Annual Fluctuations in Weather in the US", *American Economic Journal: Applied Economics*, 2011, 3(4): 152-85.

Duflo, Esther, Michael Greenstone, Rohini Pande and Nicholas Ryan. 2013. "Truth-Telling by Third-Party Auditors and the Response of Polluting Firms: Experimental Evidence from India" *Quarterly Journal of Economics*, 2013, 128(4):1499-1545.

Ebenstein, Avraham, Maoyong Fan, Michael Greenstone, Guojun He and Maigeng Zhou. 2017. "New evidence on the impact of sustained exposure to air pollution on life expectancy from China's Huai River Policy" *Proceedings of the National Academy of Sciences* Sep 2017.

Fowlie, Meredith, Michael Greenstone and Catherine Wolfram. 2018. "Do Energy Efficiency Investments Deliver? Evidence from the Weatherization Assistance Program". *Quarterly Journal of Economics.*

Greenstone, Michael, and Rema Hanna. 2014. "Environmental Regulation, Air and Water Pollution, and Infant Mortality in India." American Economic Review 104 (10): 3038–72.

Greenstone, Michael and Ted Gayer. Quasi-Experimental and Experimental Approaches to Environmental Economics, *Journal of Environmental Economics and Management*, 2009, 57(1): 21-44.

Hanna, Rema, Esther Duflo, and Michael Greenstone, “Up in Smoke: The Influence of Household Behavior on the Long-Run Impact of Improved Cooking Stoves”, *American Economic Journal: Economic Policy*, 2016, 8 (1): 80-114.

International Energy Agency (IEA 2016) *World Energy Outlook 2016* https://www.iea.org/newsroom/news/2016/november/world-energy-outlook-2016.html

International Energy Agency (IEA 2017) *Energy Access Outlook 2017: From Poverty to Prosperity* https://www.iea.org/publications/freepublications/publication/WEO2017SpecialReport_EnergyAccessOutlook.pdf

Ito, Koichiro, “Asymmetric Incentives in Subsidies: Evidence from a Large-Scale Electricity Rebate Program” *American Economic Journal: Economic Policy*, Vol. 7, No. 3, August 2015.

# Scaling Low-Carbon Energy for the Developing and Developed World

**Eric D. Isaacs**[1]

In preparing for this Forum, we were asked to read an article written by Bill Gates, in which he talked about the need for "energy miracles" – powerful, affordable new technologies that will provide the energy resources we need without emitting greenhouse gases into the atmosphere.

I have to be honest: When I first read the term "energy miracles," I was a bit annoyed. New technologies are not miraculous. They don't simply drop out of heaven into the laps of scientists and engineers. To me, as a scientist, calling energy technologies "miracles" is somewhat dismissive of the decades of hard work that must be invested in these technologies before they are ready for deployment.

But then I started thinking about one of my favorite quotes from Arthur C. Clarke, the great science fiction writer and futurist: "Any sufficiently advanced technology is indistinguishable from magic." So, for the purposes of this discussion, I'm willing to accept the term "energy miracles." Even though I know that their creation is founded on human endeavor rather than divine intervention, I can understand how miraculous some of these technologies may seem to many people.

With that said, I am reminded of a song lyric from an old Rogers & Hammerstein musical: "A hundred million miracles are happening every day." To me, that's a pretty succinct summary of what's been happening in the energy technologies space. In fact, when I think about the energy miracles that have occurred in my lifetime – or even just in the years since I graduated from Beloit College – I think that the "100 million" figure may actually be a bit low.

Think about it. When I was an undergraduate, our nation's biggest energy fear was that we would run out of fossil fuels. We were facing an oil crisis, with long lines of cars at every gasoline pump. The United States was planning a major

1 Eric D. Isaacs is President of the Carnegie Institution of Science.

expansion of its nuclear fleet. Wind energy and solar energy were just blips on the horizon. I recently ran across a review article that was published in *Nature* in 1978 that shows just how much energy technologies have evolved during my career (Ryle 1977). The article, titled "Economics of Alternative Energy Sources", included a photograph of a (then) cutting-edge experimental wind turbine capable of generating 2 kW. The article also predicted that solar power would be useful primarily for heating water for home use.

Now, 40 years later – a mere nanoblink of an eye later, in geologic terms – the world's largest wind turbine to date generates 7 MW – 3,500 times more than that once-revolutionary prototype. There are now more than 89 GW of utility-scale wind power installations in the United States, and 7 GW of that capacity was installed last year alone (GWEC 2018). There's another 1 GW of distributed applications supplying power directly to homes, farms, businesses, and communities (EERE 2018).

Solar power technologies are improving by leaps and bounds; recently, one group of scientists claimed to have constructed a solar cell that boasts 44.5% efficiency, which is about twice the efficiency of the best solar cells you can buy today (Lumb 2017). If these super-efficient new cells are successfully manufactured and deployed, they will transform the industry.

Just as importantly, there are revolutionary new battery technologies – or, if you prefer the term, energy miracles – that make it possible to store all that generated power, for use when the wind doesn't blow or the sun doesn't shine. These next-generation energy storage technologies are critical to any meaningful effort to reduce our dependence on fossil fuels and shift to renewables for both transportation and utility grid use. As of May 2018, the U.S. had over 25 GW of rated power in energy storage, with another 190 MW under construction (EDER). Late last year, San Diego Gas & Electric installed one of the world's largest lithium-ion batteries, a 30 MW project in Escondido built in less than six months and capable of powering 20,000 households for up to four hours (Spector 2018). An even larger project, a 100 MW battery system, is now being built in Long Beach (Richardson 2018). These batteries are replacing aging natural gas "peaker" plants, which are used to provide electricity during times of extremely high (or "peak") demand. To me, it's amazing – or rather, miraculous – that so much progress has been made in utility-level energy storage in just a few years.

Worldwide, even more energy miracles are happening every day. In 2016, renewables accounted for 165 GW of new net power capacity – about two-thirds of the total, with new solar capacity growing by 50% (IEAa 2017). China has responded to serious concerns about air pollution in its cities with a strong commitment to increasing renewable energy capacity; China was the site of more than 40% of the world's renewable growth in 2016, and the country has already surpassed its 2020 target for solar PV installation (IEAa 2017). Bangladesh is now the world's largest market for solar home systems, with 4 million units installed (CPI 2017).

Wind power also is being adopted swiftly around the globe. By the end of 2017, more than 530 GW of wind power had been installed worldwide, and nine nations had installed more than 10 GW (GWEC 2018). Denmark in particular has been an incredible wind power success story: In 2017, wind turbines delivered the power equivalent of more than 40% of Denmark's electricity consumption (Berggreen 2018). In fact, in February of last year, Denmark generated enough wind energy to power the entire country for a full day (Hill 2017).

We're also seeing an incredible jump in our global capacity to store renewable energy for grid use. Worldwide, installed energy storage totals about 150 gigawatts (EDER 2018). In Japan, 15% of all delivered electric power is now cycled through a storage facility (CSS). These are the types of "energy miracles" that give us some rays of hope as we confront climate change.

I would add that these advances in energy technology deployment are not limited to the more economically developed countries. In the developing world, we're seeing major increases in renewable energy used in off-grid installations. The cost of building a new power grid infrastructure from the ground up is just about insurmountable in countries with developing economies and widely scattered populations, so it's great news that, since 2010, more than 25 million off-grid solar systems have been sold worldwide (REN21 2017). Sales of distributed solar systems are soaring in sub-Saharan Africa, where solar lanterns are used along with small solar systems that power lighting, radios, television, refrigeration and provide access to the Internet. The International Energy Agency predicts that, within five years, 70 million people in Asian and sub-Saharan Africa will power their homes with these types of small-scale photovoltaic systems (IEAa 2017). These types of systems are transformative for two reasons: They provide affordable, reliable power and they replace expensive, polluting diesel-powered generators.

As a result of all these good efforts, global energy-related carbon dioxide emissions in 2016 were flat for a third straight year -- even though the global economy grew 3.1%(IEAb 2017). Those statistics show that increasing deployment of renewable energy could decouple economic growth and increased carbon emissions in the developing world, proving that increased pollution doesn't necessarily go hand-in-hand with economic expansion. So these are more of those "energy miracles" that Bill Gates is seeking.

Unfortunately, when you look at the size of the problem, you realize that those 100 million miracles are probably several orders of magnitude less than we need. The bad news is that total energy-related emissions are still hitting 32.1 gigatonnes each year, over and above the 500 gigatonnes of naturally occurring carbon in the atmosphere. That's simply not sustainable. At the same time, there are still more than 1 billion people worldwide living without electricity, and global energy demands are steadily increasing. Richard Smalley, a Nobel Prize-winning chemist, called this "the 50 terawatt problem."

Basically, if you project out to the year 2100, it looks like we will be consuming 50 terawatts of electricity worldwide – about three times as much as we use today. There is no way the planet will remain livable if we cannot find ways to generate that energy through non-emitting sources. Solving a problem of this magnitude is going to require dramatic improvement in today's energy systems, along with development of a wide array of novel, high-impact technologies.

But as a "miracle worker" myself – or, to use the term I prefer, a scientist – I know that it's not enough to develop and deploy new, efficient, green technologies. We also need to make sure that we're using the right miracle for each situation.

Consider the complexities of electric vehicles. We've been talking for years about electrifying the fleet as a cornerstone of our carbon reduction initiatives. In the United States, it's estimated that electrifying the whole fleet, both trucks and cars, would reduce our carbon emissions by about a third and reduce our national consumption of petroleum by about a quarter. Today, we're making real progress toward that goal. Last year was the best year ever for EV sales in the United States, with 200,000 new vehicles sold (Gitlin 2018). Globally, EV growth is even stronger; sales of plug-in vehicle deliveries topped 1.2 million vehicles in 2017, up 58% from the previous year (EVWSD 2018). This is great progress.

But when you look a little deeper, you realize that the story is more complicated than we had hoped. The environmental impacts of EVs actually vary dramatically depending on the source of the electricity that charges them. At night, you have to plug the EV's battery into the grid, so the vehicle's actual environmental impact depends on how that electricity was generated. If you're operating an electric vehicle in California, that's a pretty good state for alternative energy. They lead the nation in electricity generation from non-hydroelectric renewable energy sources, including geothermal power, wind power, and solar power, and natural gas-fired power plants generate more than half of the state's electricity. In fact, there's only one coal-fired plant still operating in the entire state. So when you plug your EV into the California grid, the result is a net win in carbon emissions. If you happen to be in West Virginia, however, operating an EV is actually a terrible thing, because West Virginia's electric grid is more than 90% coal-powered grid. When your EV is powered by electricity that's been generated with coal, you're actually emitting more carbon than a gasoline-fueled internal combustion vehicle.

It's crucial to consider the energy source when you look at China, which is the world's largest automobile market. The Chinese government has been aggressive in moving toward alternative energy sources, and last year they announced that they were canceling more than 100 coal-fired power plants currently in development. Despite those steps forward, however, coal is still used to generate about two-thirds of the nation's power. So it's actually troubling that China has announced an ambitious goal to shift more than 20% of total vehicle production and sales to EVs by 2025 (Reuters 2017). While it's true that increasing the share of EVs will reduce soot and help to make the air a bit more breathable in densely populated cities, they'll need a major, concurrent shift to carbon-free sources for electricity generation if they want the EV shift to reduce carbon emissions as well. Globally, we're looking at about 1,600 coal-fired plants that are planned or under construction in 62 countries around the world (Tabuchi 2017). If those coal plants are actually built, they will expand the world's coal-fired power capacity by 43%. So a shift to EVs in those nations would actually add to the problem instead of providing a partial solution.

When I was a young scientist, we didn't really include these types of calculations when we were thinking about developing new energy technologies. When we were trying to build a new type of battery, our singular focus was trying to get it to store enough energy to power a car for 400 miles. We might daydream about building a new type of electric vehicle that would be affordable to buy and to run, making reliable transportation available to millions of people around the world, but we didn't stop to consider the likely environmental impacts if a nation decided to build a new fleet of coal-fired power plants to keep those cars on the road.

In the past couple of decades, however, scientists have begun to realize that we can't solve the problem of climate change through technology alone; we need to consider the impacts of those new technologies within the larger context.

Transformational energy technologies require new policies that address present scientific, regulatory, and commercial barriers. Scientists and engineers must work alongside economists and analysts who look at systems-level impacts. That's one area where we're seeing great leadership by the Department of Energy National Laboratories and by research universities such as my own institution, the University of Chicago. We're not only developing world-leading technologies, we're also supporting research into real-world impacts of those technologies. One great example is GREET (Greenhouse gases, Regulated Emissions, and Energy use in Transportation), a full life-cycle model developed at Argonne National Laboratory's renowned Center for Transportation Research (ES ANL 2017). GREET provides "well to wheels" analysis, including the environmental impacts of manufacturing those vehicles. It's considered the gold standard for fully evaluating energy and emission impacts of various vehicle and fuel combinations, which makes it possible to understand such problems as the differing impacts of EVs in different states and with different sources of power.

Another great example of the power of an integrated multidisciplinary approach is the U.S. Department of Energy's Joint Center for Energy Storage Research (JCESR), based at Argonne National Laboratory. The idea was to develop a new model that would significantly shorten the innovation pipeline as we work to build a better battery. We created an "under one roof" approach that brings together discovery science, battery design, research prototyping, techno-economic modeling and manufacturing collaboration in a single, highly interactive organization with strong scientific leadership. It's a consortium of national laboratories, universities, and private industry. At JCESR, scientists doing basic research on a novel electrochemical cell (the basic building block of a battery) can hear from industry people about potential barriers to deployment, such as the costs and availability of the underlying materials. They also can consult with economists about market forces that could have an impact on their work.

JCESR is focused on moving from today's most powerful batteries, which are based on lithium, to a new generation of battery chemistries. We're trying to invent new energy materials that will enable us to store more energy more efficiently. This effort requires tremendous creativity from our scientists and engineers, but it also requires thoughtful techno-economic modeling. If you're going to build better batteries for a billion cars, you need to make sure you have adequate materials on Earth to build those batteries, and you need to cost it out to make sure that those cars will be affordable. After six years of operation, JCESR's hub model has yielded some promising approaches to building new generations of batteries. For example, techno-economic modeling of possible battery systems led to a concept for long-duration storage based on sulfur as an anode with oxygen as a cathode; that concept is now being transferred to a startup company.

As we take this multidisciplinary approach to technological development, we're also seeing the importance of bringing public policy experts into the conversation early on, to give us insights into unexpected consequences. That's a lesson we've learned from the history of nuclear power in the United States. Nuclear power is an important source of carbon-free generation. Right now, there are 50 new nuclear power plants under construction worldwide – 20 in China alone (WNA 2018b). But in the United States, it's a very different story. We still lead the world in nuclear generation, which accounts for about 20% of our electrical power, but there are major regulatory and economic obstacles to nuclear fleet expansion. While the U.S. Nuclear Regulatory Commission has recently streamlined the licensing process for new nuclear power plants, the approval process remains extremely time-consuming and costly. In addition, utility rates that are inadequate to assure investment recovery have led to early U.S. plant retirements. Those low rates also have discouraged development and investment in new plants. Last year, for example, utilities canceled a couple of new nuclear power plants after they were partially built, and a dozen older plants are facing closure because natural gas plants are cheaper. There also has been a great deal of public resistance to nuclear expansion in response to the disasters at Chernobyl, Three Mile Island, and Fukushima.

This is a thorny problem. Although we're making great strides with grid-level storage for wind-and solar-generated electricity, we're a long, long way from having the capacity to meet all our energy needs with wind and solar. We also don't have anything close to a 21$^{st}$-century power grid that includes adequate storage for that amount of renewably generated electricity. Whether we like it or not, nuclear reactors are the only non-emitting source for baseload generation that is currently available. So we need to bring in experts in economics and public policy to help us understand and respond to the unintended consequences of America's decades-long failure to build new nuclear power plants. No one is attempting to downplay the devastating impacts of a Fukushima-level disaster, but we also need to consider the terrifying impacts of climate change caused by carbon emissions. How do we balance risks of a possible nuclear accident against the massive destruction and loss of life that Hurricane Maria inflicted on Puerto Rico?

How much of that destruction can we attribute to a storm system fueled by warmer ocean water? Perhaps most importantly, how do we begin a thoughtful, productive national conversation about these types of cost-benefit analyses?

The economic issues related to nuclear power are equally challenging. When we compare the costs of nuclear generation with the costs of natural gas power plants, natural gas just looks cheaper. No contest. But those head-to-head cost comparisons are misleading, because they don't address what's known as the "social cost" of carbon–the monetary cost of the damage caused by the release of each additional ton of carbon dioxide into the atmosphere. Those social costs include the destruction of property from storms and floods, declining agricultural and labor productivity, the costs of treating air pollution-related illnesses (such as asthma and lung cancer), and the lost productivity of people whose lives are cut short by those illnesses. Today, economists estimate the social cost of carbon at close to $50 per metric tonne. When you add in the social cost of carbon, you get a much clearer picture of the true cost of energy.

In this country, coal plants emit 1.2 billion metric tonnes of carbon per year, making up 68% of the nation's total carbon emissions (US EIA 2017). That adds up to an estimated $60 billion a year in social costs (and that's probably an understatement). The problem is, the companies that use fossil fuels to generate electricity aren't required to pay for the social cost of carbon. Instead, the rest of us pay for it, through higher food costs, higher insurance rates, higher taxes to pay for emergency response – the list goes on and on. In other words, we wind up paying massive (but generally invisible) subsidies to the fossil fuel industry. If you add those subsidies into the equation, nuclear power doesn't look so expensive in comparison with fossil fuels.

This brings me to my last point, which is that "energy miracles" don't come cheap. Transforming our energy economy will be costly (as Bill Gates has acknowledged). Achieving goals of energy transformation will require substantial, consistent government funding of energy science research. That research must be followed by development and deployment – which can be very expensive. We also face the challenges of scaling those transformative technologies to levels that actually make a difference. To understand the scope of the problem, remember that China announced last year that it will invest $360 billion in renewables by 2020 – and that's considered a "good start" (Forsythe 2017). Yet we also must keep in mind the enormous costs associated with maintaining the status quo.

I think that's why I bristle a bit at the idea of "energy miracles." There is no simple, “miraculous” solution to our world’s pressing energy crisis. There is no magical technology that is going to make the problem go away. Every new technology we come up with will have a cost, both in dollars and in social impacts, so I’m not asking for a miracle – and I’m not waiting for one. It will take all of us – scientists, engineers, economists, and policymakers – working collaboratively to create effective, affordable, pragmatic technologies, to develop smart, focused strategies to deploy these technologies at scale, and to build a healthy, sustainable, equitable, new worldwide energy economy.

## *References*


Berggreen, Jesper. 2018. "44% Wind — Denmark Set New Wind Energy Record In 2017." *CleanTechnica,* January 6. Online at https://cleantechnica.com/2018/01/06/44-wind-denmark- smashed-already-huge-wind-energy-records-2017/.

Bloomberg New Energy Finance. 2017. "Distributed Energy in Emerging Markets: Highlights from BNEF Frontier Power Analysis." November 21. Online at https://data.bloomberglp.com/bnef/sites/14/2017/11/BNEF-2017-11-21-Distributed-Energy-in- Emerging-Markets-White-Paper1.pdf.

Center for Sustainable Systems, University of Michigan. 2017. "U.S. Grid Energy Storage." August. Online at http://css.umich.edu/sites/default/files/U.S._Grid_Energy_Storage_Factsheet_CSS15- 17_e2017.pdf.

Centre for Public Impact. 2017. "The Solar Home Systems initiative in Bangladesh." October 20. Online at https://www.centreforpublicimpact.org/case-study/solar-home-systems-bangladesh.

Energy Systems, Argonne National Laboratory. 2017. GREET Life Cycle Model. Online at https://greet.es.anl.gov/.

Forsythe, Michael. 2017. "China Aims to Spend at Least $360 Billion on Renewable Energy by 2020." *The New York Times,* January 5. Online at https://www.nytimes.com/2017/01/05/world/asia/china-renewable-energy-investment.html.

Gitlin, Jonathan M. 2018. "2017 was the best year ever for electric vehicle sales in the US." *Ars Technica*, Jan. 4. Online at https://arstechnica.com/cars/2018/01/2017-was-the-best-year-ever- for-electric-vehicle-sales-in-the-us/.

Global Wind Energy Council. 2018. "Global Statistics." Online at http://gwec.net/global- figures/graphs/.

Global Wind Energy Council. 2018. "Global Status of Wind Power." Online at http://gwec.net/global-figures/wind-energy-global-status/.

Hill, Joshua S. 2017. "Denmark Generated Enough Wind Energy to Power All Its Electricity Needs on Wednesday." *CleanTechnica,* February 24. Online at https://cleantechnica.com/2017/02/24/denmark-generated-enough-wind-energy-power-power- needs-wednesday/.

International Energy Agency. 2017. *Renewables 2017.* Online at https://www.iea.org/publications/renewables2017/.

International Energy Agency. 2017. "IEA finds CO2 emissions flat for third straight year even as global economy grew in 2016." March 17. Online at https://www.iea.org/newsroom/news/2017/march/iea-finds-co2-emissions-flat-for-third-straight- year-even-as-global-economy-grew.html.

Lumb, Matthew P., et al. 2017. "GaSb-Based Solar Cells for Full Solar Spectrum Energy Harvesting." *Advanced Energy Materials,* volume 7, issue 20, October 25. Online at https://onlinelibrary.wiley.com/doi/pdf/10.1002/aenm.201700345.

Maloney, Peter. 2018. "US led surging global energy storage market in 2017, GTM says." *Utility Dive,* April 13. Online at https://www.utilitydive.com/news/us-led-surging-global-energy-storage- market-in-2017-gtm-says/521246/.

Renewable Energy Policy Network for the 21st Century. 2017. *Renewables 2017 Global Status Report.* Online at http://www.ren21.net/wp-content/uploads/2017/06/17- 8399_GSR_2017_Full_Report_0621_Opt.pdf.

Reuters. 2017. "China targets 35 million vehicle sales by 2025, NEVs to make up one-fifth." April 24. Online at https://www.reuters.com/article/us-china-autos-electric/china-targets-35- million-vehicle-sales-by-2025-nevs-to-make-up-one-fifth-idUSKBN17R086.

Richardson, Jake. 2018. "100 MW/400 MWh Fluence Energy Storage Project for Long Beach — World's Largest Li-Ion Battery Storage Project." *CleanTechnica,* January 24. Online at https://cleantechnica.com/2018/01/24/100-mw-400-mwh-fluence-energy-storage-project-long- beach-worlds-largest-li-ion-battery-storage-project/.

Ryle, Martin. 1977. "Economics of alternative energy sources." *Nature,* volume 267, May 12, pp. 111–117. Online at https://www.nature.com/articles/267111a0.

Smith, Matt. 2017. "Small-Scale Solar Is 'Leapfrogging' Limited Electric Grids in Africa and Asia." *Seeker*, October 4. Online at https://www.seeker.com/earth/energy/small-scale-solar-is- leapfrogging-limited-electric-grids-in-africa-and-asia.

Spector, Julian. 2018. "California's big battery experiment: a turning point for energy storage?" *The Guardian*, September 15. Online at https://www.theguardian.com/sustainable- business/2017/sep/15/californias-big-battery-experiment-a-turning-point-for-energy-storage

The Electric Vehicle World Sales Database. 2018. Online at http://www.ev-volumes.com/.

Tabuchi, Hiroko. 2017. "As Beijing Joins Climate Fight, Chinese Companies Build Coal Plants." *The New York Times*, July 1. Online at https://www.nytimes.com/2017/07/01/climate/china- energy-companies-coal-plants-climate-change.html.

U.S. DOE Office of Electricity Delivery and Energy Reliability (EDER). 2018. DOE Global Energy Storage Database. Online at https://www.energystorageexchange.org/projects.

U.S. DOE Office of Energy Efficiency and Renewable Energy (EERE). 2018. "2017 Distributed Wind Market Report." Online at https://www.energy.gov/sites/prod/files/2018/04/f51/2017%20DWMR%20Fact%20 Sheet%2004 2518-clean.pdf.

U.S. Energy Information Administration. 2017. "How much of U.S. carbon dioxide emissions are associated with electricity generation?" Online at https://www.eia.gov/tools/faqs/faq.php?id=77&t=11.

World Nuclear Association. 2018. "Nuclear Power in the USA." Online at http://www.world- nuclear.org/information-library/country-profiles/countries-t-z/usa-nuclear-power.aspx.

World Nuclear Association. 2018. "Plans for New Reactors Worldwide." Online at http://www.world-nuclear.org/information-library/current-and-future-generation/plans-for-new- reactors-worldwide.aspx.

# The Promise of Paris and Lessons from Paradise: Hawaii's Contributions to U.S. Pledges under the Paris Agreement

**Anukriti Hittle**[1]

## Of Pledges, National and Sub-National

With the signing of the Paris Agreement in 2015, for the first time countries came together to make voluntary pledges to mitigate climate change and keep warming to under 2 degrees Celsius over pre-industrial levels. At that time, the U.S. had taken the lead to bring countries such as China on board with climate change mitigation goals. Each country pledged what it could, bringing to the table Nationally Determined Contributions (NDCs). While the United Nations Framework Convention on Climate Change (UNFCCC) has increasingly acknowledged and included local and state efforts, the rhetoric for inclusion of such efforts reached possibly an all-time high at the 23rd Conference of the Parties (COP23) in November 2017. As the Trump administration in the U.S. made threats to desert the Paris Agreement, leading up to and at COP23 nations began to look to new leadership at the sub-national level.

This paper examines sub-national efforts in the United States to fulfill the promise of Paris, particularly in the case of Hawaii. It analyzes Hawaii's goals for the transition to clean energy and how they fit into the U.S.'s pledges (NDCs) for Paris; and lessons that a small island state like Hawaii can teach the rest of the

1 Anukriti Hittle is Policy Research Specialist, Social Sciences Research Institute, University of Hawaii and former East-West Center Visiting Scholar.

U.S., as it transitions to clean energy. Ultimately, it makes the case that sub-national participation is the key to achieving climate change mitigation, even within a global framework.

Hawaii has, arguably, the most aggressive goals for CO2 reduction in the nation. Hawaii's state-level efforts towards climate goals work intricately with its energy goals. Hawaii was the first state in the nation to set a legal deadline to become 100 percent renewable in the electric sector. The Clean Energy Initiative (HCEI) aims at making the power sector 100 percent renewable by 2045. A midterm goal is 70 percent clean energy (40 percent renewable, 30 percent energy efficiency) by 2030. Last year, California extended its climate change law signed in 2006 to change targets to slash total emissions 40 percent below the 1990 levels by 2030. [2] [3]New York has pledged to the same goals as well.[4]

Hawaii is one of 17 states and territories in the Climate Alliance, founded by Governors Jerry Brown of California, Jay Inslee of Washington and Andrew Cuomo of New York, "(i)n response to the U.S. federal government's decision to withdraw the United States from the Paris Agreement on climate change…This bi-partisan coalition of states is committed to the goal of reducing greenhouse gas emissions consistent with the goals of the Paris Agreement."[5] These states represent 36 percent of the U.S. population and approximately 40 percent of U.S. GDP. The 17 member alliance launched "America's Pledge on Climate Change" in October 2017 to "[c]ompile and quantify the actions of U.S. federal states, cities and businesses in order to help them reduce GHGs in line with the goals of the Paris Agreement…"[6]

**State Goals are Building Blocks: Lessons and Observations of Sub-national Participation**

Despite its geographic uniqueness as the only island state in the U.S., Ha-

2 Alessandra Potenza. "California Extends Its Ambitious Climate Change Law 10 Years." *The Verge*. Sep. 8, 2016. https://www.theverge.com/2016/9/8/12852556/california-climate-change-law-governor-jerry-brown-carbon-emissions

3 California Global Warming Solutions Act of 2006: emissions limit (2015-2016), Senate Bill no. 32. Chapter 249. https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=201520160SB32

4 Chelsea Harvey. "New York, California Lead State Efforts On Climate Change as Trump Retreats." *Newsweek*. Apr. 9, 2017. http://www.newsweek.com/new-york-california-state-efforts-climate-change-trump-retreats-580704

5 Climate Alliance website: usclimatealliance.org

6 Yihui Wang. "Initiative to Support U.S. Climate Pledge Under Paris Agreement." IISD. Nov. 7, 2017. http://sdg.iisd.org/news/initiative-to-support-us-climate-pledge-under-paris-agreement/

waii's experience in transitioning to renewable energy has some important lessons for the rest of the country and plays an interesting role in the fulfillment of the U.S.'s pledge towards Paris. At COP21, when the U.S. signed onto the Paris Agreement, it committed to cut emissions by 26-28 percent by 2025 over 2008 levels. With the election of Donald Trump to the Presidency in November 2016, the U.S. position has been a belligerent one as the administration threatens to pull out of the Paris Agreement. The reality of the situation is that the way the Agreement is structured, if the U.S. makes real on its intention, it will not be able to extract itself from the Agreement until 2020.[7] In any case, whichever way the national winds blow, it is clear that for many reasons, a robust sub-national effort must take place for the world's climate goals to be implemented. This is true in the United States as well, and what each state does at the sector level is central to climate change mitigation. At COP23, U.S. state-level participation came into sharper focus than ever before.

National and sub-national level goals have some similarities. It is interesting to note that the U.S. pledge and Hawaii's goals both use a high emissions year as a starting point. This means that when pledges are announced, these governments are already well on their way to accomplishing the goals. For the U.S. as a whole, this high point was in 2005, and in some scenario modeling that appears later in this paper, that is what is used for Hawaii as well for a starting point.

Focusing on even one sector can bring about significant progress towards stated goals. Hawaii has first focused on the power sector, then will tackle the transportation sector. In other states, perhaps similarly phased efforts would produce the most effective results. Additionally, Hawaii's emphasis on the power sector and its shift to renewables brings up the question of how the role of utilities will evolve—from the role of central generator and provider of power to that of buyer. By focusing on one sector, just as Hawaii is leading the nation in lessons learned regarding distributed solar generation, other states could pioneer and innovate on transportation, manufacturing, agriculture and other sectors. This would generate a state-level "lesson exchange" for achieving goals.

7 Article 28 of the Paris Agreement states:

1. At any time after three years from the date on which this Agreement has entered into force for a Party, that Party may withdraw from this Agreement by giving written notification to the Depositary.

2. Any such withdrawal shall take effect upon expiry of one year from the date of receipt by the Depositary of the notification of withdrawal, or on such later date as may be specified in the notification of withdrawal.

**Hawaii, A Fossil Fuel Dependent Paradise**

Hawaii has a unique geography in the U.S. and this makes for a unique electric grid. It is the only island state, and has a dispersed grid. It is not unlike many island nations in that it relies primarily on oil for electricity generation. This is one of many ways in which Hawaii straddles the U.S. and Pacific Island nations. According to the U.S. Energy Information Administration (EIA), Hawaii ranks 48th lowest of 50 states in the nation in per capita use of energy.[8] Hawaii's pleasant climate which requires almost no heating, and very little cooling, along with absence of heavy industry account for this low per capital energy usage.

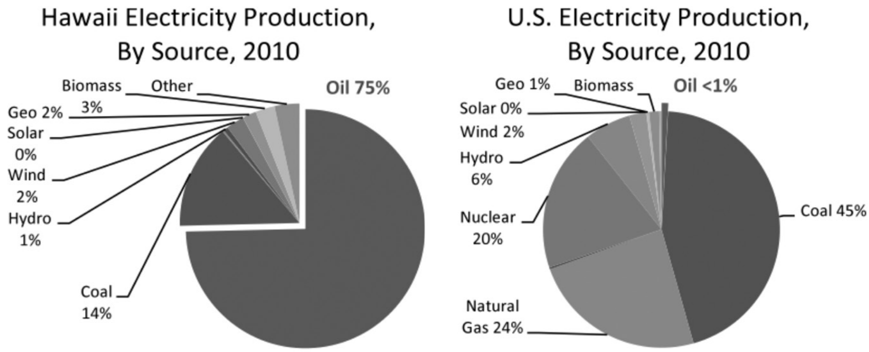
Despite low per capita energy use, Hawaii is the most petroleum dependent state in the nation. It imports oil (mostly from Pacific Rim countries) to convert to energy (EIA). It also imports coal from Indonesia and Colorado. EIA cites that "the transportation sector uses almost two-thirds of all petroleum consumed in Hawaii, and the electric power sector uses about one-fourth. Jet fuel accounts for more than half of all transportation fuels consumed in the state, and, because of significant demand from military installations and commercial airlines, jet fuel makes up a larger share of total petroleum consumption in Hawaii than in any other state except Alaska."

According to the State Energy Office, in 2011, Hawaii's energy use in the electric sector was about 75 percent from oil and only 13 percent from coal. There was no natural gas usage in Hawaii in 2011. In total, fossil fuel use in Hawaii is almost 90 percent. By contrast, national figures are 1 percent from oil and 45 percent from coal and 24 percent from natural gas. Total fossil fuel use for the nation is almost 70 percent. See Figure 1 below for details.

These numbers and the fuel mix have changed since 2011, but for this model and this paper, we use numbers from this time period.

8 Energy Information Administration website. "Rankings: Total Energy Consumed Per Capita, 2015." https://www.eia.gov/state/rankings/?sid=HI#series/12

Figure 1: Hawaii and U.S. Electricity Production by Source, 2010



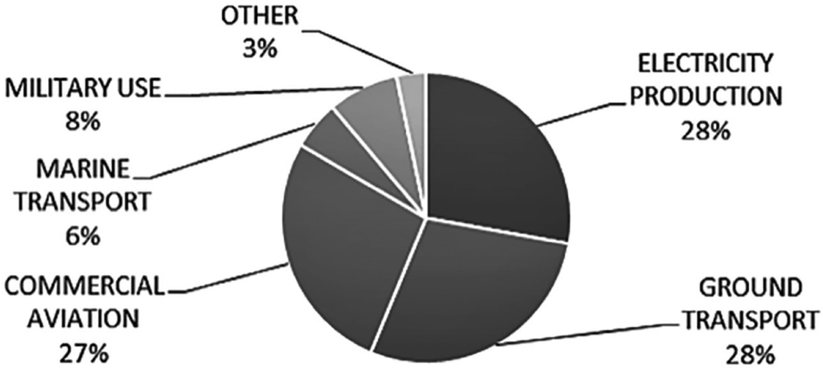

*Source: Hawaii State Energy Office*

For every dollar spent on fuel, Hawaii spends roughly 30 percent in the electric sector, 70 percent in transportation sector, which is split evenly between ground transportation and aviation. It follows then, that emissions from the electric sector, ground transportation sector and aviation sector are divided evenly at one-third each. See Figure 2 for details.

Overall, Hawaii's conversations have centered mainly around the power sector. With only one major electric utility, this makes it easier to produce results. The State's power utility, HECO, has promised cuts according to a schedule laid out by law. This year, HECO reported that these cuts will now happen five years ahead of schedule.[9]

9 AP. "Hawaii Board accepts utility company's renewable energy plan." *US News*. Jul. 19, 2017. https://www.usnews.com/news/best-states/hawaii/articles/2017-07-19/hawaii-board-accepts-utility-companys-renewable-energy-plan

Figure 2: Hawaii Petroleum Consumption by Sector




*Source: Hawaii State Energy Office. Hawaii Energy Facts and Figures. May 2016.*

**Modeling Model Behavior: How do Hawaii's Goals Measure up to US Pledges for the Paris Agreement?**

To show how Hawaii is faring in its goals, and to compare these to the U.S.'s national pledge for the Paris Agreement, a simple model was created.[10]

**Methodology**

**The timeline.** The U.S. pledge uses 2005 as a starting point, and we used this for Hawaii as well. For the U.S., the targets are to be met by 2025, and so, we modeled from 2005-2025 for the U.S.

For Hawaii, the key target years are 2030 and 2045. However, the discussion in this paper spans the period 2005-2025, which is the time frame for the U.S.'s Paris Pledge.

**Reduction levels.** The U.S.'s Paris Pledge was 26-28 % total cut over 2005 levels by 2025 to be achieved in two phases. First, reductions from 2005-2020 are to be 17%, which annualizes at 1.5%. Reductions then need to accelerate in phase 2, annualizing at 2.3-2.8%, to make the final target at the end of the 2020-2025 period.

What are the levels for Hawaii? For the power sector, the first target is a 70% reduction in emissions overall by 2030., then 100% renewable by 2040. A linear reduction to the 2030 goal was assumed. For ground transportation, the State of

10 Model and calculation spreadsheets are available upon request from the author.

Hawaii's Open Government Dashboard number for 2030 was used. The aviation sector was assumed to remain constant.

**Data used.** This model uses 2015 numbers to model out to 2025 because these were the most recent numbers released by EIA. Historical numbers used are also from EIA.[11]

**Modeling Hawaii's goals.** Hawaii's emissions were broken down into the three major emitting sectors: power, ground transportation and aviation. These sectors emit roughly one-third each (HECO 2011). Numbers from 2015 were taken and modeled out to 2025 to determine what Hawaii's emissions would look like in two different scenarios: if only the power sector goals were achieved; and if both ground transportation and power sector goals were achieved. Emission levels from aviation were left constant; we assumed gains due to efficiencies in fuel consumption and lighter aircraft materials will be offset by volume increase of flights to Hawaii. Besides, there seem to be no goals yet for the aviation sector as of the writing of this paper.[12]

**Results: Hawaii Wins the Race**

The model showed that Hawaii was ahead of the U.S. national pledge from the beginning, and will continue to race ahead. This is primarily because of the aggressive goals that Hawaii has set for itself. The historical data show that in 2008, when the economy experienced a downturn, Hawaii felt it severely. Declining tourism combined with the price of fuel led to reduced emissions overall. Since 2005, both U.S. and Hawaii emissions have continued to fall. For the U.S. this reflects the shift to natural gas, and for Hawaii, increasing renewable use, especially in the power sector.[13]

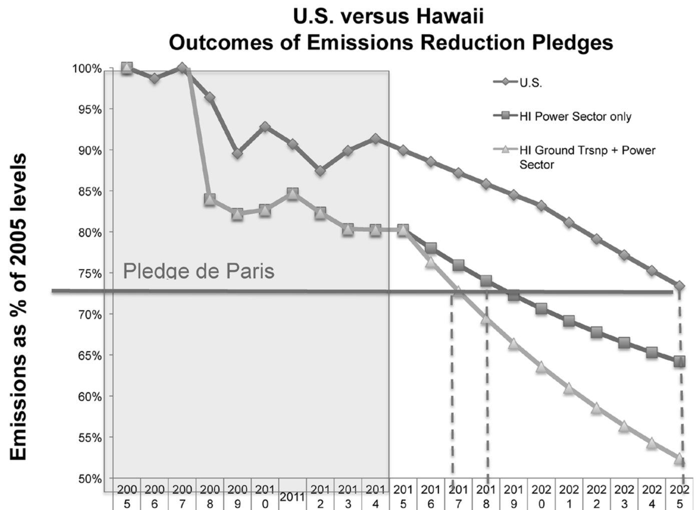
According to the annualized projections of the model, Hawaii will achieve its equivalent of the Paris goals by 2018/2019 even if it only makes cuts in the electric sector (the path indicated by the sloping red line in Figure 3). Had Hawaii done anything significant towards its published goals in the transportation

11 https://www.eia.gov/environment/emissions/state/analysis/pdf/table1.pdf

12 This was also confirmed by co-founder of the Hawaii Energy Policy Forum, Mike Hamnett, in a conversation in December 2017.

13 Hawaii State Energy Office. Hawaii Energy Facts and Figures. May 2016. *energy.hawaii.gov/wp-content/uploads/2011/10/FF_May2016_FINAL_5.13.16.pdf*

sector as well (the path indicated by the green line), these goals would have been achieved by 2017. In other words, Hawaii, if it makes good on its overall goals, will beat the U.S.'s Paris Pledge even if it only makes reductions in the power sector. Figure 3 details this discussion.




| | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| U.S. | 100% | 99% | 100% | 96% | 90% | 93% | 91% | 87% | 90% | 91% | 90% | 89% | 87% | 86% | 85% | 83% | 81% | 79% | 77% | 75% | 73% |
| HI Power Sector only | 100% | 101% | 105% | 84% | 82% | 83% | 85% | 82% | 80% | 80% | 80% | 78% | 76% | 74% | 72% | 71% | 69% | 68% | 66% | 65% | 64% |
| HI Ground Trsnp + Power Sector | 100% | 101% | 105% | 84% | 82% | 83% | 85% | 82% | 80% | 80% | 80% | 76% | 73% | 69% | 66% | 64% | 61% | 59% | 56% | 54% | 52% |



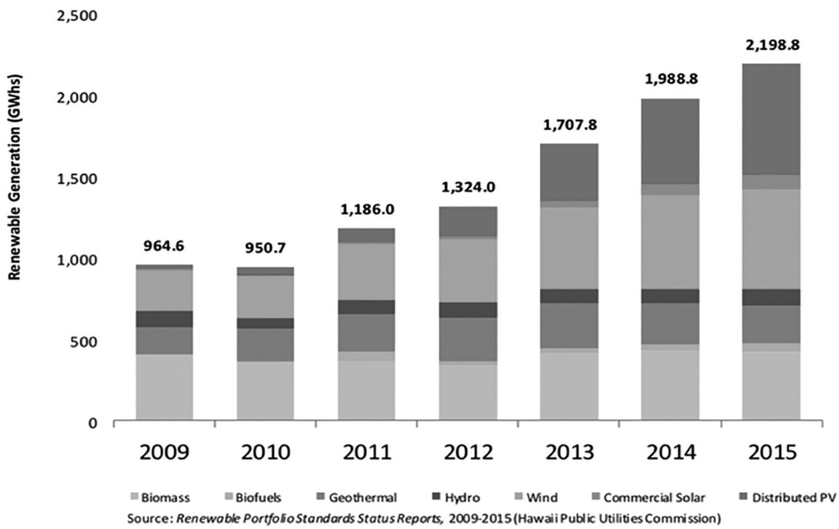
Figure 3: U.S. Versus Hawaii Outcomes of Emissions Reduction Pledges
*© Alexander Hittle and Anukriti Hittle. 2017.*

In Figure 3, the shaded grey box shows historical data from 2005 to 2015. The blue line graphs the U.S.'s total Greenhouse Gases (GHG) emissions; the (sloping) red and green lines graph Hawaii's total GHG emissions. Beyond the grey box are the model projections made from 2015 to 2025. The blue line shows total U.S. emissions of GHGs, assuming linear reductions to achieve what was pledged in Paris. The (sloping) red line graphs projections of Hawaii's total emissions with reduction occurring in the power sector only; and the green line graphs projections of Hawaii's total emissions with reductions occurring in both the power sector and the ground transportation sector. The horizontal red line (affectionately labeled "Pledge de Paris" in this graph) indicates the target reduction the U.S. announced in its NDC submission—here taken to be at 73 percent of 2005 levels (averaging 26-28 percent cuts to 27 percent, which would bring emissions levels to 73 percent).

**Renewable Energy: The Lesson from Distributed Solar in Hawaii**

To meet its climate change mitigation goals, Hawaii needs to generate electricity in a clean and efficient way. Hawaii has many sources of renewable energy: wind, solar, geothermal, biomass and wave. According to the Hawaii State Energy Office, in 2015, more than 23 percent of Hawaii's electricity generation was from renewables, mainly solar PV, wind and biomass. Figure 4 shows the renewable energy makeup in Hawaii.

Figure 4: Hawaii Renewable Energy Generation by Resource, 2009-2015




*Source: Hawaii State Energy Office. Hawaii Energy Facts and Figures, May 2016.*

At the utility scale level, wind energy generation in Hawaii outranks solar. However, in 2016, Hawaii ranked first in the nation for residential solar power per household.[14] Honolulu ranked first in the nation for solar photovoltaic (PV) capacity installed per capita and third for total solar PV capacity installed.[15] In 2001, a program called Net Energy Metering (NEM) was instated. It paid rooftop solar owners to send power back to the grid, at retail rates. The NEM program led to a significant increase in installed PV systems—doubling every year from 2010

14 Hawaii State Energy Office. Hawaii Energy Facts and Figures. May 2017. https://energy.hawaii.gov/wp-content/uploads/2011/10/HSEOFactsFigures_May2017_2.pdf

15 Environment America Center. "Shining Cities 2017." 2017.

to 2013. In 2015, the NEM program was shut down mainly because Hawaii Electric Industries (HEI), the main electricity provider could not cope with the growth in solar, as it created a glut in daytime solar energy production.[16] Since the end of the program, and now that PV owners have to pay a minimum monthly rate of $25, and are compensated only at wholesale rates, permit numbers have fallen 52 percent in the past year.

Hawaii's experience with solar energy generation has valuable lessons for other states. It shows how going too fast can make a program come to a halt. Caught between rate caps and net metering, the old utility model faced a glut and needed restructuring, something it had not planned for. The incentives were too high too early in the program, and PV adopters, having had a taste of big incentives are now holding out to see if those incentives will return. The rapid rate of solar adoption, the subsequent bottlenecks that emerged and the decline in permits issued shows that states need to roll out the energy transition plan in a more coherent and coordinated fashion. In short, a high net metering rate led to a boom and bust cycle for solar energy generation in Hawaii.

**Ground Transportation: Undefined Goals, Low Fuel Prices, and Traffic Congestion**

Americans have a love affair with personal vehicles, and Hawaii is no exception. Ground transportation contributes to about one-third of total emissions in Hawaii. While the power sector goals are easier to achieve because of the relative simplicity of the sector, transportation is a much more sticky issue, just as it is in the rest of the U.S. Ground transportation goals are not as defined for Hawaii as the goals for the power sector.[17] The Hawaii Energy Policy Forum, a consortium of energy leaders from various industry, research and citizen groups, might address goals in the relatively near future.

Hawaii has done well in setting goals for the power sector, and in making progress towards those goals. For the ground transportation sector, however, Hawaii needs to look further afield to examples in other countries, and learn some

16 Eric Wesoff. "Rooftop Solar In Hawaii Crashes With Loss Of Net Metering Lack Of Self Supply." *GTM*. Feb. 7, 2017. https://www.greentechmedia.com/articles/read/rooftop-solar-in-hawaii-crashes-with-loss-of-net-metering-lack-self-supply#gs.0TAfSD4

17 Duane Shimogawa. "Bill Sets 100 Percent Renewable Energy Goal for Hawaii Transportation Sector." *The Business Journals*. Jan. 27, 2017. https://www.bizjournals.com/.../bill-sets-100-renewable-energy-goal-for-hawaii.html

lessons from them. Norway, an oil producing country, has wiser policies than most towards how to use money from its oil resources. Famed for its disciplined people, Norway has set the most aggressive transportation goal in the world at having its fleet be 100 percent electric by 2025. Indeed, it will likely achieve its goal. Pricing gasoline at $7 per gallon, the highest in the world, according to Bloomberg's August 2017 report, Norway provides a huge disincentive to driving fossil fuel powered vehicles.

In the same vein, to own a car, consumers in Singapore pay a registration fee that starts at USD 30,000.[18] This does not include the cost of the vehicle itself nor of gasoline. Permits are auctioned monthly and in limited supply. The island city-state has implemented this to curb traffic congestion, but it is also an interesting tool for curbing emissions.

Hawaii would do well to learn from such examples. Currently, electric vehicles (EVs) number at 5,000 or 0.48% of the state's total fleet.[19] In addition to the small number of vehicles, the tricky issue of how these will be charged needs to be discussed. The Hawaii Clean Energy Initiative's Transportation Energy Analysis (2015)[20] announced that Hawaii is primed for a fast EV adoption rate, even if its absolute numbers are currently small.[21] However, EV adoption rates have not kept pace with expectations, according to the same report.

Along with adoption of renewable fuels and EVs, it would take a drastic increase in fuel prices to change consumer vehicle behavior. If the price of gasoline were 2 to 3 times that of the current price, it would be similar to that of the current electricity price situation in Hawaii. In fact, gasoline would approach Norwegian prices. Hawaii has introduced transportation bills, proposing to realign HCEI goals for the transportation sector, but where these will eventually end up still remains to be seen.[22]

18 Sebastian Tong. "Singapore Will Stop Increasing Car Numbers From February 2018." *Bloomberg*. Oct. 22, 2017.

19 Hawaiian Electric. Press Release. "As 5000th EV is registered in Hawaii, Drive Electric Hawaii Is Formed To Promote Electric Transportation For A Clean Energy Future." Dec. 20, 2016. https://www.hawaiianelectric.com/as-5000th-ev-is-registered-in-hawaii-drive-electric-hawaii-is-formed-to-promote-electric-transportation-for-a-clean-energy-future.

20 ICCT. "Hawaii Clean Energy Initiative Transportation Energy Analysis." *DBEDT and State Energy Office*. Aug. 2015. This publication notes that the total fleet in Hawaii is 1,035,000 passenger vehicles.

21 According to DBEDT monthly energy trends, there were 1,020 more EVs registered in Hawaii in March 2015 than in March 2014, suggesting annual EV sales of at least that number. Source: DBEDT (2015a). Monthly Energy Trends. Nov. 2017. http://dbedt.hawaii.gov/economic/energy-trends-2/

22 SB 1186 was introduced in the 2017 legislative session.

**Aviation: The Elephant Overhead**

Hawaii has a large tourism industry with approximately 8 million visitors per year. There are basically no alternatives to air travel to the Hawaiian Islands. The air transportation sector makes up a third of emissions in Hawaii, and has largely been ignored in energy conversations.

UN agency International Civil Aviation Organization (ICAO) announced a companion pledge to the Paris Agreement that will reduce global emissions from passenger and cargo flights. The first of such agreements, 191 nations signed this deal in October 2016. Airlines will use an offsetting scheme rather than a cap on emissions, costing up to 2 percent of the industry's total annual revenues. A benchmark will be set in 2020. Environmental groups believe this is only a beginning, and is far short of what is needed globally. In Hawaii, the conversation has not been broached at all, but a global deal in this sector may help produce some results in the State. The Hawaii Energy Policy Forum and state legislators have remained quiet on this front, preferring first to focus on the power and transportation sectors.[23]

**Will a Sub-national Climate Alliance Help Achieve the World's Collective Goal?**

My earlier co-authored paper "What did Paris Get Us? The Paris Agreement, A Carbon Club and the Decarbonization Miracle" asserted that the Paris Agreement's goals bought the global community five more years using the most optimistic assumptions.[24] Even if the U.S.'s NDCs are met under the Paris Agreement, the world will have to do much more to keep warming under 2 degrees. The Paris Agreement gives the world a few years to put some serious decarbonization policies in place, and to scale up research and development that will allow decoupling of economic growth from CO2 emissions to occur.

While a climate alliance at the sub-national level is a good start towards climate change mitigation, efforts must go beyond the Paris Agreement's nationally determined contributions. At the international level, the Global Stocktake mech-

23 Oliver Milman. "First Deal To Curb Aviation Emissions Agreed in Landmark UN Accord." *The Guardian*. Oct. 6, 2016. https://www.theguardian.com/environment/2016/oct/06/aviation-emissions-agreement-united-nations

24 Hittle, Anukriti and Alexander Hittle. "What did Paris Get Us? The Paris Agreement, the Carbon Club and the Decarbonization Miracle." Working Paper. Feb. 29, 2016. https://pages.wustl.edu/files/pages/imce/anukritihittle/fiveyearsfinal.pdf

anism has been put in place to help raise ambition among nations beyond their initially reported NDCs. Similarly, at the sub-national level, such a ratcheting up of ambition is needed to eventually feed into the national and global efforts.

**Recommendations: A Visible and Simple Scoreboard Will Ratchet Up Sub-national Ambition**

Hawaii albeit a small state, can provide some lessons for the rest of the country. As part of the Climate Alliance, Hawaii can help to ratchet up ambition within the sub-national players. A scoreboard of achievements could be constructed for the members of the Climate Alliance. Such a scoreboard would provide a visible set of achievements, and create friendly rivalry amongst the members. In the spirit of the Paris Agreement, where it is hoped nations will ratchet up ambition, and name and shame those that do not play, Hawaii should continue to lead at the sub-national level.

# Environmental Economics, Developing Nations and Michael Greenstone

**Rema Hanna**[1]

I am very excited for this opportunity to honor Michael Greenstone and his work in shaping how we think about environmental economics in developing countries. What I'd like to do today is talk about Michael's contributions in development and environmental economics, particularly around why we even really care that environmental economics is being focused on developing countries. I also will discuss work with Michael that illustrates the complexity of crafting effective environmental policy in developing countries and the potentially big pay-offs of effective policy.

Michael was my graduate school advisor. At the time, fifteen years ago, I was very interested in development economics, and I was also increasingly interested in environmental economic questions. But I also felt very disconnected from the environmental economics field, in part because it very much had a U.S.-based focus. Most of the papers at the top conferences on environmental economics were focused on U.S. environmental policies and their impacts, and I felt a little disconnected from all of that. I showed up at Michael's office as a development economist wanting to work on environmental issues in developing countries, and Michael was incredibly supportive. He was not just supportive towards me but also toward many other young scholars interested in this same area of research.

In preparation for my talk today, I did a very quick, non-scientific count to assess how the field of environmental economics has changed in the last fifteen

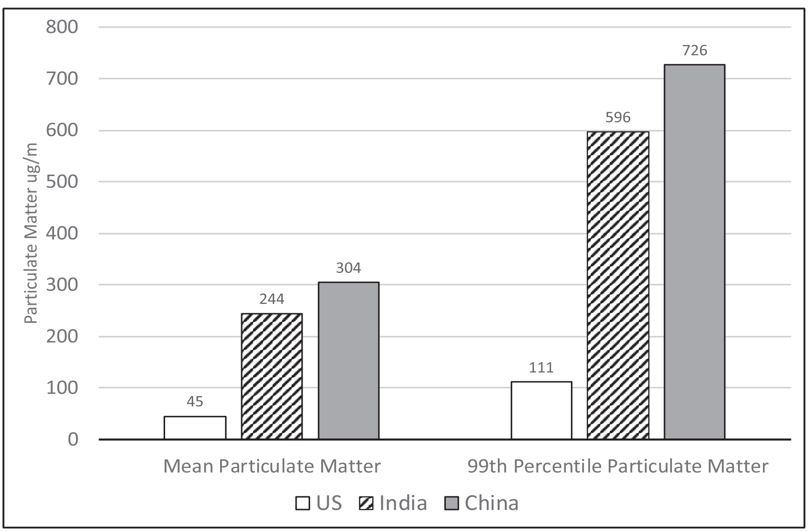
1 Rema Hanna is the Jeffrey Cheah Professor of South-East Asia Studies at the Harvard Kennedy School and Co-Director of the Evidence for Policy Design (EPoD) research program at the Center for International Development, Harvard University.

years. Today about a quarter of top working papers in environmental economics are now focused on developing countries. Many of these papers are Michael's but also many of them are by scholars, like myself, who have been students of Michael's and who he has mentored through the years. So, I cannot talk enough about his impact on the field.

Also, in preparation for my talk today, I went back to Michael's work and observed that he has written 65 papers on environmental economics published in the top journals. Most of these are very influential papers. He has worked on topics ranging from the long run impacts of air pollution on health in China, to the effect of temperature on mortality in India, to measuring the impact of improved toilets in India. Some of his most important work is on how to get developing country governments to think seriously about environmental regulation and effectively implement it.

Why do we care about whether or not environmental economics research is being done in developing countries? If there is research being done in the U.S. setting, why can't we just learn from that and apply it to developing countries? There are several different reasons why researching environmental problems in developing countries is very important.

Figure 1




*Source: (Greenstone and Hanna 2014:3040; Copyright American Economic Association; reproduced with permission of American Economic Review.)*

First, levels of air pollution differ greatly between developed and developing countries. Consider Figure 1 from Greenstone and Hanna (2014) that shows mean levels and the 99th percentile particulate levels in the U.S., India and China. Average particulate levels and 99th percentile levels in India and China are five to seven times higher than in the U.S. In fact, the 99th percentile level of particulate pollution in the U.S., the worst of the worst pollution, is way below the average pollution levels in India and China. The magnitude of differences is important if we think about the relative effect of pollution on health in developed versus developing nations.

Second, the health effects of pollution are not linearly proportional to levels of pollution. The effect of pollution varies by whether or not pollution is at a very low level or pollution is at a very high level. For example, Arceo, Hanna and Oliva (2016) demonstrate that non-linearities may exist for certain types of pollutants, such as carbon monoxide in Mexico City – doubling air pollution more than doubles its negative health effects.

Third, it is not just that pollution is higher in developing countries and has more than proportional negative impact, but people in developing nations know less about the existence of pollution and its impacts. In the U.S., pollution levels are monitored and air quality alerts issued at high levels of pollution, so people are more likely to know when it's a high pollution day. But in most developing countries, pollution levels are not measured or if they are, citizens have difficulty learning that information. In fact, a survey I ran in Mexico City showed low awareness of the severity and impact of pollution in a city which suffers from severe air pollution. People in developing countries might not know that much about pollution and its effects, and so may not make efforts to protect themselves from pollution.

Fourth, even if people in developing nations did know the extent and impact of pollution, it might be harder for them to protect themselves. In the U.S., we have very good medical care and good housing stock with air conditioning. We have lots of different ways to protect ourselves against the outside air and the outside elements. In developing countries, poor families struggling with necessities lack the resources to protect themselves from more detrimental effects of pollution in these countries. Poorer families may find it harder to make health investments that reduce the effects of pollution.

Finally, people in developing countries struggle not just with ambient air pollution but also with high pollution levels generated within their homes from solid fuel cook stoves, a problem absent in developed nations. Worldwide the number of deaths attributed to household indoor air pollution from solid fuel cook stoves is similar to that attributed to ambient particulate matter. The World Health Organization estimates that these polluting stoves pose health hazards to poor people similar to malaria and tuberculosis combined. (Hanna, Duflo, Greenstone 2016:80) Other studies rank indoor air pollution as one of the most important environmental causes of disease, contributing to acute respiratory infection, one of the leading causes of child mortality in the world, and having long-term effects on health and well-being in developing nations. (Duflo, Greenstone, Hanna, 2008:1)

Let me turn then to the case of cook stoves to illustrate the importance of carefully studying environmental problems at ground level in developing countries. Crafting effective environmental policy requires comprehensive, carefully researched policies.

At first glance, improving cook stove technology in developing nations seems to be an obvious solution to improve environmental health in developing nations. However, careful research (Hanna, Duflo, Greenstone 2016) has shown that seemingly simple technological solutions are not easily adopted and maintained and that "it is critical to allow for household behavior when evaluating health and environmental technologies to understand their actual effects." (Hanna, Duflo, Greenstone 2016:111)

This research, one of the first projects I worked on with Michael, worked with an NGO in Orissa, India, one of the poorest places in India. This NGO had raised money for a stove distribution program, and they were planning to phase in the distribution of stoves over five years. However, they had previously run a stove distribution program and thought it had not really worked. This time they wanted to research whether or not improved, cleaner cook stoves will actually produce positive effects on the health of women and children. The NGO looked at lots of different types of alternatives to this really dirty stove, and they decided to use one that is relatively common, cheap and easy to be made locally. It's also a mud stove, but it burns more efficiently, using less fuel, and has a chimney to direct smoke out of the household.

Our study followed households over a long time to evaluate the impact of the improved stoves. This was a six year study that gathered a large amount of data, but a key point from all of this was that in practice the improved stoves did not live up to their promise. Households must willingly embrace a new technology for it to improve their lives. Even at the beginning not everybody took up a stove. Even when you gave people a very, very subsidized version of this stove, only 65 percent of the households took one. Over time, the stoves broke and people stopped using them. Only 44 percent of people who got a new stove were actually using it by year three. Also, even households that had the stove were not using it regularly. They were using their old stove, which they felt was much more convenient. The number of meals cooked with the good stove started off a little bit above three meals a week and then decreased over time to less than two meals per week.

Not surprisingly, since the stoves were not really used that often by people who got the new stoves, we did not find the stoves having any positive effects on health or productivity. The stoves were predicted to decrease respiratory illness and so healthier children would attend school more and healthier farmers would cough less and work more. We saw none of this.

In the environmental economics field, this paper changed the way people thought about research methodologies around these kind of topics in three ways. First, in the past, a lot of the studies around stoves or other types of environmental technologies were often done in a lab under the best possible conditions with perfect equipment, and things worked beautifully. But life is not like that. In the real world real people make decisions for many different reasons that don't necessarily match those of researchers or policy makers. If we really want to understand impacts, we have to work with real people, with real organizations in the field. A second important feature of this paper is the scale of our study. We could have done something really small. We could have worked with 100 households, made sure all of them got the perfect stove, made sure they used it, put a lot of effort and time in terms of making sure this program went well. The truth is, we really want to understand things at large scales with real governments and non-profits distributing these kinds of stoves and running these kinds of programs. What does it look like, warts and all? How it is going to function in reality? This study was one of the first, big studies in the environmental economics field of this kind that was really trying to see what happens when you do things at a scale that you would like to do from a policy perspective.

The final way this study changed the debate around environment and development is that many similar studies done in the field at the time were often very short. For example, they would give people an environmental technology and see what happens after six months. For us, at six months, we actually saw people were using the stoves and we saw some reductions in smoke exposure. If we had stopped our study there, we would have said there was some reduction in smoke exposure. This is great. We're not seeing health effects, but they'll come in the future. So maybe we should escalate this program. It was only by year three that we saw how people changed their mind about using the technology over time. The technology depreciated. It was hard to fix. People went back to their old habits. Life happened, and we would not not have seen that in a shorter study. In the end, the new stoves did not have much of an effect. So if we did a very short run study, we would have had very different policy results than the long run study.

There are potentially large public and private health payoffs to improved cook stoves. But much more work needs to be done to discover how to overcome the significant barriers to widespread adoption of better, more efficient stoves.

## *References*

Arceo-Gomez, Eva O., Rema Hanna, and Paulina Oliva. 2012. "Does the Effect of Pollution on Infant Mortality Differ Between Developing and Developed Countries? Evidence from Mexico City." *Economic Journal*, January 2016.

Duflo, Esther, Michael Greenstone and Rema Hanna. "Cooking Stoves, Indoor Air Pollution, and Respiratory Health in Rural Orissa" *Economic and Political Weekly,* pp. 71-78, August 2008.

Duflo, Esther, Michael Greenstone and Rema Hanna, "Indoor air pollution, health and economic well-being" *Surveys and Perspectives Integrating Environment and Society*, Vol. 1(1), pp. 7-16, February 2008.

Greenstone, Michael and Rema Hanna "Environmental Regulations, Air and Water Pollution, and Infant Mortality in India," *American Economic Review*, 2014, 104 (10): 3038-3072.

Hanna, Rema, Esther Duflo, and Michael Greenstone, "Up in Smoke: The Influence of Household Behavior on the Long-Run Impact of Improved Cooking Stoves," *American Economic Journal: Economic Policy*, 2016, 8 (1): 80-114.

Hanna, Rema and Paulina Oliva, "The Effect of Pollution on Labor Supply: Evidence from a Natural Experiment in Mexico City," *Journal of Public Economics*, Vol. 122, February 2015.

Hanna, Rema and Paulina Oliva "Implications of Climate Change for Children in Developing Countries" in the *Future of Children Issue on Climate Change*, Princeton-Brookings, Spring 2016.

Hanna, Rema and Paulina Oliva. "Moving Up the Energy Ladder: The Effect of a Permanent Increase in Assets on Fuel Consumption Choices in India", *American Economic Review Papers and Proceedings*, May 2015.

# Climate and Development: Where Mitigation and Adaptation Collide

**B. Kelsey Jack** [1]

I delighted to be here participating in this forum on Energy and the Wealth of Nations featuring Michael Greenstone as the Miller Upton Scholar. I am biased since I work in this area, but I think this topic is one of the most important issues we could be discussing today.

As I was thinking about what to discuss here, I went back to a paper that Michael and I wrote a couple of years ago where we asked "Why is environmental quality so poor in developing countries?" (Greenstone and Jack 2015: 7). In this paper, we talked through some of the reasons that environmental economics might look different in a developing country, and then at the end, we had a short section on climate change. The impact of climate change in developing countries was not the point of the article, but we felt that we really could not write an article about environmental and development economics -- which we cheekily named "Envirodevonomics" -- without mentioning climate change, the elephant in the room and the most important topic in Envirodevonomics.

Today I will explain why climate change is such a big deal for thinking about environmental and development issues in developing countries. The response of households and nations to the threat of climate change can be classified into two broad categories: adaptation or mitigation. Adaptation is the term used to refer to efforts to minimize the impacts of climate change as it occurs, through technologies, like air conditioning, or other adjustments including migration. Mitigation refers to efforts to prevent or reduce future impacts by addressing the root causes of climate change, primarily anthropogenic greenhouse gas emissions.

I will make four points that might seem pretty obvious, but, when considered

1 B. Kelsey Jack is James L. Paddock Assistant Professor of Economics, Tufts University.

together, their implications are staggering. First, climate change hurts economic development and human well-being. We may all have this intuition, but I will discuss some recent research that quantifies how climate change hinders development. Second, climate change matters less if you are rich. Adaptation to warming or changing climates is easier for wealthier households and wealthier nations. The poorest places in the world will be the places most harmed by climate change and are also the places with the fewest resources to adapt to climate change. Third, a good adaptation strategy, therefore, is for households and nations to get richer so they can protect themselves from the effects of climate change. However, economic development -- getting richer -- is carbon-intensive and so undermines efforts to mitigate climate change. Which leads, consequently, to my fourth point: balancing economic development and climate damages, resolving the conflict between adaptation and mitigation, requires new strategies.

My first point is based on a growing body of research, summarized by Carleton and Hsiang (2016), that compellingly shows that climate change hurts economic development. This research tries to quantify how changes in climate impact economic outcomes. Climatic changes are hard to measure, but since a change in the climate is broadly similar to a change in average weather, researchers can use variations in weather within a particular location to learn something about the likely impacts of climate change. Hotter days, in particular, are associated with worse economic outcomes. For example, a recent paper co-authored by Michael Greenstone describes the impact of temperature on mortality in India (Burgess et al. 2017). Figure 1a of the paper shows how mortality rates in India and the United States respond to fluctuations in temperature, where the estimates come out of analysis that looks at variation relative to the long-run average temperature in a particular location within either of these countries. This analysis effectively performs the following thought experiment: what if we took a day out of a lower temperature bin and put it into a higher temperature bin? What does a permanent shift upward in these temperature bins mean for mortality outcomes? The figure provides convincing evidence that the higher temperatures caused by climate change in India will literally kill people. Mortality rates increase dramatically at higher temperatures in India. The same is not true in the United States, a point that I will return to later.

Similar negative impacts are found for other, less dire economic outcomes. As summarized in Carleton and Hsiang (2016), higher temperatures are associated with lower productivity, increased conflict, and even more mundane outcomes like increased use of profanity on social media. People are just less happy when the temperature is higher; human well-being, even on the most basic level, is potentially going to be worse in the face of climate change.

This brings me to my second point: climate change matters less if you are rich. People are decent at offsetting the negative impacts of climate change when they have the means to do so. However, what we call adaptation, the ability to experience higher temperatures and be less harmed by them, is an expensive project. So, when we compare richer places in the world with poorer places in the world, we see that the richest places in the world are less sensitive to variations in temperature or precipitation.

One study, by Burke et al. (2015), divides the world into richer and poorer countries. Analyzing the relationship between temperature and GDP, again looking only at variation relative to a country's own long run average temperature, shows striking differences in how GDP is affected by temperature. The richer countries show considerably less responsiveness to temperature fluctuations than do the poorer countries.

Returning then to the mortality impacts analyzed by Burgess et al (2017), the difference in the impact of temperature on mortality in the United States versus India shows similar patterns. Turning the temperature up a notch in India has serious impacts on mortality rates, whereas that same variation in temperature in the United States has essentially no effect on mortality rates. The authors then compare rural India and urban India in Figure 1b of their paper. Even in urban India, people have found good ways to protect themselves from variations in temperature, which shows little mortality response to temperature. There are many channels through which higher temperatures affect rural India. It is not just the heat that is killing people. Higher temperatures reduce agricultural incomes, which also affect mortality.

Another striking paper that Michael recently published compares the United States in the first half of the 1900's to the United States in the second half of the 1900's (Barreca et al. 2016). They find that, in the first half of the century, 1929 to 1959, high temperatures had huge impacts on mortality rates in the United States. Post-1960, this relationship levels off. Something changed -- lots of things have changed, right? The United States is a completely different country now than it was decades ago. Among the things that have changed has been the ability to experience hot days and not die as a result. This is potentially a useful lesson for thinking about how people adapt to climate change. If adaptation means not being impacted by some of the effects of climate change, this result suggests it is possible to adapt to global warming. Adaptation seems to be easiest in places and time periods where people are relatively well off.

These historical results for the US suggest that a good adaptation strategy for a low income country, or even a low income household in a high income country, is to increase income to be able to afford protection from the impacts of climate change. But economic growth tends to be carbon-intensive. This is my third point. Relative to poorer people, richer people consume a lot more carbon intensive things. The carbon emissions associated with the lifestyle of an average person in a high-income country are much higher than the carbon emissions from the average lifestyle of somebody in a low-income country.

In particular, Michael and his coauthors provide further evidence that one of the key factors that helped people in the United States avoid dying as a result of extreme temperatures in the 2nd half of the 20th century was air conditioners. As air conditioner penetration rates increased in the United States, the effect of climate on mortality decreases. In general, places where people have access to air conditioners are not experiencing the same kind of mortality impacts as places where people do not have access to air conditioners. Of course, many things besides the penetration rate of air conditions changed between the early and late 20th century in the U.S., but these results do suggest that a single technology can dramatically alter the impacts of higher temperatures. What does this result imply for climate policy in developing countries? One possible way forward is to find a way to get people into air conditioned buildings. The availability of air conditioners plausibly explains at least some of the difference between urban and rural India. Urban India has access to air conditioning, whereas rural India really does not. What this result suggests is that if you are a policy maker who wants to protect the population from the impacts of climate change, then find a way to get them up to the standards of living where they can afford air conditioners, rather than worrying so much about mitigation. Also, get to the point where the income sources that people have are less sensitive to climate variability; less dependent on agriculture, for example, and more dependent on economic activity that is not going to collapse in the face of warmer temperatures or less precipitation.

Higher incomes that are less dependent on agriculture may help with adaptation but are problematic from a mitigation standpoint. Evidence on the relationship between incomes and air conditioner adoption in Mexico shows that it is not necessary for governments to promote air conditioners (Davis and Gertler 2016).

Just make people a little bit richer in a hot place, and they buy air conditioners. The study finds that households begin buying air conditioners at pretty low levels of income, around $10,000 or $15,000 a year. This suggests that being cooler indoors is a really good investment in a place where temperatures are high.

As people get richer, the demand for air conditioners increases. As temperatures increases, it is not just that people buy more air conditioners, they also use them more. The whole point of buying an air conditioner is to turn it on when it is hot out. More people buying air conditioners and using them more as temperatures rise further increases energy use in developing countries. This is good news from the climate adaptation standpoint since it is consistent with people protecting themselves from high temperatures. However, it is really bad news for climate change mitigation because air conditioners are really intensive producers of greenhouse gases. Of course, I'm picking a bit on air conditioners, but plenty of other technologies that are good for adaptation are also bad for mitigation.

We all think the real way to deal with climate change is through mitigation. The problem is that mitigation is a public good, which reduces the incentive for any single nation to invest in mitigation. If India tries to cut back on its carbon emissions, India benefits some, but the rest of the world benefits as well. In contrast, adaptation investments, such as air conditioners, are private goods: a household that buys an air conditioner gets all of the benefits, even as using the air conditioner imposes costs on everyone through increased greenhouse gas emissions. Investments in adaptation do not have the same kinds of problematic market failures that undermine investments in mitigation. There is a particularly stark trade-off between adaptation and mitigation for a poor country or poor household where each dollar is really, really valuable. Poor households and poor nations have less interest in spending that dollar on something that benefits everybody. There is a problematic feedback: adaptation to a warming world leads to more warming which prompts more carbon-intensive adaptation, particularly as poorer households and nations pursue higher incomes and the climate adaptations such incomes afford. Increased adaptation then leads to more climate change.

This highlights my final point: the world needs new adaptation strategies without these kinds of negative feedbacks. One of the most important areas in climate change economics is to better understand what is going on in developing countries. Michael Greenstone's past research has highlighted many of the challenges I've described. I hope that his future research will make further progress toward answering how to resolve this conflict between climate adaptation and climate mitigation.

## *References*

Barreca, Alan, Olivier Deschenes, Joseph S. Shapiro and Michael Greenstone. 2015. "Convergence in Adaptation to Climate Change: Evidence from High Temperatures and Mortality, 1900-2004" *American Economic Review Papers and Proceedings*, 2015, 105(5): 247-51.

Burgess, Robin, Olivier Deschenes, Dave Donaldson, and Michael Greenstone. 2017. "Weather, Climate Change and Death in India: Mechanisms and Implications for Climate Change"

Burke, Marshall, Solomon M. Hsiang, and Edward Miguel. 2015. "Global non-linear effect of temperature on economic production," *Nature* volume 527, pages 235–239 (12 November 2015)

Carleton, Tamma A., and Solomon M. Hsiang. 2016. "Social and economic impacts of climate change," *Science* 09 Sep 2016: Vol. 353, Issue 6304.

Davis, Lucas W. and Paul J. Gertler. 2015. "Contribution of air conditioning adoption to future energy use under global warming" *Proceedings of the National Academy of Sciences* May 12, 2015.

Deschenes, Olivier and Michael Greenstone. 2011. "Climate Change, Mortality, and Adaptation: Evidence from Annual Fluctuations in Weather in the US" *American Economic Journal: Applied Economics*, 2011, 3(4): 152-85.

Greenstone, Michael and B. Kelsey Jack. 2015. "Envirodevonomics: A Research Agenda for an Emerging Field" *Journal of Economic Literature*, 2015, 53(1), 5-42

# Revisiting Shadow Prices and Environmental Efficiency of $SO_2$ and $NO_x$ Emissions by Coal-Burning Power Plants

**Jermaine Moulton**[1]

## *Introduction*

Measuring the cost of pollution from power plants is an important factor in formulating welfare-enhancing energy policies. While fulfilling electricity demand is the primary mandate of power plants, byproducts of such activity are pollutants such as sulfur dioxide ($SO_2$) and nitrogen oxide ($NO_x$). According to the Environmental Protection Agency (EPA), a significant proportion of all $SO_2$ and $NO_x$ emissions in the United States (U.S.) originate from electricity production. Consequently, the Clean Air Act Amendments (CAAA) stipulate targets to reduce these pollutants within two decades.

The main objective of this paper is to provide a framework to obtain shadow prices for $SO_2$ and $NO_x$. Shadow prices measure the pollution cost associated with producing an additional unit of electricity. Furthermore, it measures the cost of reducing an additional unit of a pollutant - marginal abatement cost. A good benchmark to measure the accuracy of my shadow prices is to compare them to the market prices of pollution permits (tradable permits). If they are similar, then my shadow price estimates are reliable.

Treating pollution as an undesirable output, I can model $SO_2$ and $NO_x$ emissions. To model the production of these pollutants, I estimate two "true" fixed ef-

1 Jermaine Moulton is Assistant Professor, Department of Economics, Beloit College.

fect models, one for each pollutant, proposed by Belotti et al. (2012) for 131 coal burning U.S. power plants. An advantage of this technique is its ability to separate unobserved differences between power plants from inefficiency. Obtaining pollution abatement efficiency for these pollutants is the second objective of this paper.

While electricity production is relatively straightforward to model, there is no consensus on how to model pollution. With electricity as the output variable in a production function, some studies include pollution as inputs (Lovell et al., 1995; Reinhard et al., 1999; Hailu and Veeman, 2001). Färe et al. (2005, 2006) criticized this approach because it assumes power plants can freely eliminate or reduce pollution emissions at no cost.[2] This criticism reflects costs power plants incur from purchasing tradable permits or from installing, maintaining, and using abatement technologies.[3] Additionally, with this approach, there is no method to compute efficiency estimates for reducing pollution abatement technologies.

As an alternative to the strong disposability approach, several studies use directional output distance functions to incorporate pollution in their models (Weber and Domazlicky, 2001; Ball et al., 2002; Färe et al., 2005, 2006; Feng and Serletis, 2014). This technique allows for the simultaneous increase in electricity production and the reduction of pollution. However, these studies could only obtain a composite efficiency measure. Specifically, these studies do not distinguish between efficiency in electricity production (technical efficiency) and reducing pollution (environmental efficiency). Furthermore, it is difficult to determine welfare improvement from a simultaneous increase in technical and environmental efficiencies without knowing the economic value of pollution (Färe et al., 2006). Thus, obtaining shadow prices for pollutants provide additional insights into abatement efforts by power plants.

Given the shortcomings of the conventional production function (strong disposability of pollution) and directional output distance functions in modeling pollution, Malikov et al. (2015) and Kumbhakar et al. (2016) use a system of equations approach. Assuming weak disposability of pollution, these papers use the "by-production technology" approach to separate electricity production from pollution. While Malikov et al. (2015) account for heterogeneity across power plants, they do not include an energy variable, a key input for pollution, in their model. Although

2 This is called the strong disposability of pollution in the literature.

3 These abatement technologies include, but are not limited to, low sulfur content coal and scrubber technologies.

Kumbhakar et al. (2016) include an energy variable in their specification, they do not control for heterogeneity across power plants. Additionally, both papers only estimate the shadow price elasticities for $SO_2$ and $NO_x$. To the best of my knowledge, this paper is the first to estimate shadow prices within a "true" fixed effect framework, while controlling for heterogeneity across power plants.

This paper has similar objectives to Coggins and Swinton (1996) and Mekaroonreung and Johnson (2012). While Coggins and Swinton (1996) use a translog output distance function to calculate shadow prices, Mekaroonreung and Johnson (2012) use a non-parametric technique proposed by Johnson and Kuosmanen (2011). However, both papers do not account for differences across power plants. Furthermore, the data Coggins and Swinton (1996) use do not include the total impact of the CAAA on power plants' abatement efforts. Thus, this paper is timely as I seek to investigate these gaps in the literature.

Since applying the weak disposability assumption is a newer approach to model pollution, there is no consensus on reasonable environmental efficiency levels for power plants. While Malikov et al. (2015) and Kumbhakar et al. (2016) both have similar environmental efficiency estimates, this paper provides an alternative to their system of equations "by-production technology" approach. Thus, the environmental efficiency estimates from this paper provide well-needed comparisons to previous studies.

**Method**

$SO_2$ and $NO_x$ emissions are determined by the following:

$$b_{j,it} = f(y_{it}, x_{it}, t)e^{u_{j,it}}, \quad j = 1, 2 \tag{1}$$

where $b_{1,it}$ and $b_{2,it}$ represent the production of $SO_2$ and $NO_x$, respectively, $y_{it}$ represents net electricity, $x_{it}$ represents the heat content of fuel, $t$ is the time trend, $f(\ )$ is the functional form for pollution emissions, and $u_{j,it}$ represents the error term for each pollutant. However, the true functional form to capture the production of these pollutants is unknown. Thus, it is useful to add nonlinearity to (1) to account for various possibilities. Therefore, (1) becomes:

$$lnb_{j,it} = \alpha_i + \beta_1 lny_{it} + \beta_2 lnx_{it} + \beta_3 t + \beta_4 (lny_{it})^2 + \beta_5 (lnx_{it})^2 + \beta_6 t^2 + \beta_7 lny_{it} lnx_{it} + \beta_8 lny_{it} t + \beta_9 lnx_{it} t + v_{j,it} + u_{j,it} \tag{2}$$

$v_{j,it}$ represents inefficiency in reducing $SO_2$ and $NO_x$. Thus, *ceteris paribus*, a power plant would emit more pollution the more inefficient it is in reducing pollutants, which seems intuitive. $\alpha_i$ accounts for any additional unknown differences between power plants. I estimate (2) by using the "true" fixed effect technique introduced by Belotti et al. (2012).[4]

Technical change is the change in the production of each pollutant over time. Technical change is different from technological change because technical change is influenced by organizational behavior, regulatory influence, and changes in inputs. From (2), there is technical progress if the derivative of the pollutant *w.r.t.* time is negative $\left(\frac{\partial lnb_{j.it}}{\partial t} < 0\right)$, while a positive value for the derivative, $\left(\frac{\partial lnb_{j.it}}{\partial t} < 0\right)$, indicates technical regress.[5]

The effect of electricity on emissions captures the cost of increasing electricity production in terms of increased pollution generation. This effect is the shadow price of pollution. Since it is a 'price', it must be non-negative. Said differently, power plants emit these pollutants mainly when they are generating electricity. As a result, each observation in the data must have $\frac{\partial lnb_{j.it}}{\partial lny_{it}} > 0$ for the shadow prices to be accurate. This is called the monotonicity condition in microeconomic theory.

**Shadow Prices for $SO_2$ and $NO_x$**

Assuming power plants are profit maximizers and are efficient, the profit maximization problem is:

$$\pi(p_x, p_y, p_b) = \max \ p_y y - p_x x - p_b b$$
$$s.t. \ f(x, b) = y \tag{3}$$

where $py$ is the price of electricity, $pb$ is a price vector for the pollutants (the shadow price of pollution), and $px$ is the price vector for the inputs that creates pollution. The Lagrangian would then be:

$$L = \ p_y y - p_x x - p_b b + \lambda[f(x, b) - y] \tag{4}$$

4 See Belotti et al. (2012) for more details.

5 Since pollution is costly to abate, a negative (positive) value for the derivative is technical progress (regress).

Solving for, the shadow prices gives us:

$$p_{b_j} = p_y \frac{\partial y_{it}}{\partial b_{j,it}}$$

**Environmental Efficiency**

I make the following distributional assumption on the inefficiency term:

$$v_{j,it} \sim N^+(0, \sigma_v^2), \quad j = 1,2$$

where the efficiency term has a half normal distribution with mean zero and variance $\sigma_v^2$. We need the half normal assumption to guarantee that all the efficiency scores are non-negative. With this assumption, I use the Battese and Coelli technique to calculate environmental efficiency for $SO_2$ and $NO_x$. The formula is:

$$EE_{j,it} = E\left[exp\{u_{j,it} | \varepsilon_{j,it}\}\right], j = 1, 2$$

where $EE_{j,it}$ represents environmental efficiency for each pollutant and $\varepsilon_{j,it}$ is the sum of the inefficiency and error terms.[6]

**Data**

The data consist of a balanced panel of 131 power plants from 2001 to 2012. Using Pasurka (2006) definition for coal-burning utilities, I only include power plants if coal consists of 95 percent of their fuel input. Additionally, I exclude power plants whose fuel consumption other than coal, oil or natural gas is more than 0.00001 percent of their total heat content.[7]

$SO_2$ and $NO_x$ are measured in tons. The two inputs, net electricity and heat, are measured in megawatt hours (mWh) and millions of British Thermal Units (mmbtu), respectively. Like Mekaroonreung and Johnson (2012), I use heat input as the indicator for fuel utilization. Heat is the heat content of coal and oil. The price of electricity is measured in dollar per megawatt hours (mWh).

6 See Battese and Coelli (1995) for technical details.

7 See Pasurka (2006) for more details on the definition of coal-burning power plants.

Table 1: Summary Statistics

| Variable | Mean | Standard Deviation | Min | Max |
|---|---|---|---|---|
| $SO_2$ | 25.12 | 29.74 | 0 | 206.44 |
| $NO_x$ | 9.60 | 8.82 | 0 | 47.37 |
| Price | 71.17 | 19.37 | 21.02 | 167.31 |
| Heat | 270.59 | 81.44 | 48.81 | 571.56 |
| Electricity | 6,394.12 | 5,197.09 | 15.01 | 25,190.00 |

The units of measurements for $SO_2$, $NO_x$, and electricity are $10^3 \times$ton, $10^3 \times$ton, and $10^3 \times$mWh, respectively.

Data for $SO_2$ and $NO_x$ emissions come from the EPA's Clean Air Market dataset. The data for heat content, electricity prices, and electricity production are from the EIA 767, EIA 861, and EIA 923 surveys, respectively. I collect data for the age of power plants and boiler size from the Federal Energy Regulatory Commission's Form 1 survey.

**Results**

Table 2 reports summary statistics of shadow price estimates for both pollutants. Consistent with the literature, most shadow prices for $SO_2$ are lower than $NO_x$. Specifically, on average and *ceteris paribus*, it would cost a power plant \$307.22 and \$790.75 to abate an additional ton of $SO_2$ and $NO_x$, respectively. There is more variability in $SO_2$ shadow prices. Furthermore, the average technological change for both pollutants is negative. These results indicate an average annual reduction in $SO_2$ and $NO_x$ emissions by 2.69 percent and 2.24 percent, respectively. Further analysis of the technological change results reveals symmetry in the estimates for both pollutants.

Table 2: Distribution of shadow prices, technological change, and efficiency.

| | Mean | Median | Min | Max |
|---|---|---|---|---|
| **Shadow Price** | | | | |
| $SO_2$ | 307.22 | 310.60 | 42.97 | 4,118.32 |
| $NO_x$ | 790.75 | 683.66 | 189.43 | 2,695.24 |
| **Technological Change** | | | | |
| $SO_2$ | -0.0269 | -0.0274 | -0.0884 | 0.0526 |
| $NO_x$ | -0.0224 | -0.0226 | -0.0484 | 0.0376 |
| **Environmental Efficiency** | | | | |
| $SO_2$ | 0.6000 | 0.6460 | 0.0041 | 1.0000 |
| $NO_x$ | 0.8550 | 0.8913 | 0.2306 | 1.0000 |

In Table 3, I report the average shadow price estimates of each pollutant to actual EPA's market prices of tradable permits. While my shadow price estimates only use production data, the market prices reflect additional factors such as further environmental compliance. Yearly market prices for $NO_x$ permits are consistently higher than their $SO_2$ counterparts. Lower supply of tradable $NO_x$ permits is one reason for the higher $NO_x$ market prices.

Table 3: Shadow Prices and Market Prices of $SO_2$ and $NO_x$.

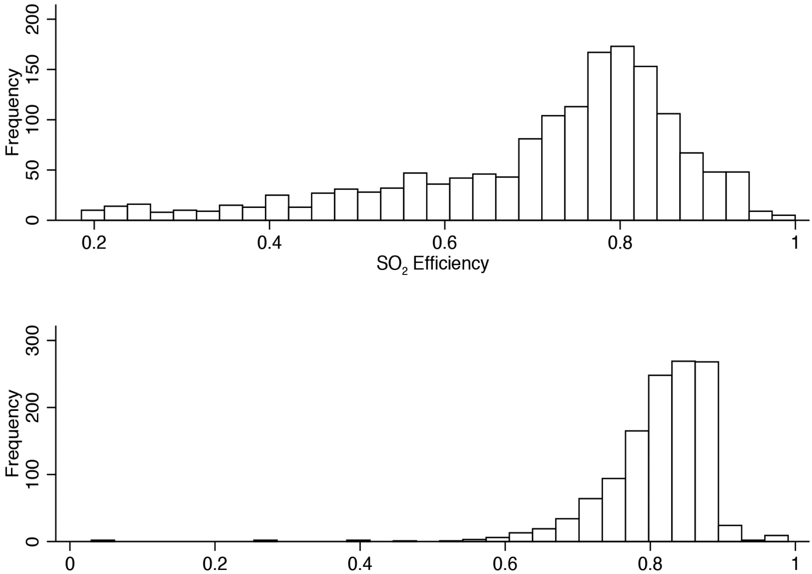
| | $SO_2$ | | $NO_x$ | |
|---|---|---|---|---|
| **Year** | **This Paper** | **Market Prices** | **This Paper** | **Market Prices** |
| 2001 | 172 | 135-210 | 486 | 600-1700 |
| 2002 | 179 | 130-170 | 506 | 600-1700 |
| 2003 | 188 | 150-220 | 538 | 2500-8000 |
| 2004 | 199 | 215-700 | 585 | 2100-3700 |
| 2005 | 315 | 700-1500 | 728 | 2000-3500 |
| 2006 | 234 | 430-740 | 673 | 900-2725 |
| 2007 | 270 | 500-600 | 759 | 500-1000 |
| 2008 | 318 | 179-509 | 831 | 592-1400 |

1. The prices are in $/ton.
2. I only report the weighted average of the prices.
3. I obtain market price data for $SO_2$ from the EPA's Acid Rain Program Progress Report. The EPA's Ozone Transport Commission (OTC) $NO_x$ market prices.
4. The $NO_x$ market prices are the same for 2001 and 2002 because the EPA published one year for both years.

For $SO_2$, the shadow price estimates closely match the range of market prices, especially for the first four years. Conversely, my $NO_x$ shadow prices underestimate their market prices during the earlier years in the sample period. In 2007 and 2008, however, the $NO_x$ shadow prices and their market prices are closely aligned. In 2005, both mean shadow prices increase by a greater percentage compared to previous years. In fact, this increase is also present in market prices for $SO_2$ tradable permits for that year. This increase coincides with the announcement of the Clean Air Interstate Rule (CAIR), which requires power plants to reduce emissions beyond the targets from the CAAA. This announcement results in an increase in the demand for more tradable permits to save for future use. I do not report the shadow price estimates after 2008 because they are not comparable to market prices. The implementation of the CAIR results in an uptick in the availability of banked emission allowances. Also, there is an increase in abatement technologies used by power plants. The increase in the supply of allowances and the use of abatement technologies result in a significant decline in market prices for pollution permits.[8]

8 The latest progress report reveals that the allowance prices for $SO_2$ and $NO_x$ are less than $1 per ton and $40 per ton, respectively.

Figure 1: $SO_2$ and N




The average environmental efficiency score for $SO_2$ and $NO_x$ are 0.60 and 0.86, respectively. *Ceteris Paribus*, given the same resources, power plants can, on average, reduce $SO_2$ and $NO_x$ emissions by 40 percent and 14 percent, respectively. Figure 1, reveals significant variations in $SO_2$ efficiency across power plants. Though to a lesser extent, there are variations in $NO_x$ efficiency across power plants. Similar to Mekaroonreung and Johnson (2012), Malikov et al. (2015), and Kumbhakar et al. (2016), I find most power plants are more efficient in reducing their $NO_x$ emissions. A key factor explaining the higher $NO_x$ efficiency is higher, on average, prices for tradable permits. Since $NO_x$ tradable permits are costlier to obtain, power plants would have to be more efficient in reducing $NO_x$ emissions to meet their pollution targets.

Table 4: Yearly Efficiency Score for $SO_2$ and $NO_x$.

| Year | Pollutant | Mean | Min | Max |
|---|---|---|---|---|
| 2001 | $SO_2$ | 0.5979 | 0.0041 | 0.9998 |
| | $NO_x$ | 0.8433 | 0.2824 | 0.9707 |
| 2002 | $SO_2$ | 0.6368 | 0.0057 | 0.9999 |
| | $NO_x$ | 0.8428 | 0.2419 | 0.9752 |
| 2003 | $SO_2$ | 0.6519 | 0.0068 | 0.9998 |
| | $NO_x$ | 0.8451 | 0.2306 | 0.9714 |
| 2004 | $SO_2$ | 0.6484 | 0.0068 | 0.9998 |
| | $NO_x$ | 0.8539 | 0.2817 | 0.9733 |
| 2005 | $SO_2$ | 0.6381 | 0.0058 | 0.9998 |
| | $NO_x$ | 0.8504 | 0.3298 | 0.9706 |
| 2006 | $SO_2$ | 0.6208 | 0.0149 | 0.9998 |
| | $NO_x$ | 0.8392 | 0.3139 | 0.9799 |
| 2007 | $SO_2$ | 0.6343 | 0.0107 | 0.9998 |
| | $NO_x$ | 0.8480 | 0.2787 | 0.9797 |
| 2008 | $SO_2$ | 0.6384 | 0.0092 | 0.9998 |
| | $NO_x$ | 0.8415 | 0.4092 | 0.9722 |
| 2009 | $SO_2$ | 0.6121 | 0.0141 | 0.9998 |
| | $NO_x$ | 0.9040 | 0.6247 | 1.0000 |
| 2010 | $SO_2$ | 0.5694 | 0.0251 | 0.9998 |
| | $NO_x$ | 0.8841 | 0.5457 | 0.9944 |
| 2011 | $SO_2$ | 0.4959 | 0.0823 | 0.9998 |
| | $NO_x$ | 0.8617 | 0.4735 | 0.9959 |
| 2012 | $SO_2$ | 0.4555 | 0.1026 | 0.9998 |
| | $NO_x$ | 0.8459 | 0.3948 | 0.9897 |

Table 4 details the temporal results of the efficiency scores. The $NO_x$ efficiency scores for most power plants are stable throughout the sample period. In contrast, the $SO_2$ efficiency scores for a number of power plants fall drastically over time. Interestingly, parent companies (utilities) are retiring most of these power plants or have reduced electricity production. These retiring power plants might give little thought on being efficient in reducing $SO_2$ emissions and are more concerned with merely fulfilling their emissions targets.

**Conclusion**

In this paper, I examine the cost of reducing $SO_2$ and $NO_x$ emissions to meet targets set by the CAAA. I also examine how efficient power plants are in reducing these pollutants. I achieve these objectives by using a "true" fixed effect frontier technique proposed by Belotti et al. (2012).

Using data from 2001 to 2012 for 131 power plants, I find the average shadow prices for $NO_x$ are higher than those for $SO_2$. The yearly shadow price estimates are in-line with actual tradable permit market prices published by the EPA. Since NO*x* shadow prices (and their tradable permits) are more expensive, power plants must be more efficient in reducing those emissions (this is in comparison to $SO_2$). This is the main reason pollution abatement efficiency scores, on average, are higher for $NO_x$. For most power plants, I find evidence of technical progress for both pollutants. Additionally, most power plants are more efficient in reducing $NO_x$, which is consistent with findings from previous studies.

## *References*

Ball, V. E., Färe, R., Grosskopf, S., Hernandez-Sancho, F., and Nehring, R. (2002). The Environmental Performance of the U.S. Agricultural Sector. *Agricultural Productivity*, pages 257-275. Springer.

Battese, G. E. and Coelli, T. J. (1995). A Model for Technical Inefficiency Effects in a Stochastic Frontier Production Function for Panel Data. *Empirical Economics*, Vol. 20(2): 325-332.

Belotti, F., Daidone, S., Illardi, G., and Atella, V. (2012). Stochastic Frontier Analysis using Stata. *CEIS Working Paper*.

Coggins, J. S. and Swinton, J. (1996). The Price of Pollution: A Dual Approach to Valuing $SO_2$ Allowances. *Journal of Environmental Economics and Management*, Vol. 30(1): 58-72.

Feng, G. and Serletis, A. (2014). Undesirable Outputs and a Primal Divisia Productivity Index Based on the Directional Output Distance Function. *Journal of Econometrics*, Vol. 183(1): 135-146.

Färe, R., Grosskopf, S., Noh, D., and Weber, W. (2006). Shadow Prices and Pollution Costs in U.S. Agriculture. *Ecological Economics*, Vol. 59: 89-103.

Färe, R., Grosskopf, S., Noh, D., and Weber, W. (2005). Characteristics of a Polluting Technology: Theory and Practice. *Journal of Econometrics*, Vol. 126: 369-492.

Hailu, A., and Veeman, T. (2001). Non-Parametric Productivity Analysis with Undesirable Outputs: An Application to the Canadian Pulp and Paper Industry. *American Journal of Agricultural Economics*, Vol. 83: 605-616.

Johnson, A. and Kuosmanen, T. (2011). One-Stage Estimation of the Effects of Operational Conditions and Practices on Productive Performance: Asymptotically Normal and Efficient, Root-*n* Consistent Stonzed Method. *Journal of Productivity Analysis*, Vol. 36(2): 219-230.

Kumbhakar, S. C., and Tsionas, E. G. (2016). The Good, the Bad and the Technology: Endogeneity in Environmental Production Models. *Journal of Econometrics*, Vol. 190: 315-327.

Lovell, C., Pastor, J., and Turner, J. (1995). Measuring Macroeconomic Performance in the OECD: A Comparison of European and Non-European Countries. *European Journal of Operational Research*, Vol. 87(3): 507-518.

Malikov, E., Kumbhakar, S. C., and Tsionas, E. G. (2015). Bayesian Approach to Disentangling Technical and Environmental Productivity. *Social Science Research Network*.

Mekaroonreung, M. and Johnson, A. L. (2012). Estimating the Shadow Price of Sulfur Dioxide and Nitrogen Oxide for U.S. Coal Burning Power Plants:

A Convex Nonparametric Least Squares Approach. *Energy Economics*, Vol. 34(3): 723-732.

Pasurka, C. (2006). Decomposing Electric Power Plant Emissions within a Joint Production Framework. *Energy Economics*, Vol. 28: 26-43.

Reinhard, S., Lovell, C., and Thijssen, G. (1999). Econometric Estimation of Technical and Environmental Efficiency: An Application to Dutch Dairy Farms. *American Journal of Agricultural Economics*, Vol. 81: 44-60.

Weber, W. L. and Domazlicky, B. (2001). Productivity Growth and Pollution in State Manufacturing. *Review of Economics and Statistics*, Vol. 83(1): 195-199.

## Contributors

Michael Greenstone   Andrew Revkin   Eric D. Isaacs   Anukriti Hittle
Rema Hanna   B. Kelsey Jack   Jermaine Moulton

Department of Economics

Beloit College

ISBN 978-0-578-20660-8
90000 >
9 780578 206608