



Electricity without Greenhous Gases: Essential to meeting the challenge of climate change

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It is particularly fitting...

...that I am speaking to you today from Pittsburgh, PA.



Rachel Carson graduated in biology from the Pennsylvania College for Women, now Chatham University, which is located just up the street from my CMU office.

As you can see from the image below, the Pittsburgh region proudly counts her as one of its own.

Rachel Carson – Pittsburgh's Conservationist

People > Rachel Carson – Pittsburgh's Conservationist

Today I will talk about three things:

1. Some basic background on:
 - Climate science
 - The electricity system
2. Why electric power is critical to climate change:
 - As a leading source of CO₂ and other GHG emissions and how to reduce those emissions
 - As the most viable option to replace fossil fuels
3. The need to expand electric power transmission capacity and some efforts we are undertaking to address the problem.

To be an informed participant...

...in public discourse about climate change people need to know three simple facts:

1. Burning coal, oil, and natural gas produces carbon dioxide that enters the atmosphere.
2. Carbon dioxide in the atmosphere warms the earth, and that warming changes the climate.
3. Once carbon dioxide gets into the atmosphere, much of it remains there for many hundreds of years.

My social science colleagues and I first studied what people know 30 years ago

Risk Analysis, Vol. 14, No. 6, 1994

What Do People Know About Global Climate Change? 1. Mental Models

Ann Bostrom,¹ M. Granger Morgan,² Baruch Fischhoff,² and Daniel Read²

Received August 16, 1993; revised February 7, 1994

A set of exploratory studies and mental model interviews was conducted in order to characterize public understanding of climate change. In general, respondents regarded global warming as both bad and highly likely. Many believed that warming has already occurred. They tended to confuse stratospheric ozone depletion with the greenhouse effect and weather with climate. Automobile use, heat and emissions from industrial processes, aerosol spray cans, and pollution in general were frequently perceived as primary causes of global warming. Additionally, the "greenhouse effect" was often interpreted literally as the cause of a hot and steamy climate. The effects attributed to climate change often included increased skin cancer and changed agricultural yields. The mitigation and control strategies proposed by interviewees typically focused on general pollution control, with few specific links to carbon dioxide and energy use. Respondents appeared to be relatively unfamiliar with such regulatory developments as the ban on CFCs for nonseasonal uses. These beliefs must be considered by those designing risk communications or presenting climate-related policies to the public.

KEY WORDS: Climate change; global warming; mental model; risk communication; decision making.

1. INTRODUCTION

The last decade has been marked by growing public concern and widespread media coverage surrounding the possibility of global warming due to an increased greenhouse effect.^(1,2) To a significant degree, the effectiveness with which society responds to this possibility depends on how well it is understood by individual citizens. As voters, citizens must decide which policies and politicians to support. As consumers, they must decide whether and how to consider environmental effects when making choices such as whether our resources are most efficiently deployed by using paper or polystyrene foam cups.⁽³⁾ Despite the crucial implications of their knowledge and opinions for public policy, little is

known regarding the public's literacy about global climate change.

The United States spends approximately \$1.5 billion annually researching global environmental change, including climate change. For that research to have any practical value, its results must find their way to decision makers, including individual citizens and policy makers. In order to educate the citizenry, we must start by educating ourselves about what they already know and believe and how it differs from what they need to know in order to make effective decisions. We cannot trust technical experts' intuitions about public beliefs.^(4,5) Indeed, many controversies in risk communication arise when experts either underestimate or overestimate the public's knowledge. Consequently, the provision of information should begin with an empirical assessment of what people already know, along with a scientific determination of what missing information is most critical to their decisions.^(6,7)

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Risk Analysis, Vol. 14, No. 6, 1994

What Do People Know About Global Climate Change? 2. Survey Studies of Educated Laypeople

Daniel Read,¹ Ann Bostrom,² M. Granger Morgan,¹ Baruch Fischhoff,¹ and Tom Smuts¹

Received August 16, 1993; accepted February 7, 1994

Drawing on results from earlier studies that used open-ended interviews, a questionnaire was developed to examine laypeople's knowledge about the possible causes and effects of global warming, as well as the likely efficacy of possible interventions. It was administered to two well-educated opportunity samples of laypeople. Subjects had a poor appreciation of the facts that (1) if significant global warming occurs, it will be primarily the result of an increase in the concentration of carbon dioxide in the earth's atmosphere, and (2) the single most important source of additional carbon dioxide is the combustion of fossil fuels, most notably coal and oil. In addition, their understanding of the climate issue was encumbered with secondary, irrelevant, and incorrect beliefs. Of these, the two most critical are confusion with the problems of stratospheric ozone and difficulty in differentiating between causes and actions specific to climate and more general good environmental practice.

KEY WORDS: Climate change; global warming; risk communication; public understanding.

1. INTRODUCTION

In the preceding paper,⁽¹⁾ we used open-ended interview methods to study how well several convenience samples of well-educated laypeople understand the issues surrounding climate change. We discovered a mixture of correct and incorrect beliefs (e.g., viewing the ozone hole as the principle cause of climate change, not realizing the role of carbon dioxide and fossil fuel consumption). We hypothesized that some of these misunderstandings could misdirect the public's support for proposed policies, as well as leave it vulnerable to manipulation by interest groups.

Open-ended elicitation procedures allow people to express their beliefs naturally, with a minimum of constraints imposed by the investigator's perspective. Unfortunately, they are very labor intensive and, thus, tend to have small samples. We used results from our previous interviews, and from related studies by Kempton,⁽²⁾ to construct a structured questionnaire which can be administered to large numbers of subjects. In this paper we give a more precise indication of the frequency with which beliefs observed by Bostrom *et al.* and by Kempton are encountered among well-educated laypeople. We reasoned that the beliefs and opinions of such well-educated people are of particular importance because they may be opinion leaders in their communities and are likely to take on activist and leadership roles—indeed, one of our samples comprised a group aspiring to leadership positions in the city of Pittsburgh. Moreover, the beliefs about technical issues held by well-educated people will probably constitute an "upper boundary" of sophistication; if our sample makes an error, it is unlikely that the error will be less common in a less educated sample.

Our work is designed to direct the content of risk communications as well as assess the level of public understanding. Risk communication will be most successful if it is based on a realistic assessment of what people already know, along with a scientific determination of what missing information is most critical to their decisions.^(3,4)

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1994

Risk Analysis, Vol. 30, No. 10, 2010

DOI: 10.1111/j.1539-6924.2010.01448.x

Now What Do People Know About Global Climate Change? Survey Studies of Educated Laypeople

Travis William Reynolds,^{1,*} Ann Bostrom,¹ Daniel Read,² and M. Granger Morgan³

In 1992, a mental-models-based survey in Pittsburgh, Pennsylvania, revealed that educated laypeople often conflated global climate change and stratospheric ozone depletion, and appeared relatively unaware of the role of anthropogenic carbon dioxide emissions in global warming. This study compares those survey results with 2009 data from a sample of similarly well-educated laypeople responding to the same survey instrument. Not surprisingly, following a decade of explosive attention to climate change in politics and in the mainstream media, survey respondents in 2009 showed higher awareness and comprehension of some climate change causes. Most notably, unlike those in 1992, 2009 respondents rarely mentioned ozone depletion as a cause of global warming. They were also far more likely to correctly volunteer energy use as a major cause of climate change; many in 2009 also cited natural processes and historical climatic cycles as key causes. When asked how to address the problem of climate change, while respondents in 1992 were unable to differentiate between general "good environmental practices" and actions specific to addressing climate change, respondents in 2009 have begun to appreciate the differences. Despite this, many individuals in 2009 still had incorrect beliefs about climate change, and still did not appear to fully appreciate key facts such as that global warming is primarily due to increased concentrations of carbon dioxide in the atmosphere, and the single most important source of this carbon dioxide is the combustion of fossil fuels.

KEY WORDS: Climate change; global warming; laypeople; mental models; risk communication; United States

1. INTRODUCTION

In 1992 we conducted a survey of beliefs and attitudes in the United States concerning global climate change.⁽¹⁾ Since that time both the public discourse and media coverage of the issue have changed almost beyond recognition. By 2008 climate change

was at the forefront of popular media. Al Gore had starred in an Academy Award winning movie on climate change; rock stars like David Gilmour and U2 offered "carbon neutral" CDs; and marketers, auto manufacturers, and even airlines were beginning to promote their products based on their reduced effects on climate change.² Whereas in 1992 there was little official acknowledgment of global warming, in 2008 both U.S. presidential candidates proposed explicit policies designed to reduce or slow climate change.

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³ Department of Engineering and Public Policy, Carnegie Mellon University, Pittsburgh, PA, USA.

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⁴ For an example, see <http://www.easj.net/en/Environment/index.html>. Accessed April 15, 2010.

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2010

1994

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Today most American's ...

...now
know
these first
two facts.

1. Burning coal, oil, and natural gas produces carbon dioxide that enters the atmosphere.
2. Carbon dioxide in the atmosphere warms the earth, and that warming changes the climate.

BUT, most
do not
know this
third fact.

3. Once carbon dioxide gets into the atmosphere, much of it remains there for many hundreds of years.

When we add...

...carbon dioxide (CO_2) to the atmosphere some of it is absorbed in the ocean or taken up by plants.

HOWEVER, most of the balance stays in the atmosphere **for hundreds of years.**

That means that some of the CO_2 you are breathing as you listen to me was emitted in Britain several hundred years ago during the industrial revolution!

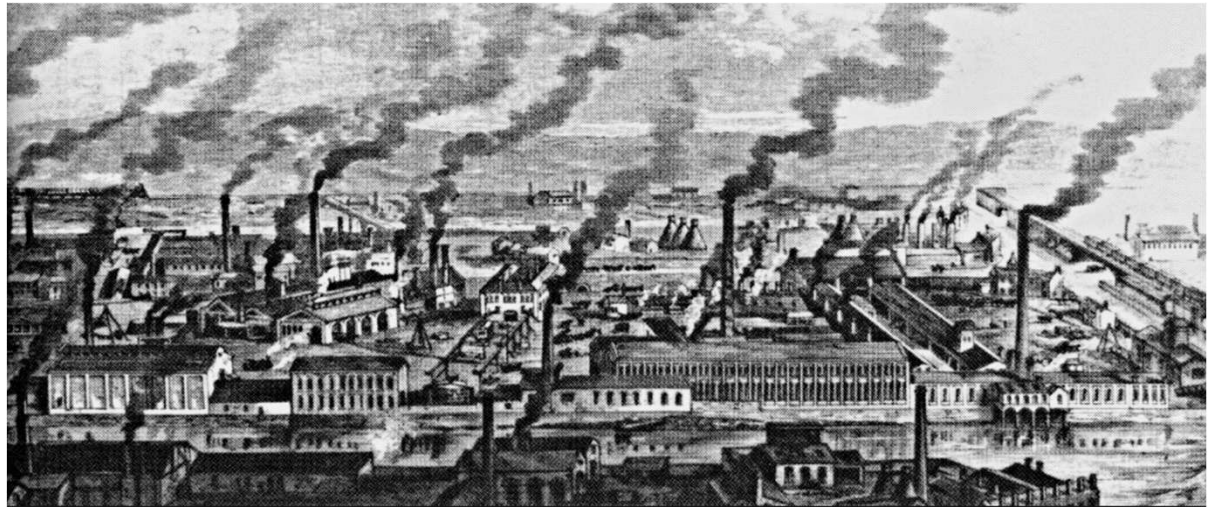
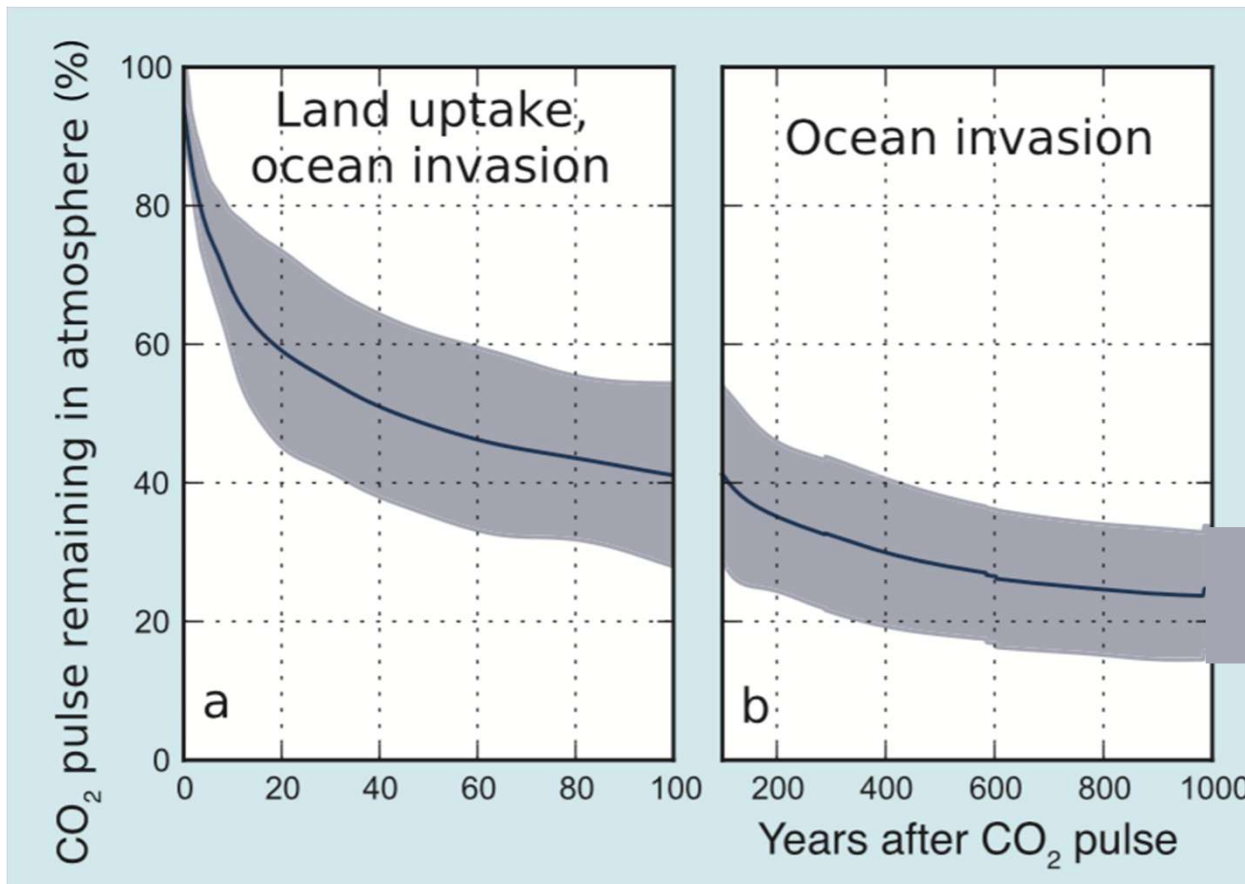


Image from: top5resources.blogspot.com/2014/05/industrial-revolution.html

There is no *single* residence time for CO₂.

Here is how a pulse of CO₂ added today decays over time:



Then, on time scales of thousands of years, it mineralizes.

Most people...

...think CO₂ stays in the atmosphere about as long as conventional air pollution.

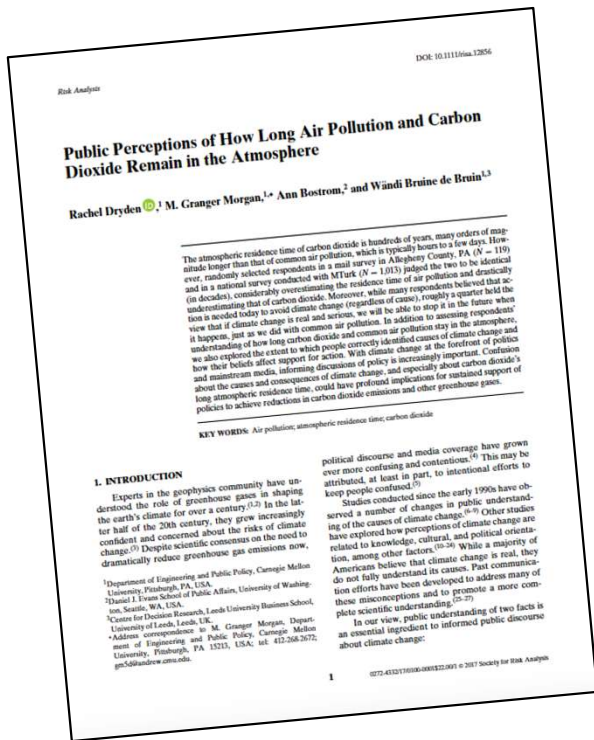
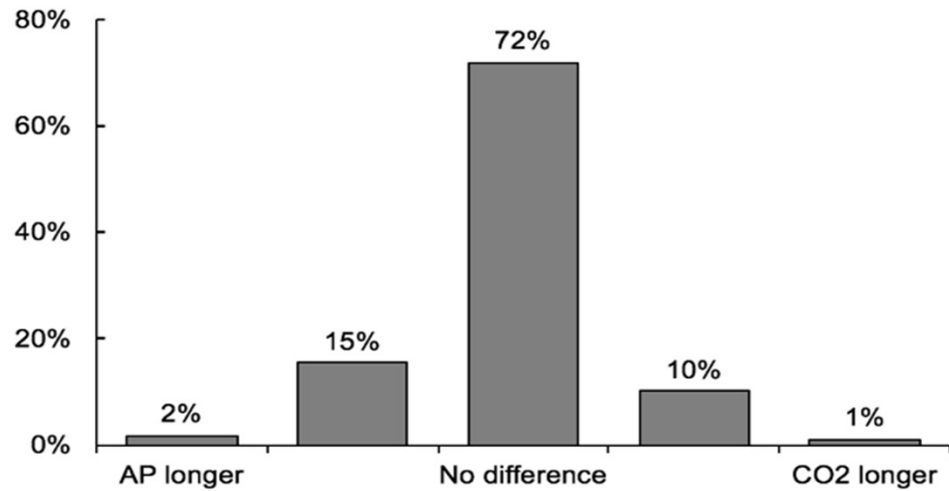
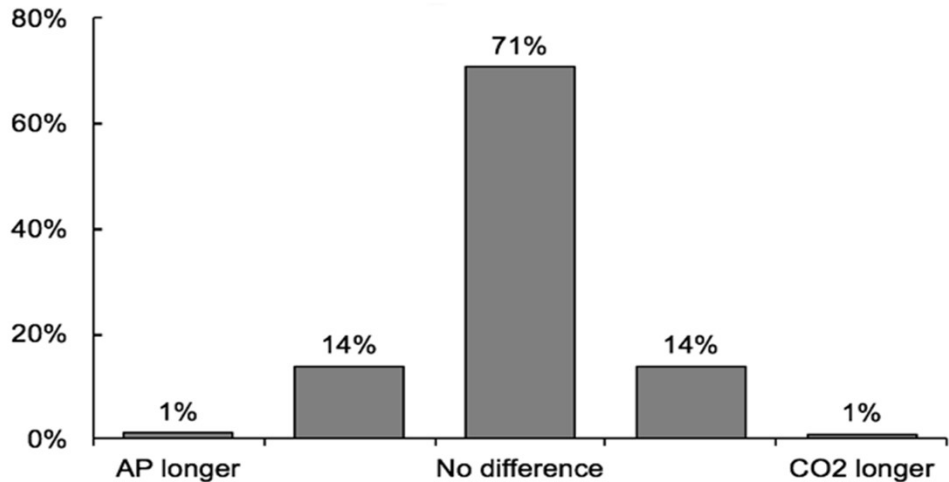


Image from: Dryden, R., Morgan, M. G., Bostrom, A., & Bruine de Bruin, W. (2018). Public perceptions of how long air pollution and carbon dioxide remain in the atmosphere. *Risk Analysis*, 38(3), 525-534.

Allegheny County PA mail sample:



M-Turk national sample:



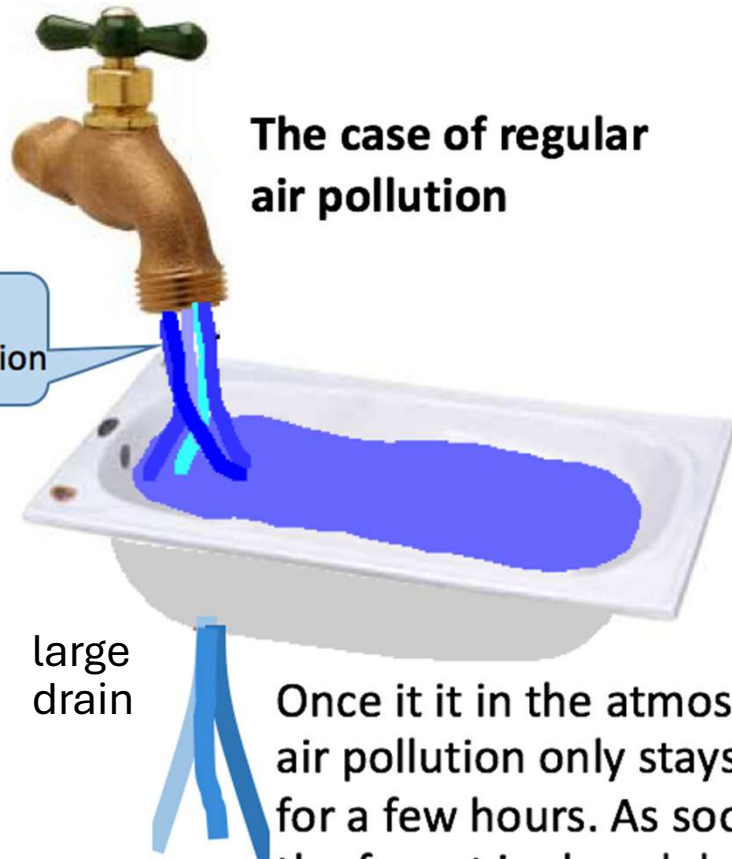
Difference in people's estimates of how long air pollution (AP) and CO₂ stay in the atmosphere

Percentage of respondents

Here is a bathtub model that helps explain

**The case of regular
air pollution**

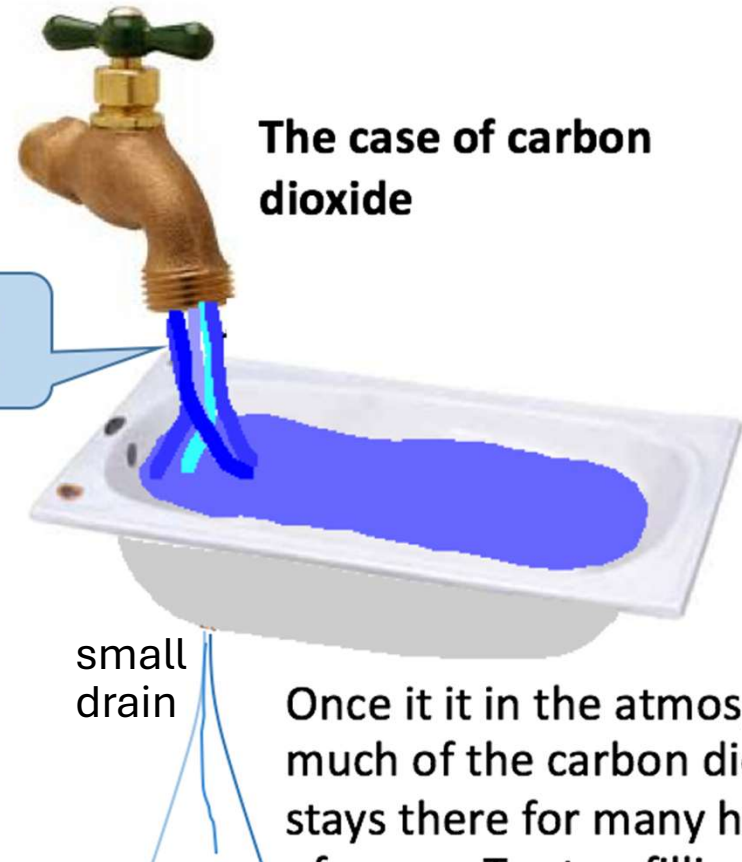
Regular
air pollution



Once it it in the atmosphere
air pollution only stays there
for a few hours. As soon as
the faucet is closed down (i.e.
emissions are reduced) the
tub starts to drain.

**The case of carbon
dioxide**

Carbon
dioxide



Once it it in the atmosphere
much of the carbon dioxide
stays there for many hundreds
of years. To stop filling the tub
the faucet has to be *almost
completely shut off*.

The bottom line

We can argue about how fast we should reduce our emissions of carbon dioxide and other greenhouse gases – how best to make the tradeoff between incurring inconvenience and costs today *versus* leaving a habitable world for our children tomorrow.

But neither proceeding full steam ahead pretending the problem of climate change doesn't exist - which appears to be the new policy of the U.S. government - nor going along with that policy because folks figure that in a few years when things get bad enough, we'll just fix the problem – is simply not going to work.

Much of carbon dioxide we add to the atmosphere today will still be there, warming the planet and changing the climate for our grandchildren.

Today I will talk about three things:

1. Some basic background on:

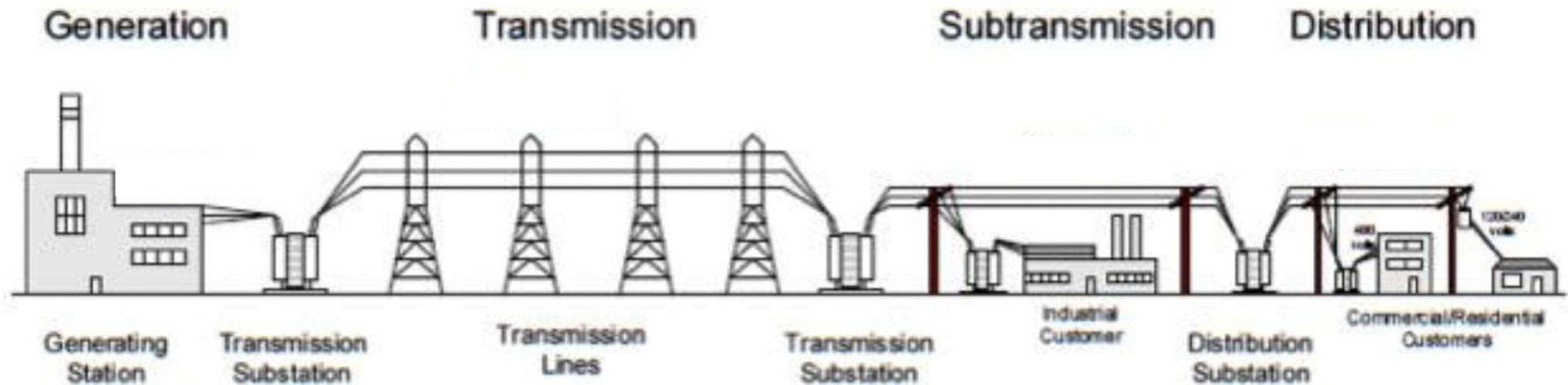
- Climate science
- The electricity system

2. Why electric power is critical to climate change:

- As a leading source of CO₂ and other GHG emissions and how to reduce those emissions
- As the most viable option to replace fossil fuels

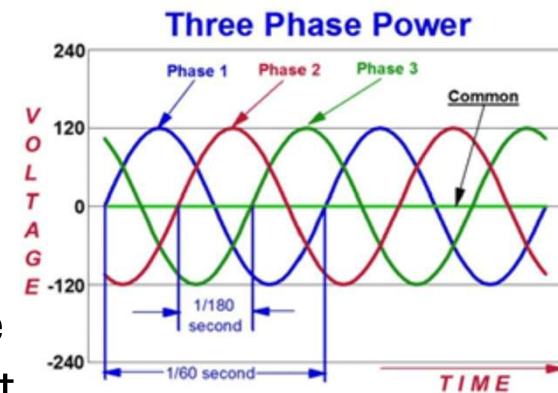
3. The need to expand electric power transmission capacity and some efforts we are undertaking to address the problem.

The traditional structure of the electricity system



A few things to notice:

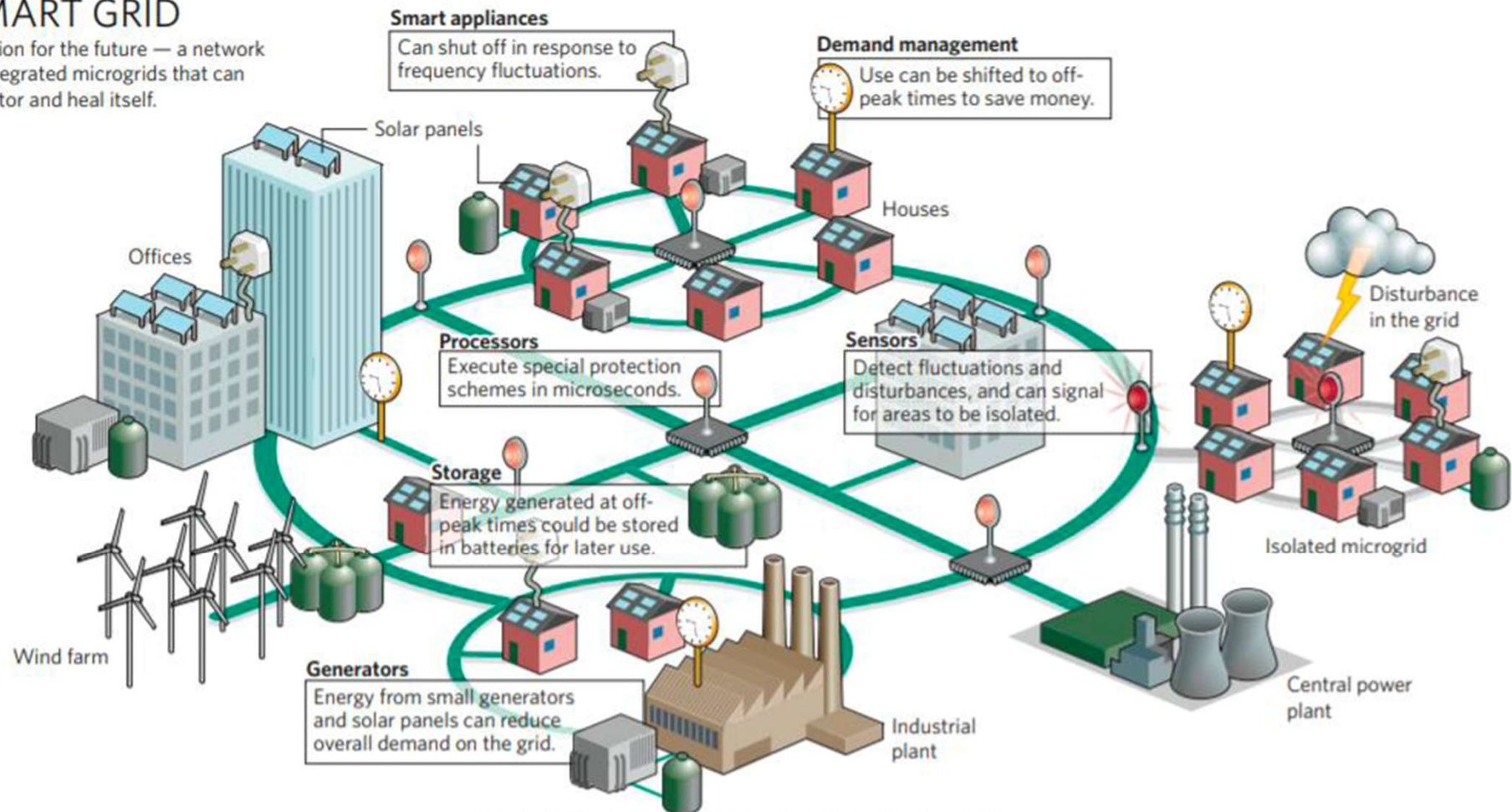
- Three conductors because using three phase alternating current (AC) is more efficient for long transmission and for many heavy loads like big motors.
- High voltage (V) is used for transmission since power is the product $V \times I$, but losses go as $I^2 R$, so moving a given amount of power using a higher voltage means lower current (I) and lower losses.
- While many large customers take three phase power at thousands of volts, most residential customers take single phase power typically at 240/120 volts



Today that simple traditional system is getting more and more complicated

SMART GRID

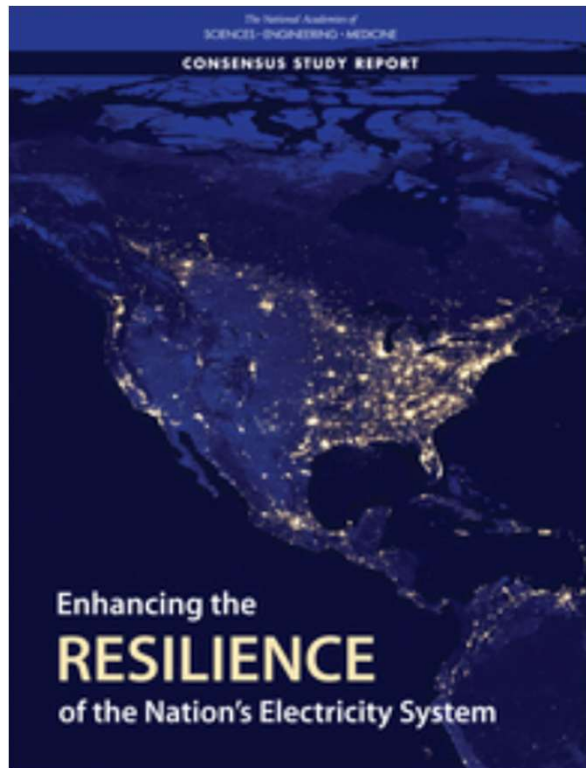
A vision for the future — a network of integrated microgrids that can monitor and heal itself.



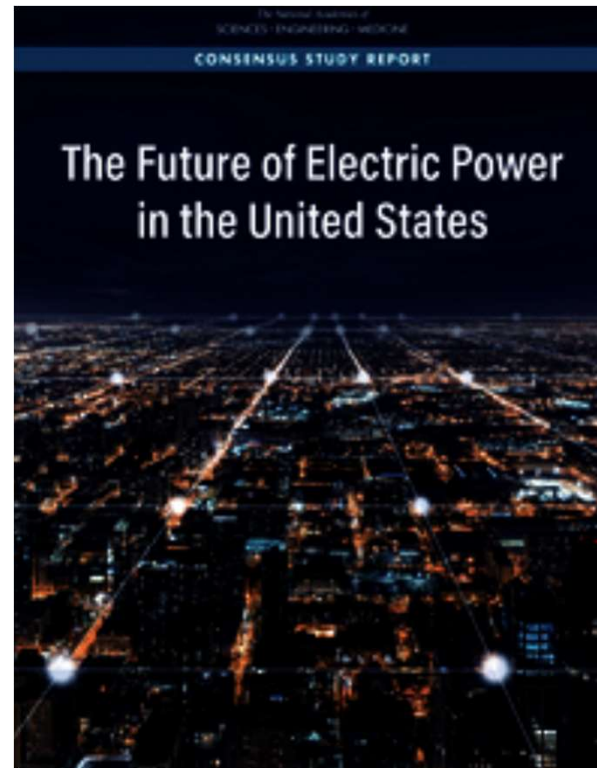
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These two National Academy Consensus studies...

...that I chaired provide background on the U.S. electricity system. They can be downloaded for free from the web site of the National Academy Press



2017



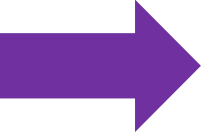
2021

Today I will talk about three things:

1. Some basic background on:

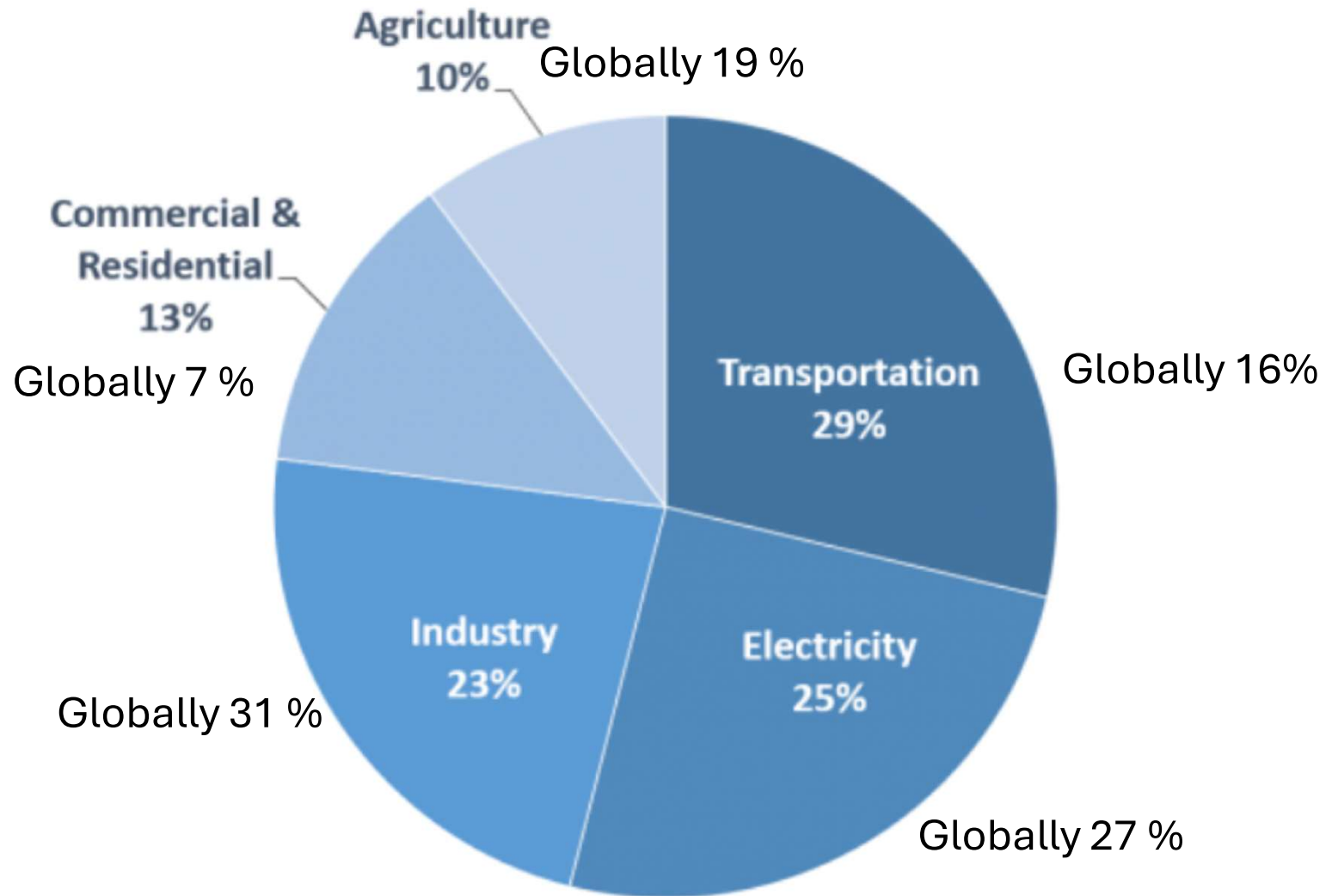
- Climate science
- The electricity system

2. Why electric power is critical to climate change:

- 
- As a leading source of CO₂ and other GHG emissions and how to reduce those emissions
 - As the most viable option to replace fossil fuels

3. The need to expand electric power transmission capacity and some efforts we are undertaking to address the problem.

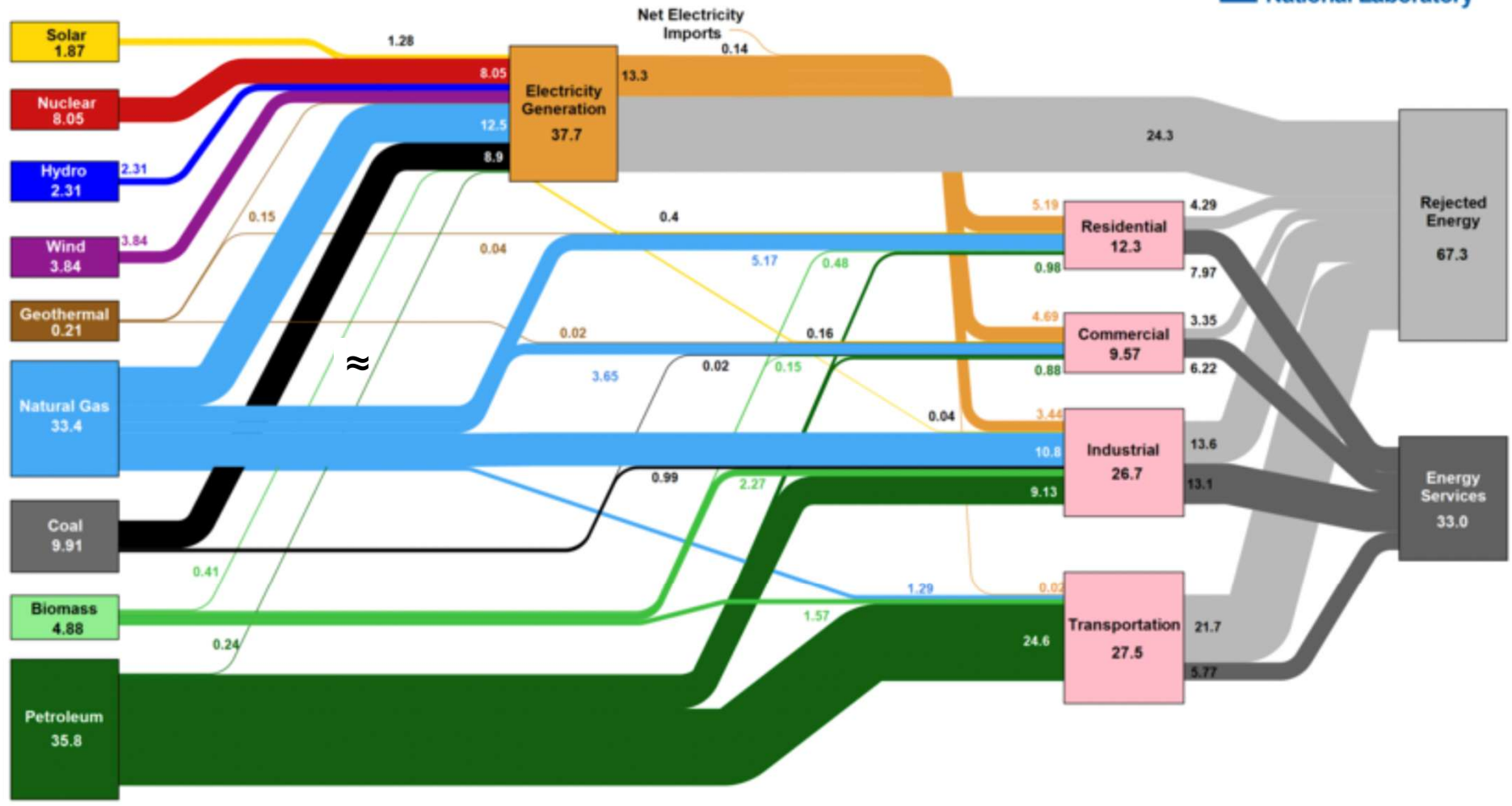
Where CO2 comes from, in the U.S. and globally:



1 quad is 10^{15} BTU or $\approx 0.3 \times 10^{12}$ kW-hr

The US energy system:

Estimated U.S. Energy Consumption in 2022: 100.3 Quads

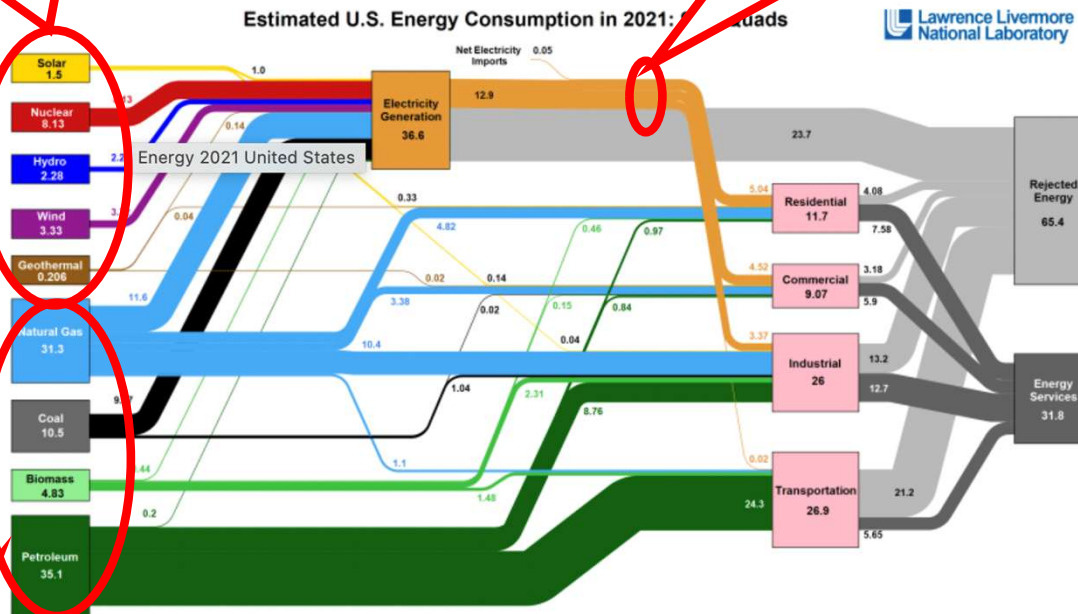


Source: LLNL July, 2023. Data is based on DOE/EIA SEDS (2021). If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. Distributed electricity represents only retail electricity sales and does not include self-generation. EIA reports consumption of renewable resources (i.e., hydro, wind, geothermal and solar) for electricity in BTU-equivalent values by assuming a typical fossil fuel plant heat rate. The efficiency of electricity production is calculated as the total retail electricity delivered divided by the primary energy input into electricity generation. End use efficiency is estimated as 0.65% for the residential sector, 0.65% for the commercial sector, 0.49% for the industrial sector, and 0.21% for the transportation sector. Totals may not equal sum of components due to independent rounding. LLNL-MI-410527

Basically, three strategies:

Use more generation that does not produce CO₂

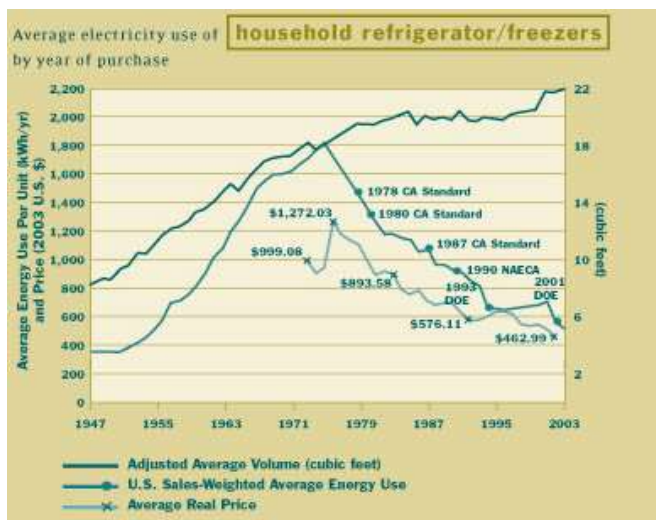
Use the electricity we generate more efficiently so we don't need to make as much.



Don't let the CO₂ enter the atmosphere.

There is an enormous potential to reduce CO₂ emissions through more efficient use of electricity. Here are four examples:

Refrigerators:

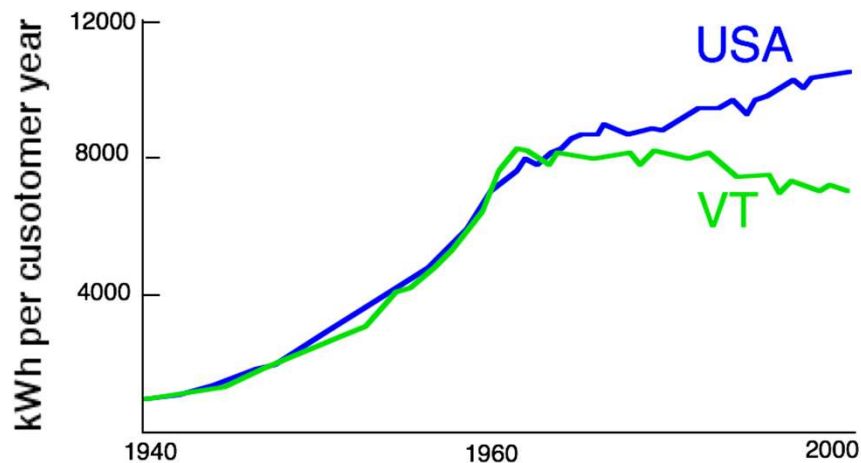


Heat pumps:

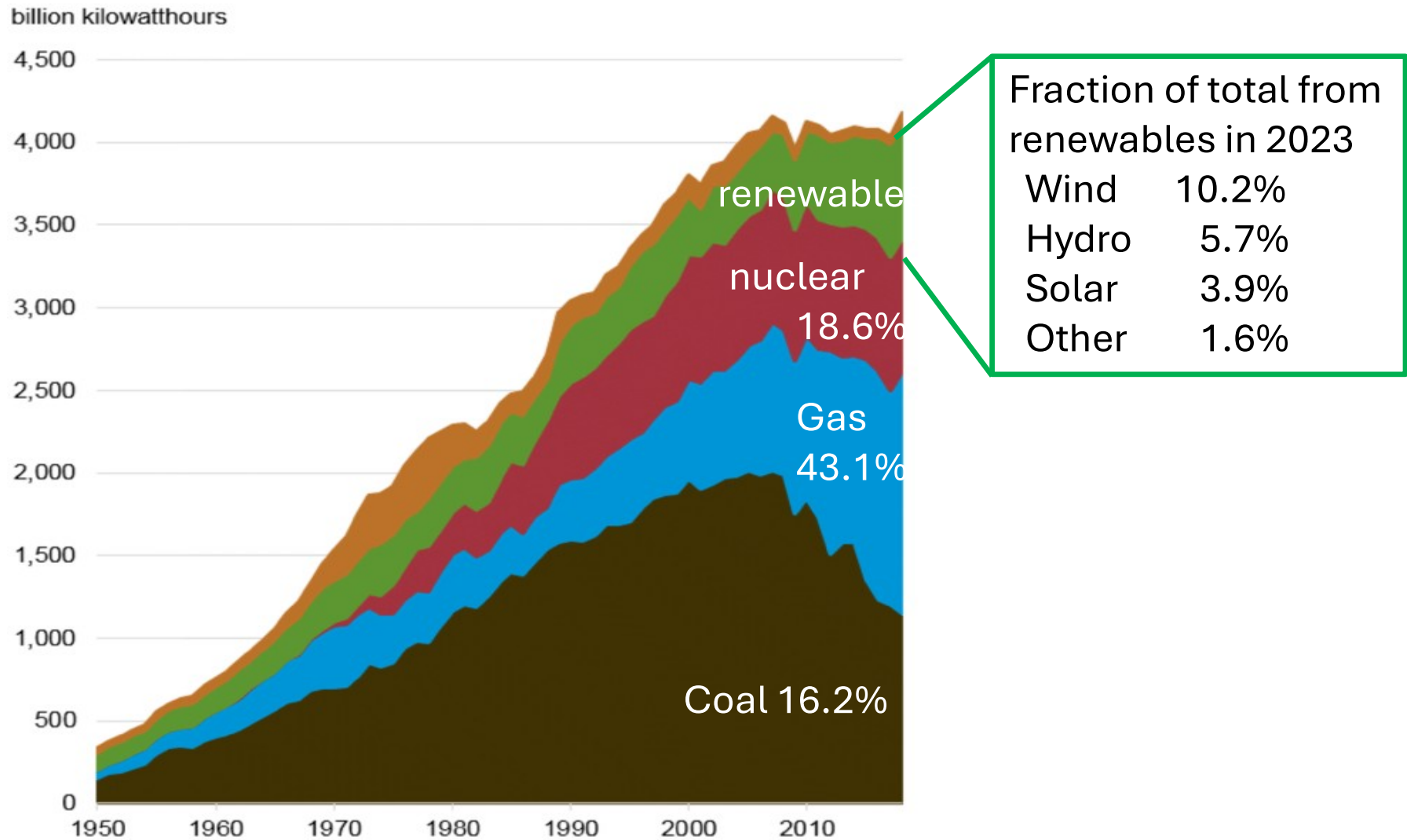


Efficiency VT:

Solid state lighting:



How the US generates electricity



Note: Electricity generation from utility-scale facilities.

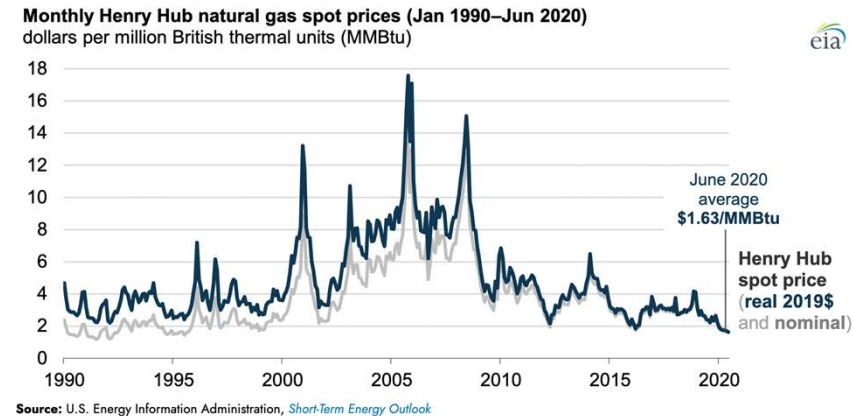
Source: U.S. Energy Information Administration, *Monthly Energy Review*, Table 7.2a, March 2019





The switch to natural gas

In the early 2000s the shale gas revolution took off, and gas prices fell dramatically. Because producing electricity with gas produces only half as much CO₂ as using coal, some describe the switch to gas as a “bridge to decarbonizing electricity.”



BUT... a bridge needs an abutment at the far end and, so far not much has been done to build that!



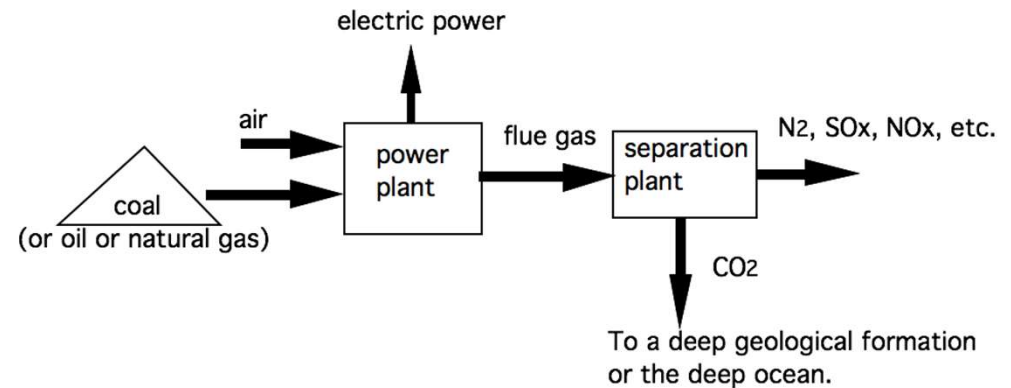
We've got lots of coal and gas...

...and, while wind and solar should play a *much* bigger role, we are not likely to be able to completely decarbonize just using renewables.

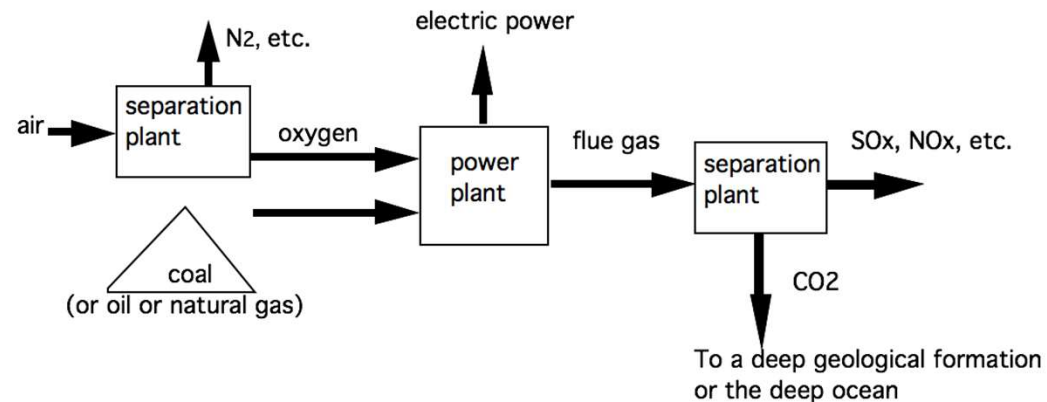
That means we need to find ways to use gas (and perhaps some coal) while *not* releasing CO₂ to the atmosphere.

Capturing CO₂ from coal or gas plants

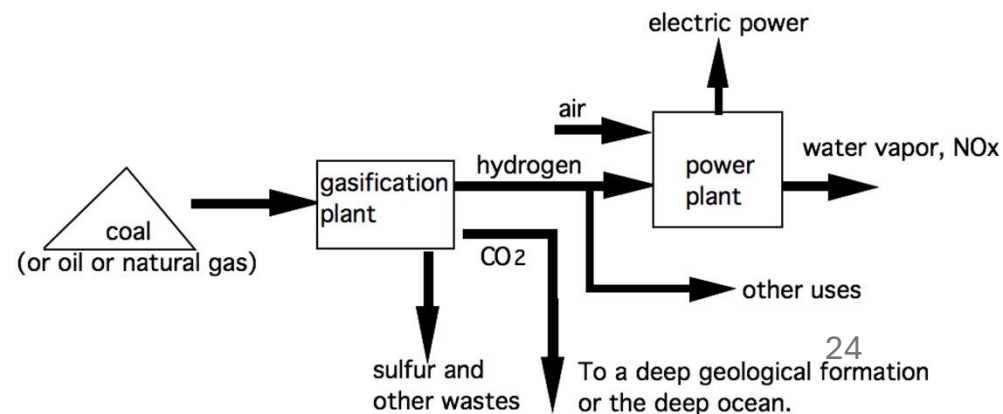
1. Burn it in the normal way and then scrub the carbon dioxide out of the “flue gas” (which is mainly made up of nitrogen since that is what makes up most of air).



2. Separate oxygen from the air and burn the coal or gas in oxygen. That way there the flue gas is mostly carbon dioxide so its easy to capture.



3. Extract the hydrogen run the plant on hydrogen. When hydrogen burns it combines with oxygen to make H₂O, which of course is just water.



This is not just pie in the sky



Sources: www.free-pictures-photos.com and movementbuilding.org

W.A. Parish Plant

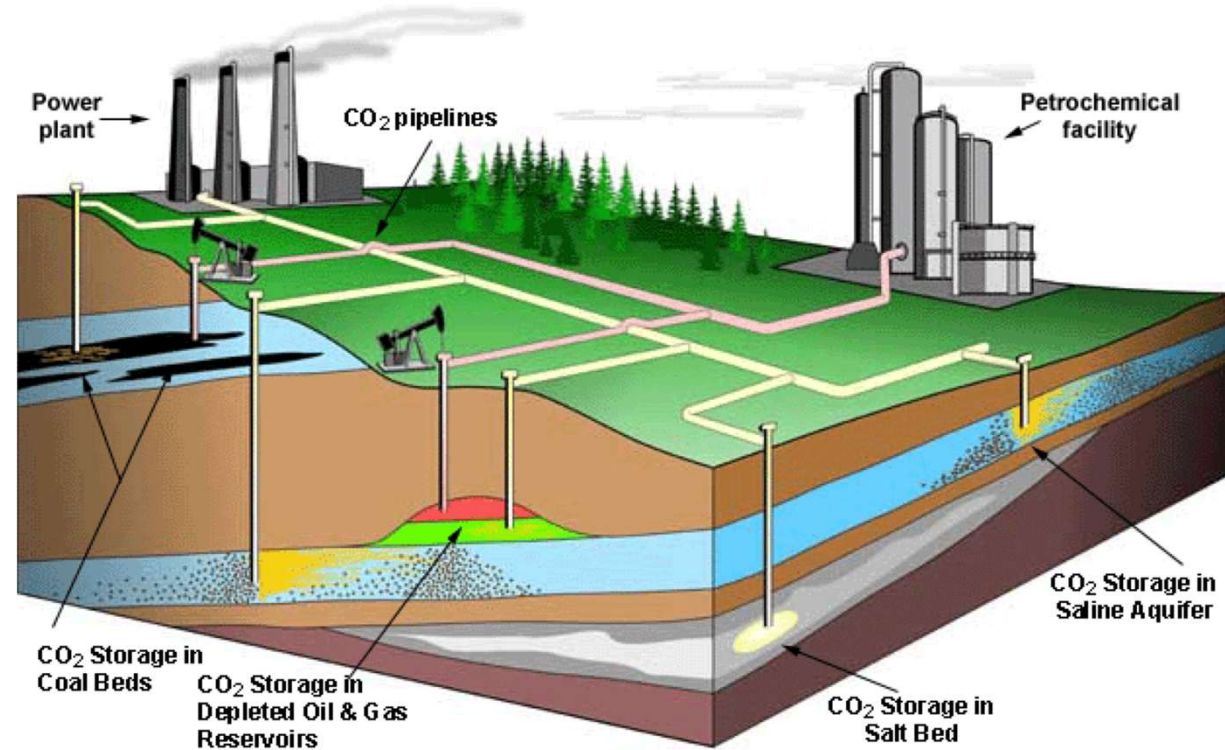


240Mw exhaust steam from a coal-fired power plant southwest of Houston

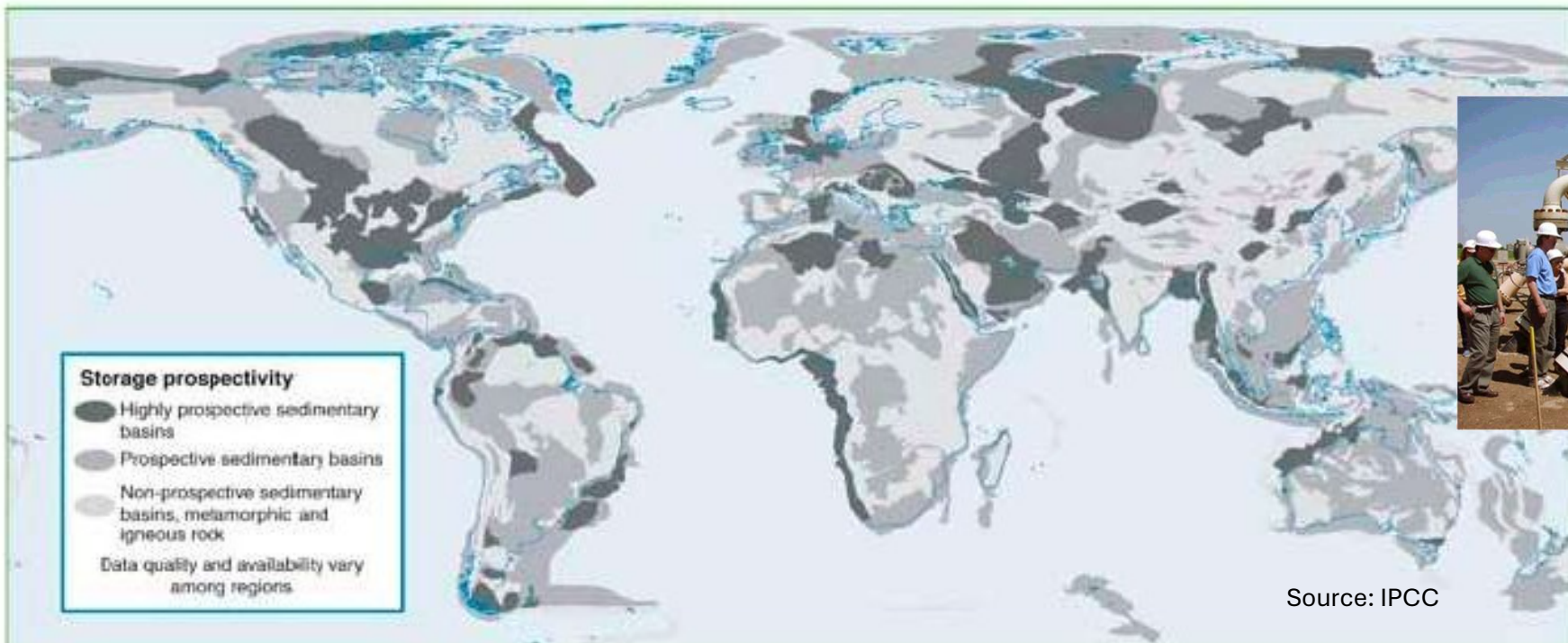
Image from NRG

Once the CO₂ has been captured...

...it must be compressed and injected into suitable geological structures deep under ground (>1km).



Source: www.nrcan.gc.ca



Source: IPCC



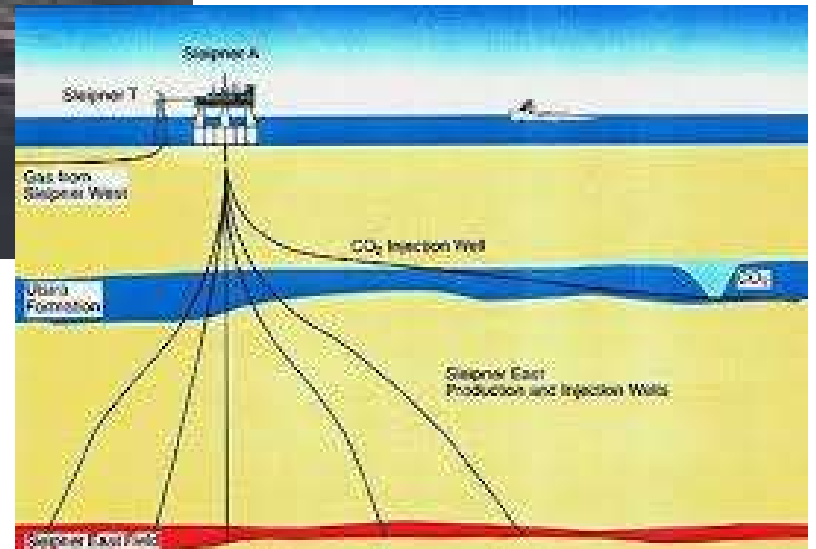
<http://gsc.nrcan.gc.ca>



Sleipner Field



Capturing CO₂ since 1996





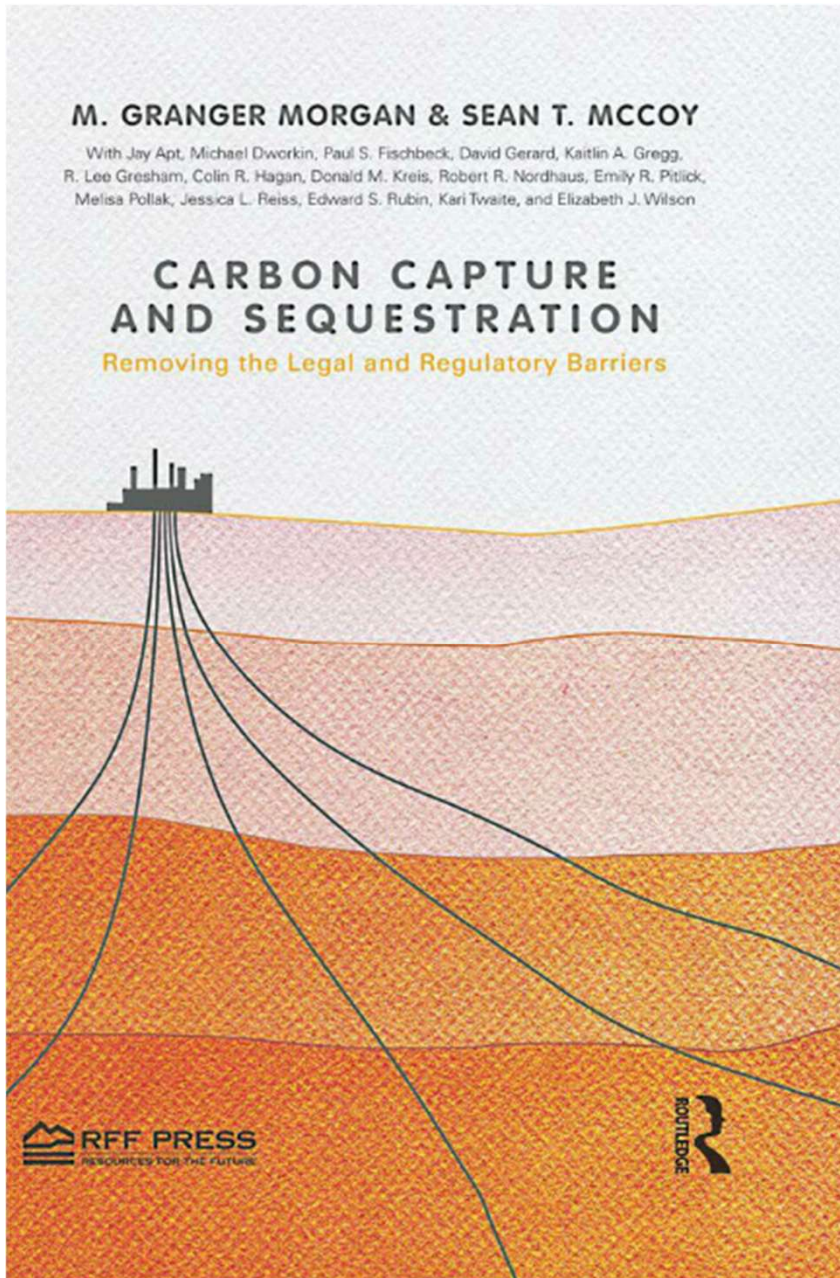
Melkøya near Hammerfest



This facility (at 70.6 °N) receives and processes natural gas from the Snøhvit field in the Barents Sea. The gas is conveyed in a 160 km gas pipeline to the facility, which became operational in the autumn of 2007

We ran a big project on CCS ...

...and published a book through RFF Press.



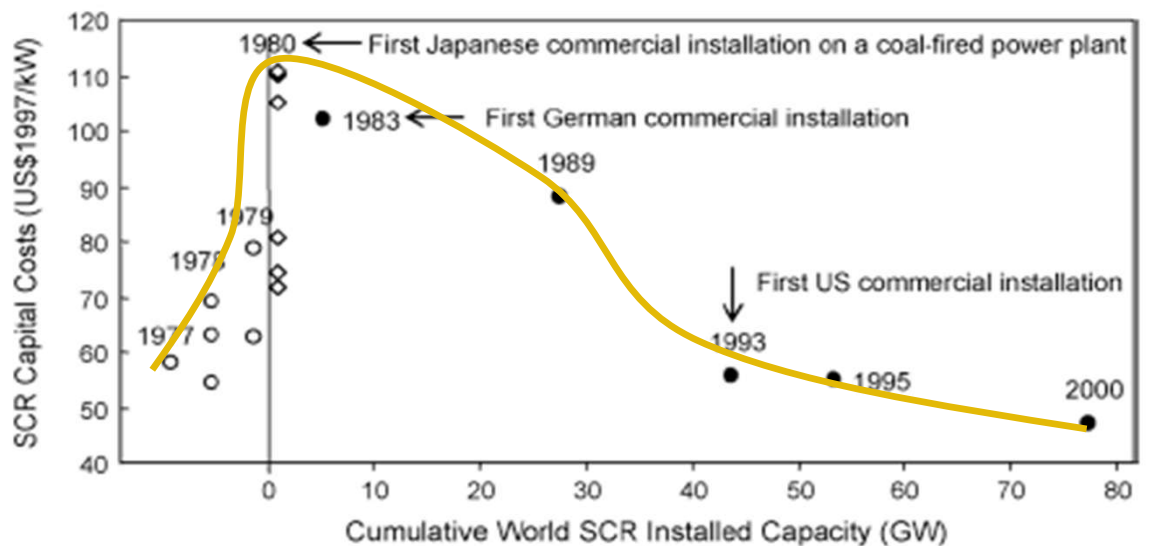
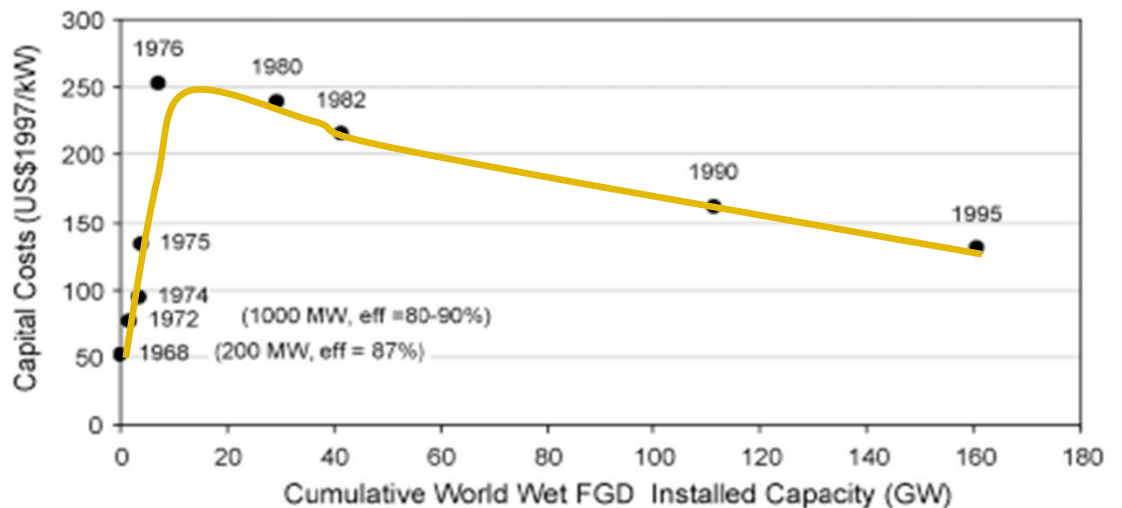
Contents

1. The Importance of CCS in a Carbon Constrained World
2. Technology for Carbon Capture and Geologic Sequestration (CCS)
3. Siting CO₂ Pipelines for Geologic Sequestration
4. Permitting Geological Sequestration Sites
5. Learning from and Adapting to Changes in Geologic Sequestration Technology
6. Access to Pore Space for Geological Sequestration
7. Liability and the Management of Long-term Stewardship
8. Greenhouse Gas Accounting for CCS
9. Making CCS a Reality
10. Conclusions and Recommendations

Learning takes time

In the case of both SO₂ scrubber technology and in the case of NO_x control technology, Ed Rubin has found that costs rose significantly after problems were encountered with the design and performance of the first few plants.

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



The US and the world are moving *MUCH* too slowly on CCS!

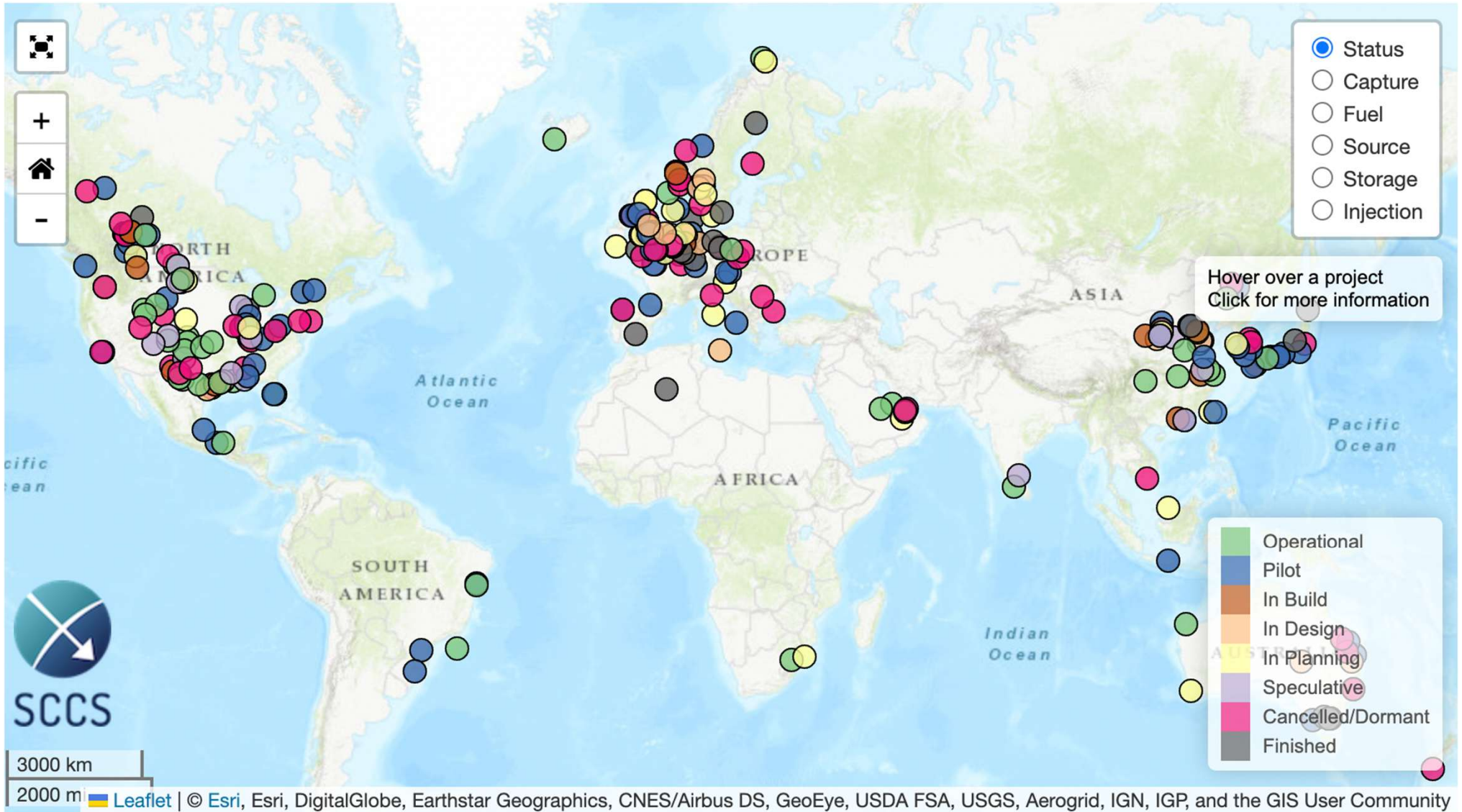


Image source: <https://www.sccs.org.uk/resources/global-ccs-map>

Today about 40% of US electricity is carbon free

Today in the US we make about:

5.7 % from hydropower

18.6 % from nuclear

10.2 % from wind

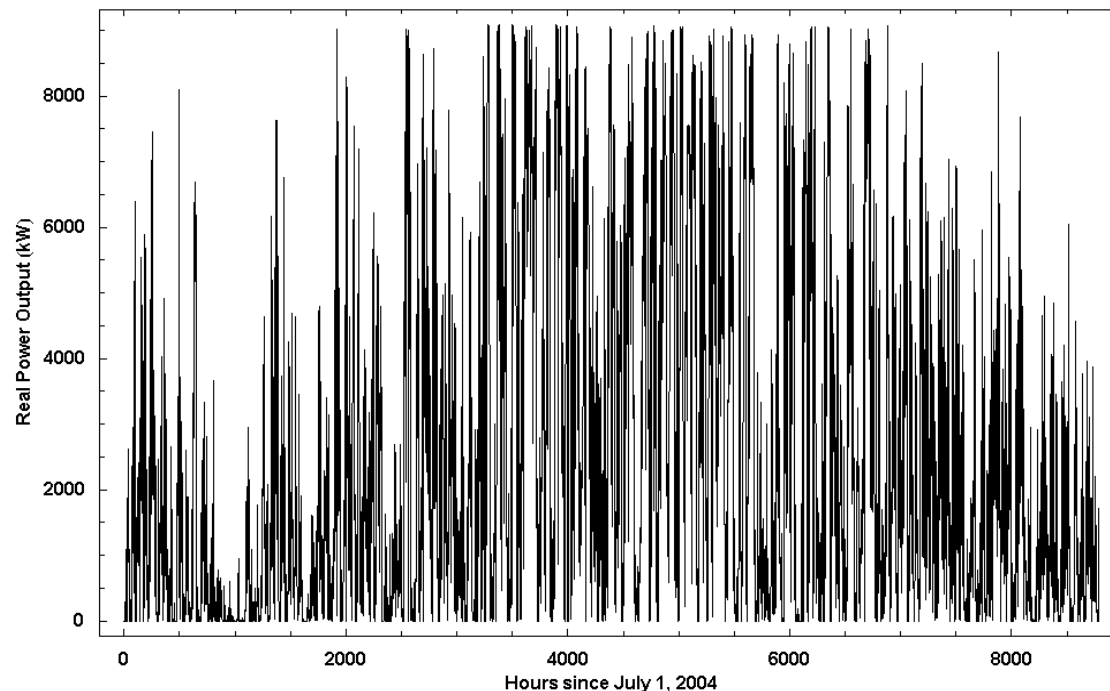
3.9 % from solar

1.1 % from biomass & geothermal

To fully decarbonize by 2035, we'll need to build ≥ 55 GW new carbon free electricity *per year*. Although the U.S. built 60 GW of natural gas generators per year in 1999 and 2000, it has not built more than 15 GW of renewables in a single year. We can do it – but it will take a BIG push.

Wind can play a bigger role

But, as the fraction of installed capacity grows, dealing with intermittency becomes a major problem.

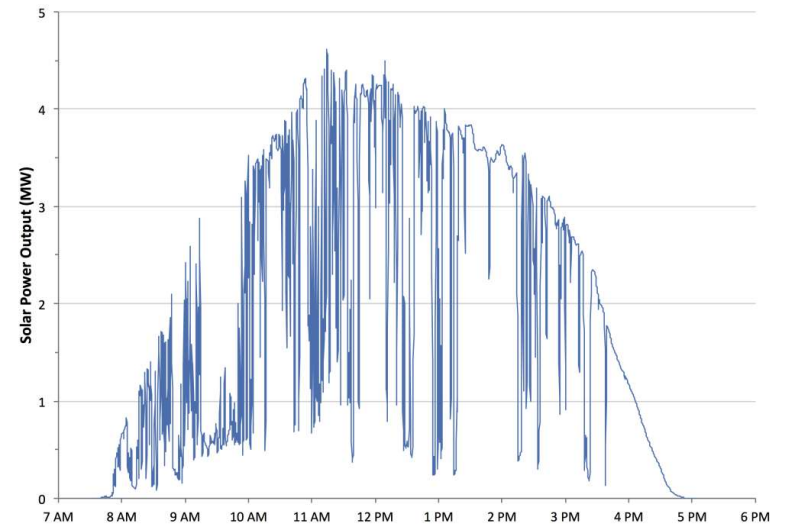
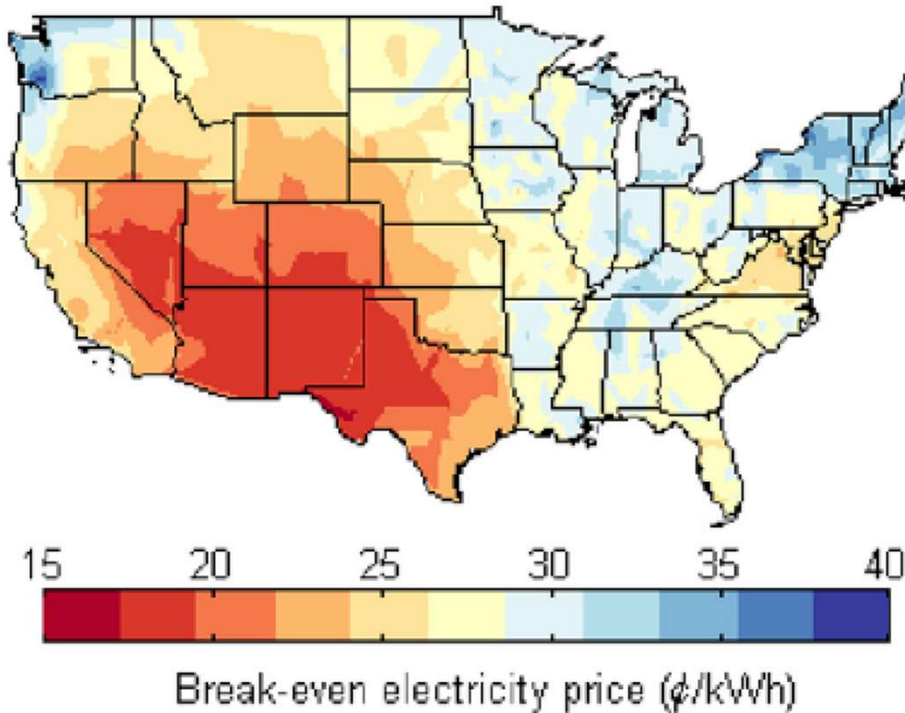


In places with lots of hydro power, like the U.S. Pacific Northwest and Scandinavia, this can be handled. Elsewhere it is a serious problem

Sources: GE, Jay Apt, USBoR



Solar PV



Shelly Hagerman, Paulina Jaramillo and M. Granger Morgan, "Is Rooftop Solar PV at Socket Parity Without Subsidies?," *Energy Policy*, 89, 84-94, 2016.



The U.S. Department of Energy SunShot Initiative is a national effort to drive down the cost of solar electricity and support solar adoption. SunShot aims to make solar energy a low cost electricity source for all Americans through research and development efforts in collaboration with public and private partners.

Photo from energynext.in

Nuclear

As the French have clearly shown, despite its various issues, nuclear power is capable of serving a nation's electricity needs without CO₂ emissions. In years past about 88% of EDF's electricity has been generated in 58 nuclear power plants at 19 different sites.

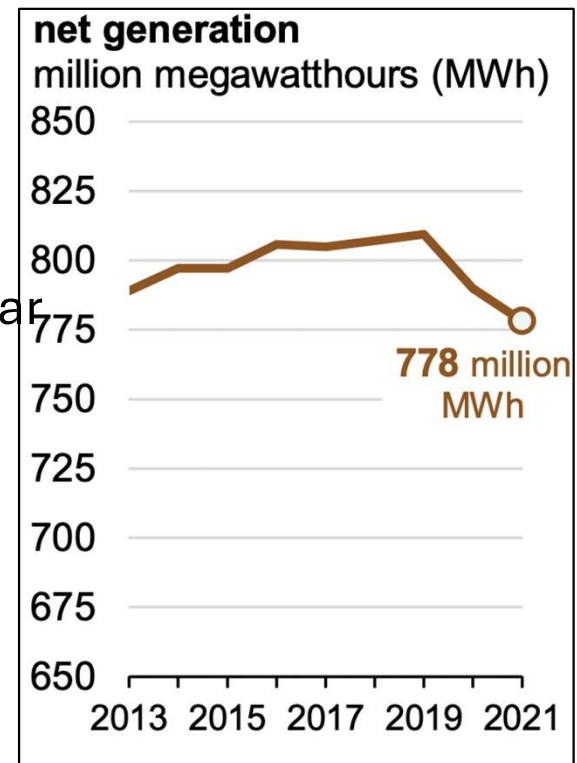
In the US ~20% of our electricity has been coming from nuclear power. That is carbon free electricity. These plants are getting old so there are major efforts underway to engage in “life extension”.

Issues include **cost**, public acceptance, safety, risk of nuclear proliferation, and waste management



U.S. Nuclear over time

In 2023 18.6% of U.S. electricity generation came from nuclear



U.S. nuclear power plant capacity additions and retirements (2018–2025)
megawatts (MW)

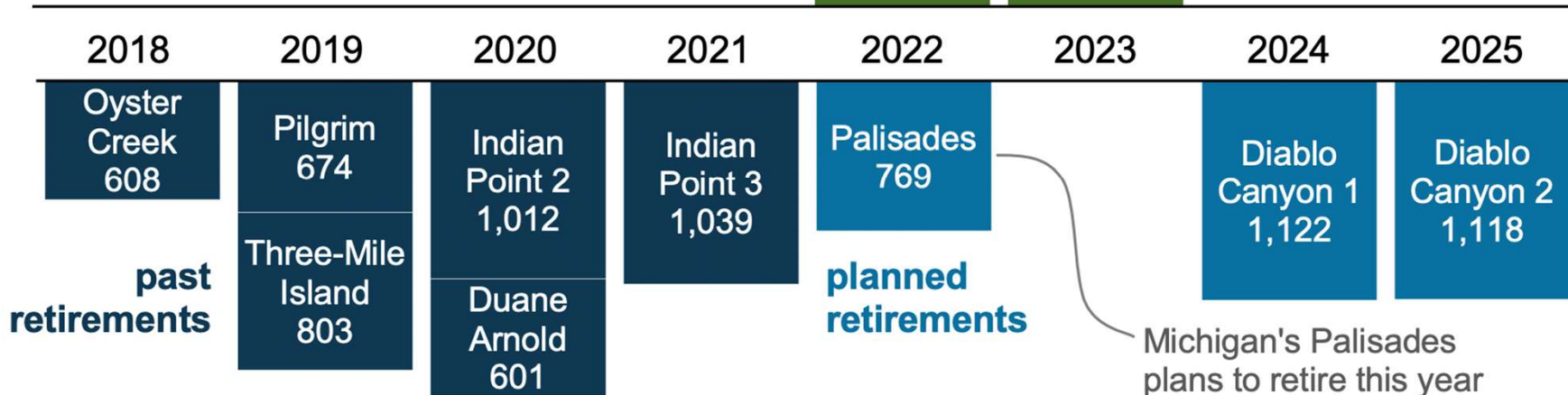
Georgia's Vogtle Unit 3 plans to come online later this year

planned additions

Vogtle 3
1,114

Vogtle 4
1,114

Vogtle was 7 years late and \$17-billion over budget



Michigan's Palisades plans to retire this year

Imaged from EIA

SMR and micro reactors

Many argue that if new nuclear plants are going to play a role in decarbonizing the US energy system over the next 3-4 decades, it will be via factory mass-produced light water small modular reactors (SMRs) and even smaller micro- reactors.

While SMR's could be used to produce electricity, they could also be used for process heat for many industrial processes.



Images from NuScale

While there is lots of talk, I think for the next several decades we'll not see significant new nuclear

PERSPECTIVE

US nuclear power: The vanishing low-carbon wedge

M. Granger Morgan^{a,1}, Ahmed Abdulla^b, Michael J. Ford^c, and Michael Raft^d

Edited by B. L. Turner, Arizona State University, Tempe, AZ, and approved May 30, 2018 (received for review March 20, 2018)

Nuclear power holds the potential to make a significant contribution to decarbonizing the US energy system. Whether it could do so in its current form is a critical question: Existing large light water reactors in the United States are under economic pressure from low natural gas prices, and some have already closed. Moreover, because of their great cost and complexity, it appears most unlikely that any new large plants will be built over the next several decades. While advanced reactor designs are sometimes held up as a potential solution to nuclear power's challenges, our assessment of the advanced fission enterprise suggests that no US design will be commercialized before midcentury. That leaves factory-manufactured, light water small modular reactors (SMRs) as the only option that might be deployed at significant scale in the climate-critical period of the next several decades. We have systematically investigated how a domestic market could develop to support that industry over the next several decades and, in the absence of a dramatic change in the policy environment, have been unable to make a convincing case. Achieving deep decarbonization of the energy system will require a portfolio of every available technology and strategy we can muster. It should be a source of profound concern for all who care about climate change that, for entirely predictable and resolvable reasons, the United States appears set to virtually lose nuclear power, and thus a wedge of reliable a nd low-carbon energy, over the next few decades.

decarbonization | nuclear power | wedges | SMRs

The need to mitigate emissions of global warming gases is critical. Once carbon dioxide enters the atmosphere, more than a third of it remains there, causing warming for hundreds of years (1), a fact that few Americans recognize (2). Despite this lack of awareness and the current absence of political will to address climate change, technological improvements, continuing political pressure, and a growing familiarity with adverse climate effects will likely result in the United States decarbonizing its energy system to some extent over the coming decades. However, to come anywhere close to meeting the targets enshrined in the Paris Agreement of limiting temperature increases to "well below 2 °C above pre-industrial levels" (3), the United States and the world as a whole are going to have to achieve drastic emission cuts, and perhaps even negative emissions, in the next several decades (4, 5).

It has been widely argued that the most plausible and cost-effective strategy to achieve deep decarbonization is by deploying a portfolio of "everything we've got." Given the myriad technical, economic, and

political constraints that challenge the deployment of all energy infrastructure, relying on a large number of different technologies and strategies, executed in parallel, would reduce overall costs and risks (6, 7), with each one of these contributing a "wedge" to the overall mitigation effort (8). Indeed, most models of decarbonization incorporate a large suite of technologies and assume that they are deployable when the political will to mitigate emissions emerges.

Nuclear power is one of those technologies. For several years, we have been evaluating the potential role that new nuclear power technologies might play in this decarbonization by conducting a variety of studies that investigate the technical, economic, and political challenges that face it, both in the United States and around the world. We have concluded that, barring some dramatic policy changes, it is most unlikely that nuclear power will be able to contribute to decarbonization in the United States, much less provide a new carbon-free wedge on the critical time scale of the next several decades. With the exception

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Author contributions: M.G.M., A.A., M.J.F., and M.R. performed research and wrote the paper.
The authors declare no conflict of interest.
This article is a PNAS Direct Submission.
Published under the PNAS license.

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PERSPECTIVE

Energy Policy (2018) 7, 194–200
Contents lists available at ScienceDirect
Energy Policy
Journal homepage: www.elsevier.com/locate/enpol

Expert assessments of the state of U.S. advanced fission innovation

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ARTICLE INFO

Keywords:
Advanced nuclear
Advanced fission research
Energy transition

ABSTRACT

Deep decarbonization in the U.S. will require a shift to an electrified society dominated by low-carbon generation. Many studies assume a role for nuclear power in low-carbon energy systems, and the nuclear industry anticipates an eventual transition from light water reactors to advanced, non-light water designs. The development of these advanced reactors is emblematic of the type of dynamic change that is needed to transition from fossil fuels and deeply decarbonize the energy system. The Office of Nuclear Energy (ONE) in the U.S. is entrusted with the allocation of public sector expenditures for the transition, but there is little to show for its efforts: no advanced design is remotely ready for deployment.

Here, we report results from structured interviews we conducted with 30 nuclear energy veterans to elicit their impressions of the state of U.S. fission innovation. Most experts assumed NE is having been largely unsuccessful in enabling the development of advanced designs. The interview results highlight the importance of leadership and programmatic discipline, and how their absence leads to poor performance during change. Responses point to the likely demise of nuclear power and nuclear science in the U.S. without significant improvements in leadership, focus and political support.

Environmental Research Letters

LETTER

A retrospective analysis of funding and focus in US advanced fission innovation

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^d Author to whom any correspondence should be addressed.

Keywords: nuclear power, advanced reactor, energy innovation, fission research and development

Abstract

Deep decarbonization of the global energy system will require large investments in energy innovation and the deployment of new technologies. While many studies have focused on the expenditure that will be needed, here we focus on how government has spent public sector resources on innovation for a key carbon-free technology: advanced nuclear. We focus on nuclear power because it has been contributing almost 20% of total US electric generation, and because the US program in this area has historically been the world's leading effort. Using extensive data acquired through the Freedom of Information Act, we reconstruct the budget history of the Department of Energy's program to develop advanced, non-light water nuclear reactors. Our analysis shows that—despite spending \$2 billion since the late 1990s—no advanced design is ready for deployment. Even if the program had been well designed, it still would have been insufficient to demonstrate even one non-light water technology. It has violated much of the wisdom about the effective execution of innovative programs: annual funding varies fourfold, priorities are ephemeral, incumbent technologies and fuels are prized over innovation, and infrastructure spending consumes half the budget. Absent substantial changes, the possibility of US-designed advanced reactors playing a role in decarbonization by mid-century is low.

1. Introduction

Substantial scholarship has emerged around the need for radical innovation in energy technologies to reduce emissions and stabilize the climate (1, 2). Along with recommending a large increase in public sector spending on fundamental innovation and early deployment (3–5), this work has also emphasized the need for a wide array of technologies, including nuclear power (6). For the study of energy innovation, nuclear power is particularly interesting because it has been generating almost 20% of total US electricity for three decades, and accounts for more than half of all extremely low-carbon US electricity. Also, there is a history of efforts to invest in new designs, and that history can reveal how the public sector may need to reorganize its efforts to innovate.

Here we focus on a particular type of nuclear power—advanced, non-light water reactors. Energy planners worldwide have long envisioned a nuclear enterprise in which these designs would replace the current fleet of light water reactors (LWRs). Some of these would operate at higher temperatures, allowing reactors to provide energy services that existing reactors cannot (7). Some could operate for decades without refueling and burn up most of their fuel, which would reduce the volume of spent nuclear fuel generated, though that waste may be of higher toxicity (8–11). Moreover, some are theorized to be safer than LWRs, or more resistant to proliferation (12). In the US, the Department of Energy's (DOE) Office of Nuclear Energy (ONE) has embraced this transition, and its support is needed if this future is ever to materialize in the US, since it is charged with analyzing nuclear fission innovation (13). However, despite repeated commitments to a non-light water future (15–18) and non-trivial investments by NE, no such design is remotely ready for deployment today (19).

Once the global leader, the US pioneered several non-light water concepts in the first two decades of the

will require a shift to an electrified generation (Pathways to Deep Decarbonization, 2016). Our results suggest that the most credible technologies that include a light water reactor (LWR) make a nuclear technologies difficult. For instance, a move to standardized, non-light water designs, which are associated with LWRs, including both safety and waste (Nuclear Engineering of the National Academy of Engineering, 1992). In the U.S., stewardship of the Office of Nuclear Energy (ONE) has failed to fulfill this mission, and no advanced reactor design is remotely ready for deployment.

In a recent analysis of NE's budget expenditures over the past two decades, we found that it lacks both the funding levels and programmatic focus to ensure its non-light water reactor mission (Abdulla, et al., 2017). NE's difficulties in fulfilling its role highlight a fundamental challenge to major transitions in the energy system. How can limited government support for emergent energy technologies be allocated judiciously, and specifically, how can NE better enable nuclear innovation? Answering these questions ultimately requires expert judgment. Here, we report results from interviews we conducted with 30 nuclear energy veterans from across the enterprise—all with extensive knowledge of NE and the history of nuclear technology development—to elicit their impressions of the state of nuclear innovation in the U.S. and its likely future prospects.

2. Method

We conducted semi-structured interviews with subject matter experts that lasted two hours on average, making this one of the most

Today I will talk about three things:

1. Some basic background on:

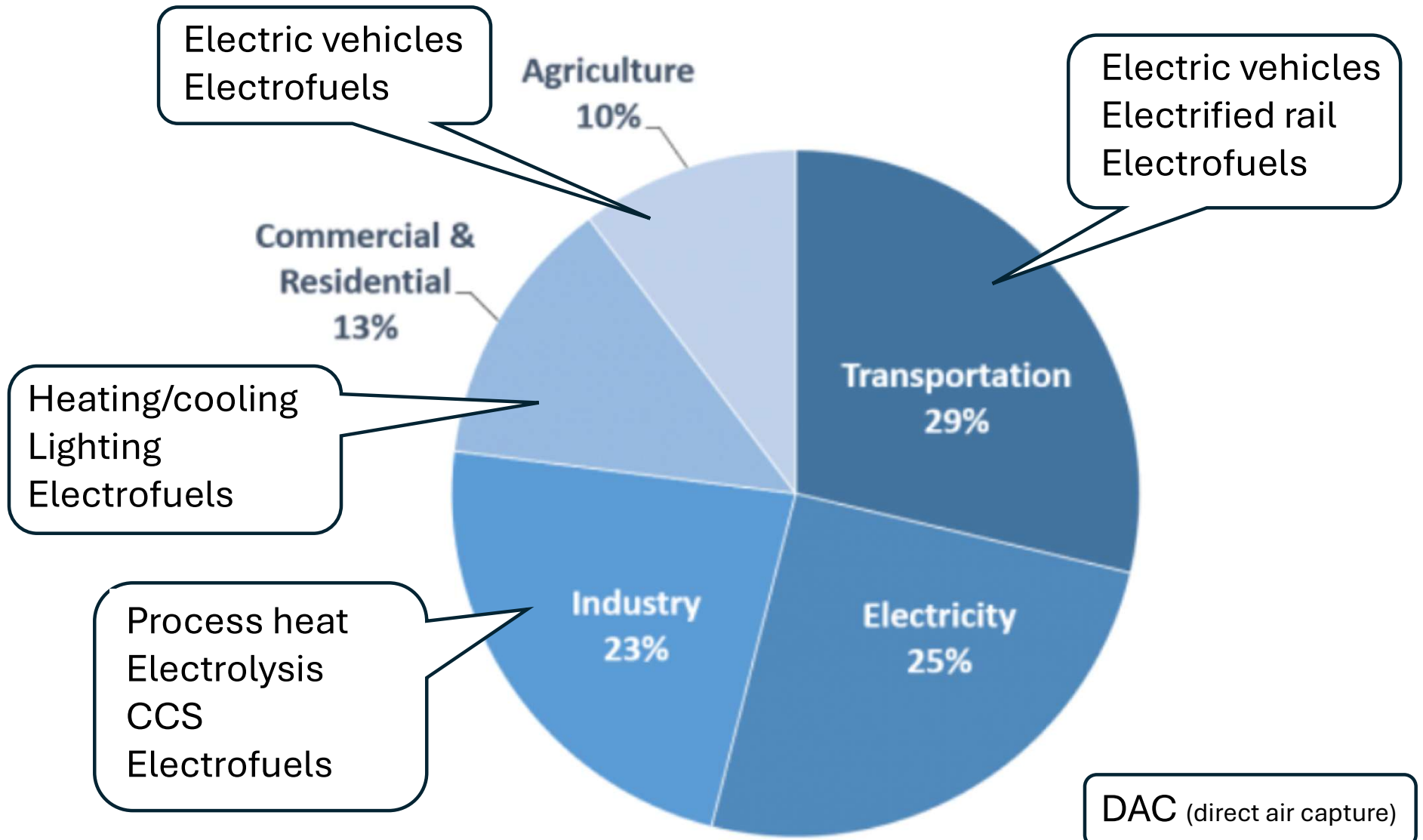
- Climate science
- The electricity system

2. Why electric power is critical to climate change:

- As a leading source of CO₂ and other GHG emissions and how to reduce those emissions
- As the most viable option to replace fossil fuels

3. The need to expand electric power transmission capacity and some efforts we are undertaking to address the problem.

Options to use electricity to decarbonize the other sectors:



Electrofuels

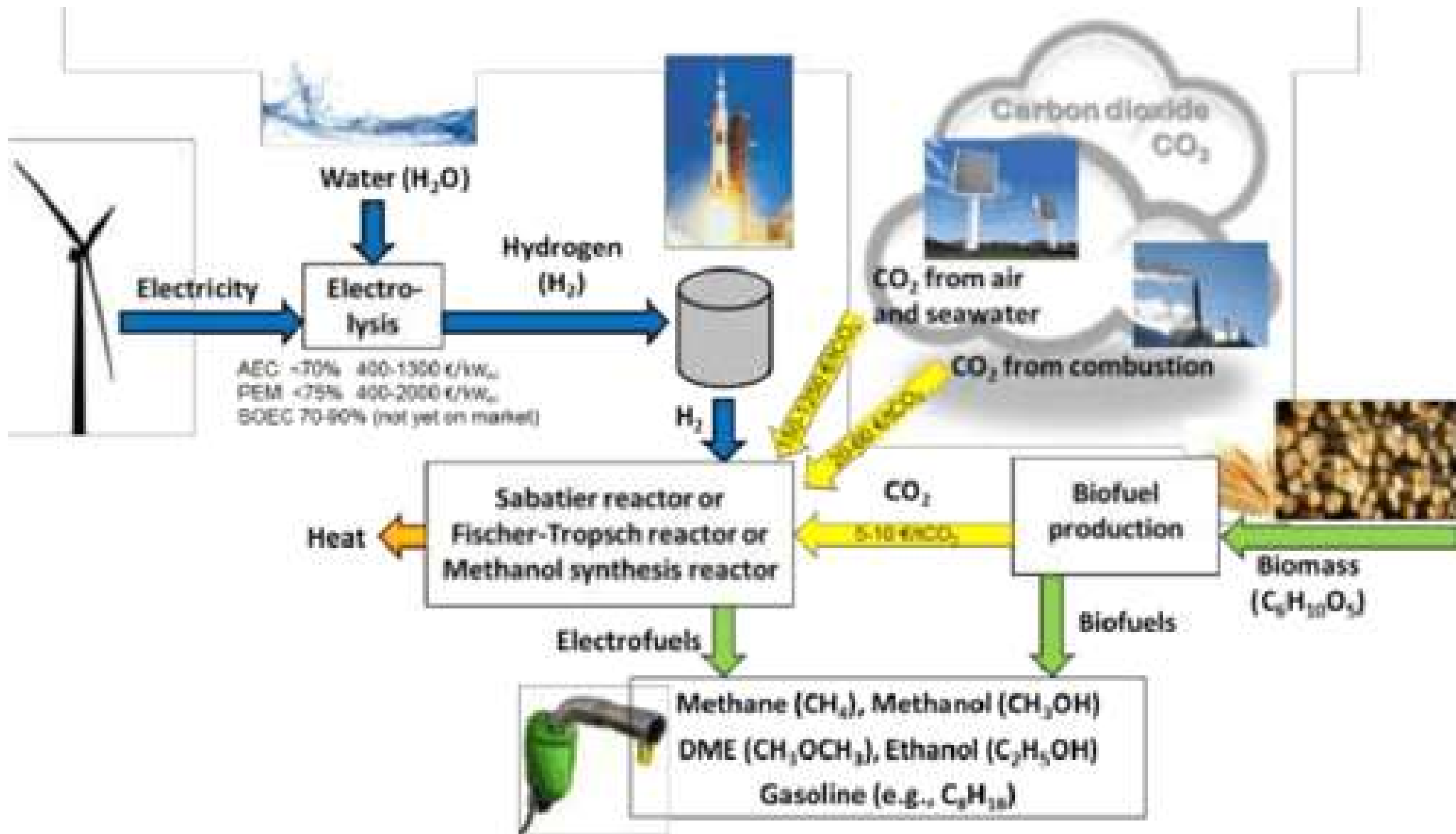


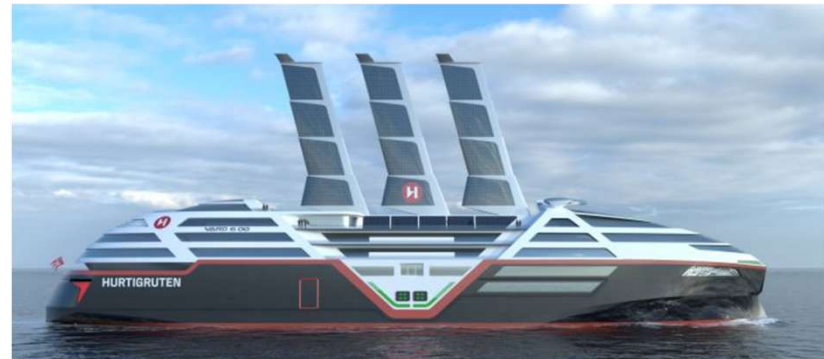
Image from M. Grahnet al, 2016.

Electric vehicles

All electric



Hybrid electric



Electrified Rail



OPEN ACCESS

RECEIVED
5 June 2017

REVISED
27 June 2018

ACCEPTED FOR PUBLICATION
24 July 2018

PUBLISHED
17 September 2018

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TOPICAL REVIEW

Decarbonizing intraregional freight systems with a focus on modal shift

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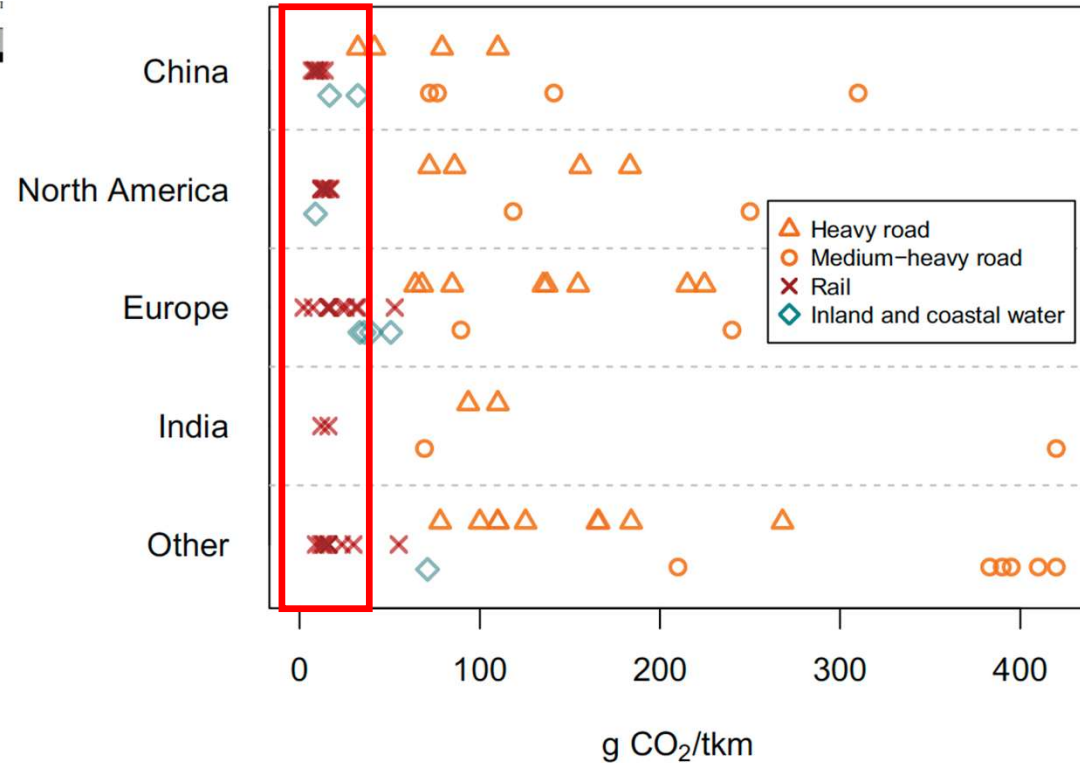
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Keywords: modal shift, intermodal, rail freight, decarbonization, freight, transportation, climate change

Supplementary material for this article is available [online](#)

Abstract

Road freight transportation accounts for around 7% of total world energy-related carbon dioxide emissions. With the appropriate incentives, energy savings and emissions reductions can be achieved by shifting freight to rail or water modes, both of which are far more efficient than road. We briefly



Images from: Virginiamercury; railmagazine

Heating, cooling and lighting

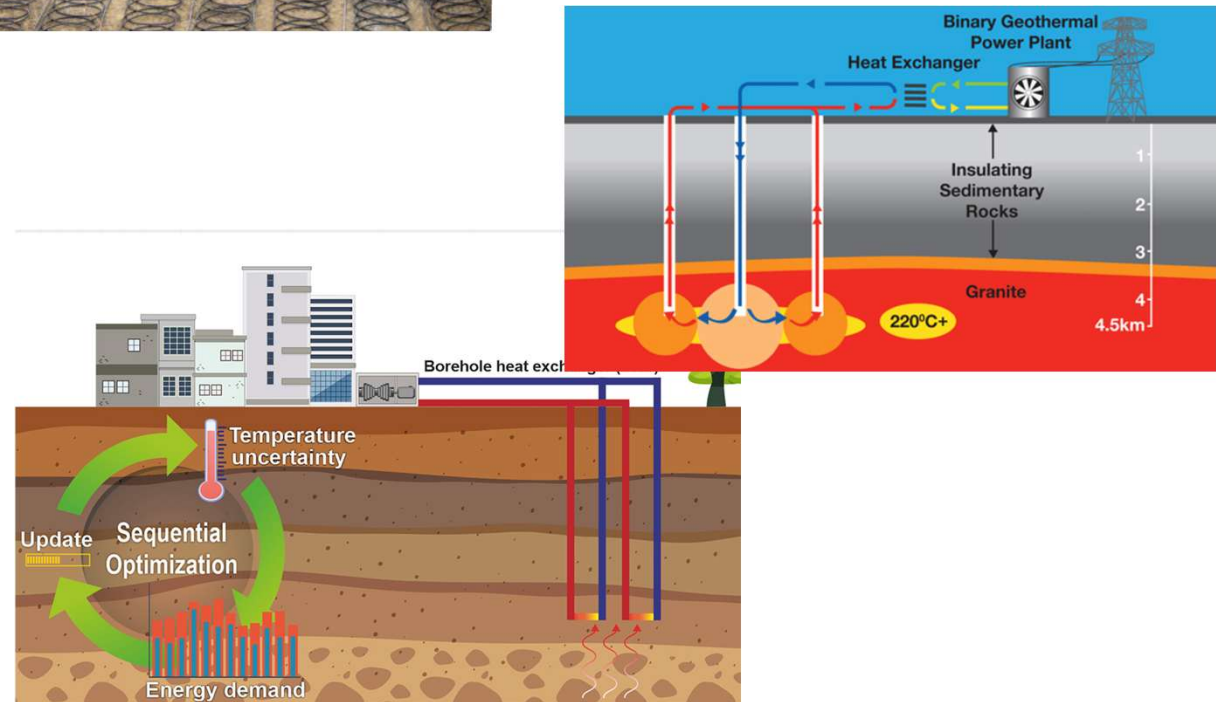
Solid state lighting:



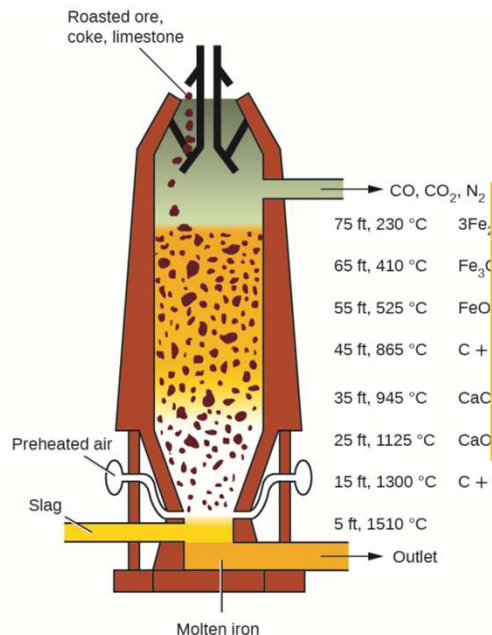
Air source



Ground source



Heavy industry...I'll make simple comments on two examples



Rather than use coke do direct reduction with hydrogen made with electricity.

CO₂ is generated from several sources.

Process Step	Direct CO ₂ emission (tCO ₂ /t)
Coke plant	0.794
Sinter plant	0.200
Pellet plant	0.057
Blast furnace	1.219
BOS plant	0.181

Source: <https://www.steelonthenet.com/kb/co2-emissions.html#:~:text=The%20main%20process%20steps%20that,produce%20large%20volume%20of%20CO2>.



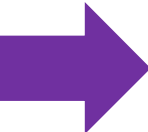
Use CCS and/or a different feed stock and electrofuel.

CO₂ is generated from three independent sources:

- decarbonation of limestone in the kiln (about 525 kg CO₂ per tonne of clinker),
- combustion of fuel in the kiln (about 335 kg CO₂ per tonne of cement) and
- use of electricity (about 50 kg CO₂ per tonne of cement).

Source: <https://www.ctc-n.org/technologies/clinker-replacement>

Today I will talk about three things:

1. Some basic background on:
 - Climate science
 - The electricity system
2. Why electric power is critical to climate change:
 - As a leading source of CO₂ and other GHG emissions and how to reduce those emissions
 - As the most viable option to replace fossil fuels
-  3. The need to expand electric power transmission capacity and some efforts we are undertaking to address the problem.

Do we really need more transmission?

Won't distributed generation (DG) like rooftop solar and moving large loads such as data centers to where electricity is generated make it unnecessary to expand transmission capacity?

The answer is no. Those things will help but we still need to move power to where loads are from:

- wind power in the Midwest and offshore platforms,
- solar in the Southwest
- hydro from Canada and other remote locations

And we also need it to assure continued system resilience (e.g. with more inverter-based power etc.)

But we face a logjam...

... arising from public opposition and legal, regulatory and other constraints including the incentives faced by utilities, that makes it difficult, often even impossible, to move clean energy from the locations where it is produced to the locations where it is needed, while assuring that the power system remains resilient.

MILES OF 345 KV+ TRANSMISSION LINES ADDED EACH YEAR

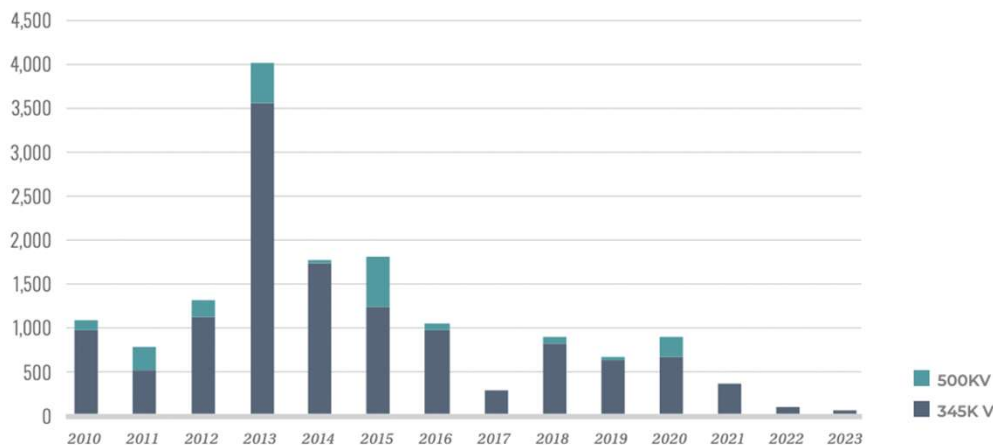


Figure from Shreve et al. (2024)

Growing backlog in the interconnection queue

Data are from seven independent system operators and regional transmission organizations and 26 utilities as of the end of 2023. The completion rate shown is calculated based on number of projects, not capacity. For projects entering queues in recent years, the final outcome may have yet to be determined.

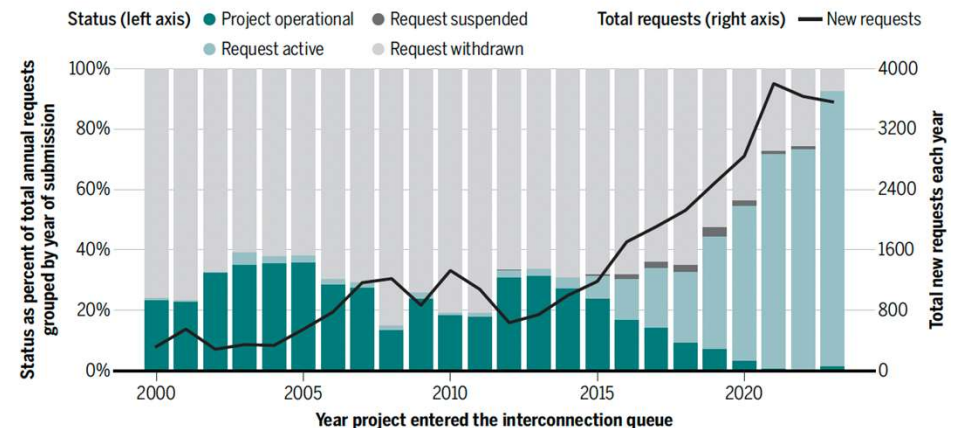


Figure from Armstrong et al. (2024).

The Federal Energy Regulatory Commission (FERC)...

...several DoE labs, and others are working on this issue, *but most of what they are doing is **very incremental*** and typically does not contemplate possible fundamental institutional, legal or regulatory changes, nor does it address public understanding and resistance.

It therefore fails to address and develop solutions for a number of key issues.

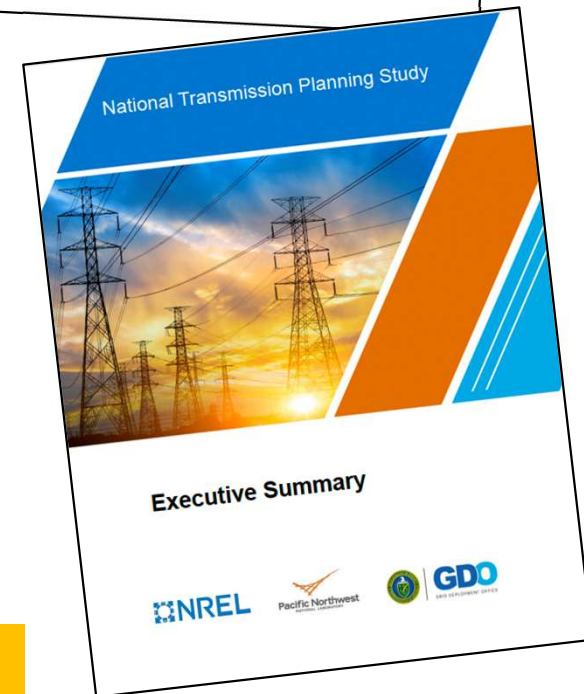
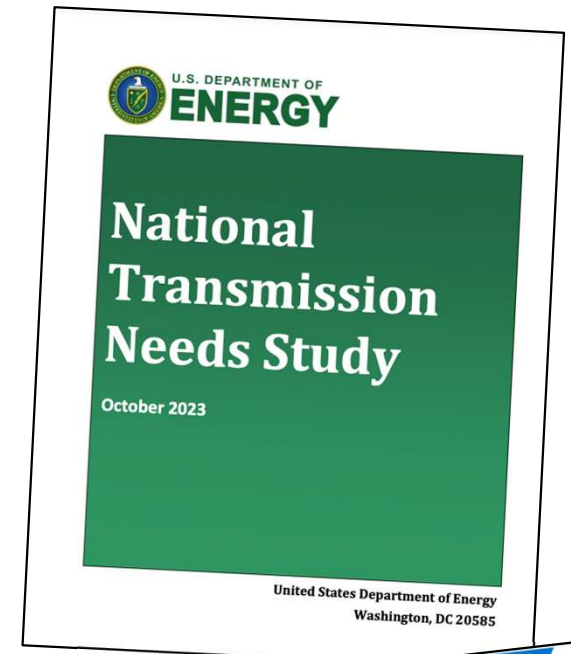
In two recent studies...

...DOE has argued that if the economy is going to stay strong, and the nation is going to make good progress in reducing CO₂ emissions, by 2050 the U.S. will need to ***more than double*** the capacity of our high-voltage transmission system. DOE has also laid out a set of optimal ways in which to expand the transmission system.

However, what neither of these DOE studies does is address the issue of *how to actually get this new transmission built*.

As I'll explain

That is what a team we've assembled proposes to do



With several colleagues, we are working to create...

...a multi-disciplinary multi-institutional (CMU, UCSD, USC, UCB, Penn State, PNNL) consortium that will identify and facilitate solutions to the problem of expanding U.S. transmission capacity.

While a solid technical and economic underpinning will be essential, we see the key challenges as:

- studying public perceptions and improving public understanding of the need for expanded transmission;
- assessing legal, regulatory, institutional, and political obstacles and those arising from interest groups.

And then:

- *proposing and actively promoting* needed fundamental structural, legal, regulatory, public communication, policy and other changes.

Public perceptions and improving public understanding

While there have been a few recent studies conducted in Europe, there do not appear to be any modern US-focused studies that use good modern social science research methods.

We are now designing such studies.

While it is important to...

...continue to work on facilitating the construction of new conventional overhead HVAC transmission lines and making incremental changes to existing legal and regulatory environments.

It is also important to complement that work by:

1. Developing ways to expand the amount of power that can be moved through existing high voltage transmission corridors.
2. Using HVDC cables embedded in both traditional and non-traditional right-of-ways (ROWs).

1. More power through existing ROWs

Three strategies hold potential to move more power through existing transmission ROWs.

1. Make greater and better use of the large amounts of data now being collected on modern transmission systems in order to operate those systems more efficiently.
2. Upgrade the capacity of existing HVAC lines. Because the amount of power that can be moved through a line is proportional to the product of the voltage and the current ($P=VI$), increasing either or both allows one to move more power. Doing this often requires reconductoring, new insulator strings, and/or wider ROWs. Anytime one does anything to a transmission line, issues of regulatory approval and public concerns and possible opposition become significant.
3. Convert existing HVAC lines to HVDC. Previous work we have done suggests that this may allow three times as much power to be moved through the same corridor. While the U.S. has not yet employed such a strategy, it is being done in Germany. Even to a greater extent than for reconductoring, issues of regulatory approval and public concerns are likely to play important roles in this case.

Three papers in these strategies for those who'd like to learn more:

The Electricity Journal 53 (2020) 106770

Contents lists available at ScienceDirect

The Electricity Journal

journal homepage: www.elsevier.com/locate/tej

Expanding Transmission Capacity: Examples of Regulatory Paths for Five Alternative Strategies

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ARTICLE INFO ABSTRACT

Keywords: Electricity Transmission Regulation
HVDC
Right-of-way
Siting

Transmission capacity expansion using existing lines and rights-of-way (ROW) is a strategy that deserves greater attention. The need to acquire siting approval and ROW for a new line can increase a project timeline by many years, and in some cases may even lead to project cancellation. Projects that use or expand an existing ROW face different regulatory pathways and typically result in different responses from the public and other entities than those that involve siting an entirely new line. In order to identify and compare some of the issues that arise in reconfiguring existing lines, expanding rights of way for existing lines, and building entirely new lines, we obtained input from a number of PUCs and siting authorities across the United States, reviewed a large number of projects, and identified the types of approvals that different types of projects can expect. In this paper, we develop a taxonomy of technical strategies that can be used to increase the capacity in an existing transmission corridor and identify the regulatory and other issues that must be addressed in each case. We compare those options with that of building an entirely new line and illustrate the various strategies with examples drawn from U.S. transmission projects that have been undertaken over the past 20 years.

circumstances than planners currently consider, converting an existing transmission line to high voltage direct current (HVDC) is the least cost solution for distances as short as 150 miles. (Reed et al., 2019).

In addition to cost, obtaining regulatory approvals is an important consideration for project selection. In this paper we compare the regulatory processes that apply to five different technical strategies for increasing transmission capacity and power flow:

- (1) reductoring to increase current,
- (2) increasing voltage,
- (3) installing a Flexible Alternating Current Transmission System (FACTS),
- (4) converting to HVDC, and
- (5) building a new line.

Importantly, FACTS cannot increase thermal capacity but can be used to increase the transmission capacity of lines whose performance is limited by the system dynamics rather than the line materials.

The regulatory competition is important because the electricity load is likely to increase with increased transportation and industrial electrification, and with the incorporation of more renewable generation sources. These changes are projected to require at least 50% more

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<https://doi.org/10.1016/j.tej.2020.106770>

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Converting existing transmission corridors to HVDC is an overlooked option for increasing transmission capacity

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Edited by Peter O. Blair, National Academy of Sciences, Washington, DC, and accepted by Editorial Board Member Susan Hanson May 21, 2019 (received for review April 15, 2019).

A changing generation mix and growing demand for carbon-free electricity will almost certainly require dramatic changes in the infrastructure and topology of the electricity system. Rather than build new lines, one way to minimize social opposition and regulatory obstacles is to increase the capacity of existing transmission corridors. In addition to upgrading the capacity of high-voltage alternating current (HVAC) lines, we identify a number of situations in which conversion from HVAC to high-voltage direct current (HVDC) is the least-cost strategy to increase the capacity of the corridor. If restricted to the existing right-of-way (ROW), we find DC conversion to be the least-cost, and in some cases the only, option for distances of >200 km or for increases of >50% capacity. Across all configurations analyzed, we assess HVDC conversion to be the lower-cost option at >350 km and >50% capacity increases. While we recognize that capacity expansion through HVDC conversion may be the optimal solution in only some situations, with future improvements in the cost and performance of solid-state power electronics, conversion to HVDC could be attractive in a growing set of circumstances.

Many utilities already look for opportunities to increase the capacity of existing transmission rights of way, typically through “reductoring” which can increase alternating current (AC) power transmission capacity by up to 50%. Venturing beyond this paradigm, in Germany, the Ultramet HVDC expansion project is currently converting an existing AC corridor to a hybrid AC/DC corridor to bring wind power from the north of the country to loads in the south (11). This project is a first. Up until now, because of the cost and the operational limitations of previous technologies, most utilities have only considered HVDC for new, high-power, long-distance transmission. However, if it were faster and cost-effective, HVDC conversion could increase the active power transfer capacity up to 4 times depending on the allowable DC voltage and the existing AC operating conditions (12), and could theoretically transmit 3.5 times the total power in a corridor using existing lines and structures, based on the thermal limits of the lines (13).

The International Council on Large Electric Systems concluded, in a 2016 study, that expanding capacity through HVAC to HVDC conversion is typically only attractive when building new transmission is not possible (14). This situation now applies to much of the United States. Current planning tools do not incorporate HVDC conversion (6), so such conversion is typically not considered. Here we demonstrate why HVDC conversion warrants consideration when there is a need to increase the capacity of an existing transmission corridor.

HVDC | transmission planning | electricity transition | decarbonization

While it is impossible to know with certainty the future of the electricity system, 3 developments are highly likely. First, changes in the mix of generation toward more renewable sources that have already occurred will accelerate. This will partly result from changing market conditions but, more fundamentally, from a growing commitment to creating a more sustainable energy system through a dramatic reduction in emissions of greenhouse gases and conventional air pollutants. Second, after years of low, and in some regions even negative, demand growth, there will be much wider electrification. Growth in demand will occur because, with affordable carbon-free electricity available, electrification is an effective strategy for decarbonizing much of the energy system. Third, these 2 developments will result in a need for large changes in the nature and topology of the infrastructure of the bulk electric power system (1–4).

Recent studies have shown that the use of more high-voltage direct current (HVDC) transmission could provide many benefits as part of these topological changes. A national HVDC overlay or macrogrid could be a cost-competitive route to decarbonization, provide interregional stability between the western and eastern interconnection, and increase reliability and resilience in the grid in the face of changing weather patterns (5–7). Even if that vision is not realized, it is clear that the country will need to move more power through the high-voltage system, often over routes that are operating at close to capacity. However, siting and building new high-voltage power lines has become much more difficult, indeed, in some cases impossible, due to regulatory constraints, entrenched interests of utilities and generation owners, and aesthetic and environmental opposition from the public (8–10).

Author contributions: L.R., M.G.M., P.V., and D.E.A. designed research; L.R., M.G.M., P.V., and D.E.A. performed research; L.R. analyzed data; and L.R., M.G.M., and P.V. wrote the paper.

The authors declare no conflict of interest.

This article is a PNAS Direct Submission. P.D.B. is a guest editor invited by the Editorial Board. Published under the PNAS license.

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This article contains supporting information online at www.pnas.org/lookup/suppl/doi:10.1073/pnas.1905656116/-/DCSupplemental.

Published online June 20, 2019.

www.pnas.org/cgi/doi/10.1073/pnas.1905656116

PNAS | July 9, 2019 | vol. 116 | no. 28 | 13879–13884

PNAS RESEARCH ARTICLE ENGINEERING ENVIRONMENTAL SCIENCES

Accelerating transmission capacity expansion by using advanced conductors in existing right-of-way

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Edited by M. Granger Morgan, Carnegie Mellon University, Pittsburgh, PA; received June 4, 2024; accepted August 15, 2024

As countries pursue decarbonization goals, the rapid expansion of transmission capacity for renewable energy (RE) integration poses a significant challenge due to hurdles such as permitting and cost allocation. However, we find that large-scale reductoring with advanced composite-core conductors can cost-effectively double transmission capacity within existing right-of-way, with limited additional permitting. This strategy unlocks a high availability of increasingly economically viable RE resources in close proximity to the existing network. We implement reductoring in a model of the US power system, showing that reductoring can help meet over 80% of the new international transmission needed to reach over 90% clean electricity by 2035 given restrictions on greenfield transmission build-out. With \$180 billion in system cost savings by 2050, reductoring presents a cost-effective and time-efficient, yet underutilized, opportunity to accelerate global transmission expansion.

power systems | decarbonization | transmission | renewable energy

Increasingly, the energy transition discourse is focusing on electricity transmission: the need to build it and the challenges of doing so. The International Energy Agency estimates that the global length of transmission lines must increase from 3.5 million to 15 million km—approximately 2.7 times—to reach net zero emissions by 2050, not including the eventual replacement of aging infrastructure (1). In the United States and Europe, however, new overhead lines take an average of over 10 yr to build (1, 2). Grids are increasingly becoming the bottleneck of the energy transition, with over 1,200 GW of renewable energy (RE) projects in the United States, and over 3,000 GW globally, awaiting connection to the grid (3, 4). Challenges related to permitting—such as securing new right-of-way (ROW), completing environmental impact assessments, and cost allocation—often result in project delays (1, 2). In the United States, for example, the rate of transmission build-out has fallen by nearly 50 percent over the past decade, threatening decarbonization timelines (5, 6).

Recent rapid declines in the costs of solar, wind, and batteries (7) along with incentives from the Inflation Reduction Act (IRA) have presented an opportunity for a paradigm shift in low transmission is planned and sited. Specifically, there is a narrowing gap in cost between RE sited at locations with the highest resource potential and RE sited at locations that are in close proximity to the existing transmission network and load. This RE capacity could be unlocked through a wide range of technological solutions that can increase the transmission capacity of the existing grid. Some strategies, known under the umbrella term of Grid-Enhancing Technologies (GETs) and including Power Flow Controllers, Flexible AC Transmission Systems devices, Dynamic Line Ratings (DLR), and demand-side measures, can either enhance the physical capability of a transmission asset or the efficiency of power flow throughout the system. However, while these technologies are extremely important to expanding grid capacity, their potential is dependent on real-time operating conditions and thus typically limited and temporary. Other strategies can provide a larger and lasting increase of transmission capacity, such as reductoring with advanced composite-core conductors, voltage upgrades, and AC-to-DC conversion. Yet whereas voltage upgrades may necessitate widening of the existing ROW and AC-to-DC conversion is generally most suitable for long lines, reductoring—the replacement of a transmission line's existing conductors with either larger-diameter conductors or a different type of conductor—is a practice used by utilities to increase ampacity within existing ROW.

In recent decades, the development of advanced composite-core conductors has opened up new possibilities for rapid transmission capacity expansion through reductoring (8). While most of the high-voltage grid today is wired with a century-old technology known as Aluminum Conductor Steel Reinforced (ACSR) featuring aluminum strands around a steel core (9), advanced conductors swap the steel for a stronger yet smaller

Significance

The integration of renewable energy sources at speed and scale in order to reduce emissions and achieve climate goals will likewise require the increase of transmission capacity at speed and scale. While the build-out of new greenfield lines is often plagued by challenges related to permitting and cost allocation, leveraging existing right-of-way, particularly through reductoring with advanced conductors, can rapidly expand transmission capacity. However, advanced conductors have been traditionally viewed as a niche solution and their deployment is limited, requiring targeted policy to spur uptake and unlock their potential to contribute to cost-effective decarbonization.

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Author contributions: E.C., U.P., N.A., C.B., R.O., D.C., and A.P. designed research; E.C. and U.P. performed research; E.C. and U.P. analyzed data; and E.C., U.P., and D.C. wrote the paper.

The authors declare no competing interest.

This article is a PNAS Direct Submission.

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This article contains supporting information online at <https://www.pnas.org/lookup/suppl/doi:10.1073/pnas.2411207121/-/DCSupplemental>.

Published September 23, 2024.

PNAS 2024 Vol. 121, No. 40 e2411207121 <https://doi.org/10.1073/pnas.2411207121> 1 of 9

2. More power via HVDC cables in traditional and non-traditional ROWs

- Existing lower-voltage transmission corridors
- Existing state and federal highways
- Existing rail corridors
- Waterways (lakes, rivers, canals)
- Abandoned and repurposed rail corridors
- Existing pipeline corridors

Champlain Hudson Power Express



This >300-mile transmission line now under construction will deliver >1GW of low-carbon power from Quebec to New York City.



Soo Green



Four strands of our planned research

1. Improve understanding of public knowledge and perceptions	2. Lay key foundations and background	3. Analysis of expanded capacity using traditional ROWs	4. Analysis of expanded capacity using non-traditional ROWs
<ul style="list-style-type: none"> • Perform mental model studies of public beliefs about the role about transmission and need for capacity expansion. • Develop, evaluate, refine and disseminate communication materials to improve public understanding. 	<ul style="list-style-type: none"> • Identify and analyze past siting & upgrade failures and successes. • Develop engineering/economic models of capacity expansion strategies. • Use power system models to assess expansion options. 	<ul style="list-style-type: none"> • Identify obstacles to the use of: <ul style="list-style-type: none"> ○ reconductoring ○ HVAC to HVDC conversion ○ others • Develop and promote legal, regulatory and other strategies to align incentives to overcome obstacles. 	<ul style="list-style-type: none"> • Identify obstacles to the use of: <ul style="list-style-type: none"> ○ highway ROWs ○ rail ROWs ○ lake/river/canal ROWs ○ others • Develop and promote legal, regulatory and other strategies to align incentives to overcome obstacles.

By the end of the project...

...we plan to:

- Have created material to improve public understanding of the need for expanded transmission capacity and together with the pros and cons of different ways of doing that.
- Have systematically identified legal regulatory and other barriers to expanding transmission capacity through both traditional and nontraditional ROWs and developed recommendations for how they might best be overcome.

That concludes my talk...

thanks very much for your attention

Acknowledgments

Much of our work has been supported by the U.S. National Science Foundation through a series of center grants on climate and energy decision-making, as well as by EPRI, the US DOE and several others.

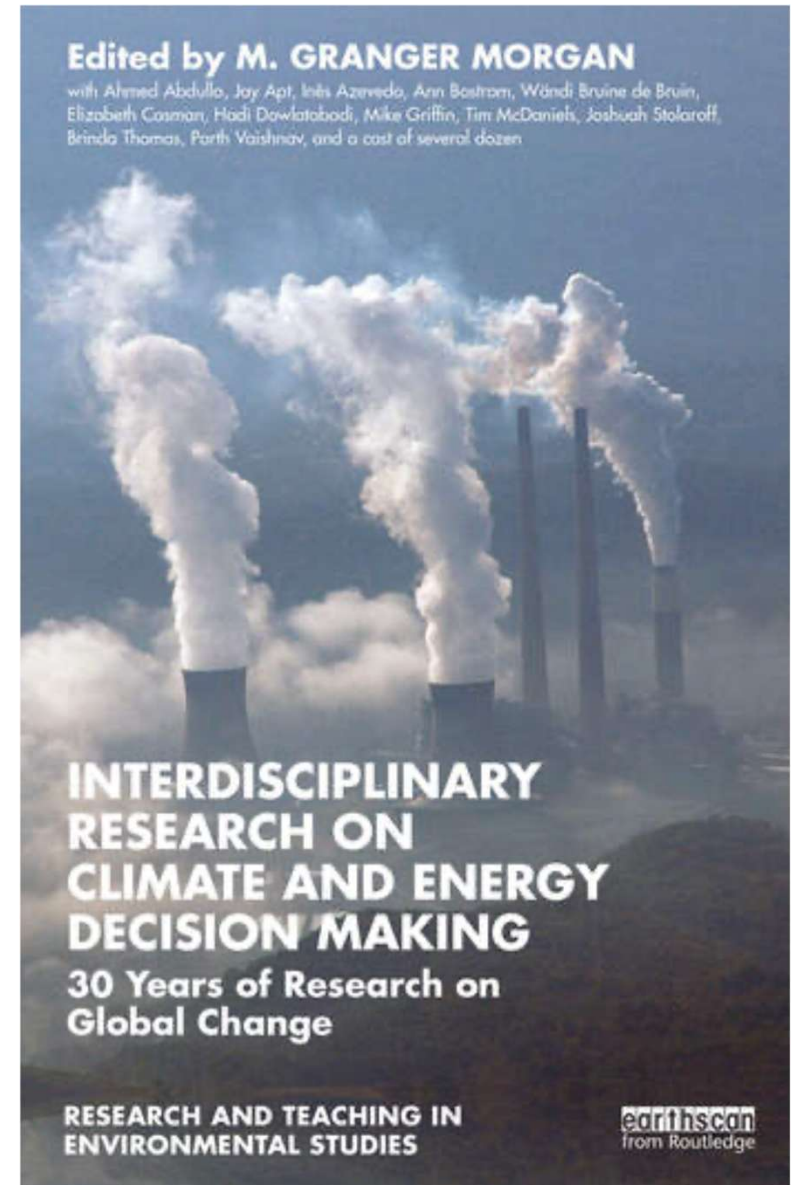
More recent work on power electronics, and the expansion of the transmission system is being supported by the Alfred P. Sloan Foundation

PS

We recently published a book that summarizes 30 years of work we did in three large NSF-supported distributed centers on climate and energy decision making.

It contains first person accounts in lay language. At the end of each chapter are a set of citations (often with abstracts) to some of the work we have discussed.

Then in an appendix we provide citations to more than 650 journal publications and scores of book chapters and PhD theses that have resulted from our work.



Routledge, 2023, 336pp.

Here are many of our collaborators whose work is summarized in that book.

