Achieving a low-carbon energy system in the Northeast

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Princeton University

The Council of State Governments/Eastern Regional Conference
Northeastern Legislative Climate and Energy Summit:
Promoting the Environment, Public Health and a Sustainable Energy Future

Andlinger Center for Energy and the Environment
Princeton University

May 11, 2018

Warming depends on the emissions path

Thirty year changes for Massachusetts for two paths:

2010-2039:
Done!

2040-2069:
Princeton vs. Washington

2070-2099:
Baltimore vs. South Carolina

This graph probably shows how winters could feel too (to be verified).

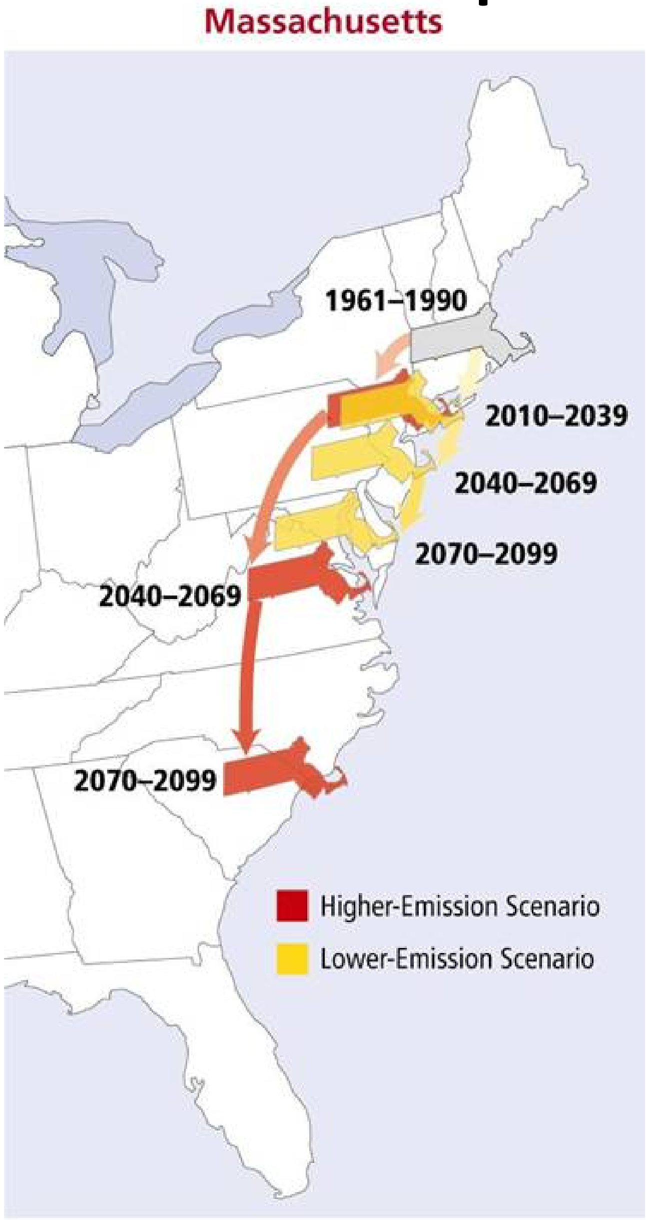
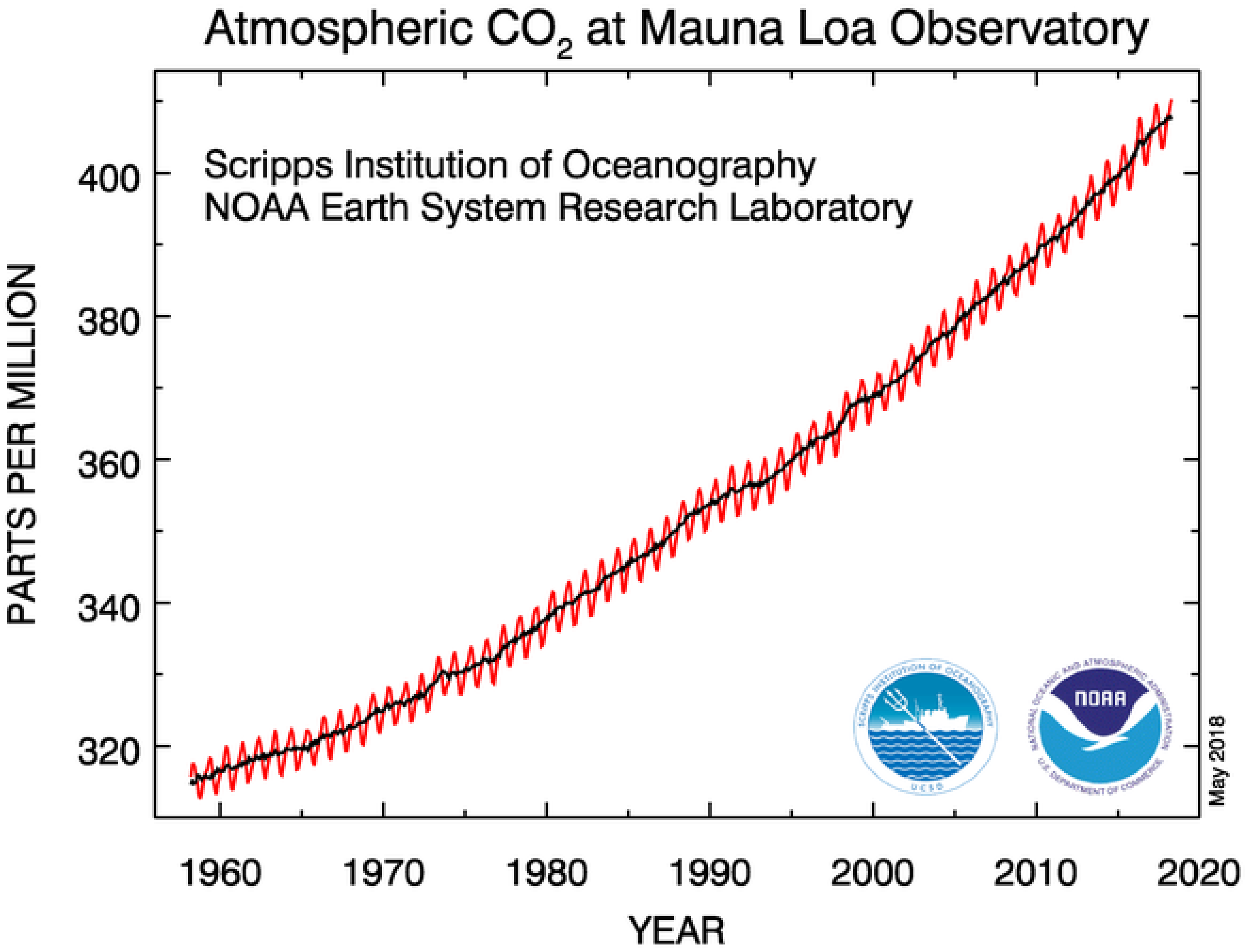
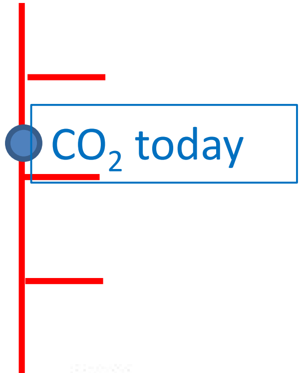


Figure at NECIA, 2007 (see: www.climatechoices.org/ne/) , shown by James McCarthy, Harvard

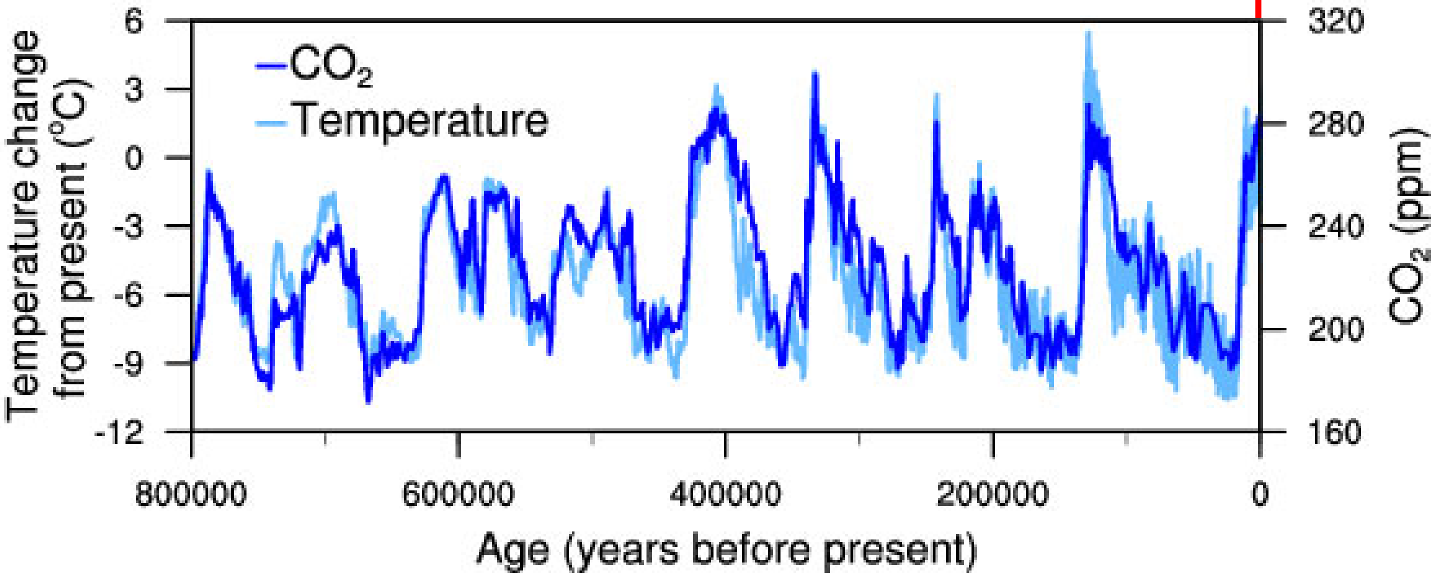
Above 410 for the first time last month



Antarctic CO_2 and temperature vary together



CO_2 today



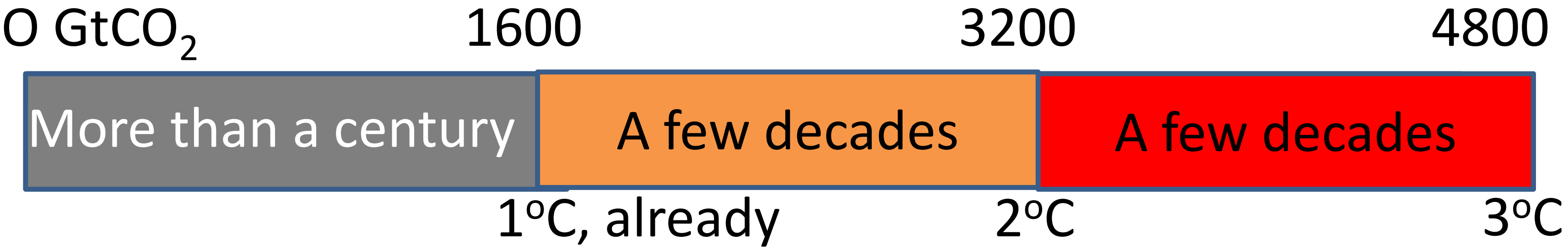
A single big idea

We are confronting one overarching, counterintuitive, new idea:
Human beings are able to change the planet at global scale.

This new idea is unwelcome. We wish we lived on a larger planet.

We must all agree on at least this much.

Cumulative emissions and temperature



1°C will result from anthropogenic CO_2 emissions to date.

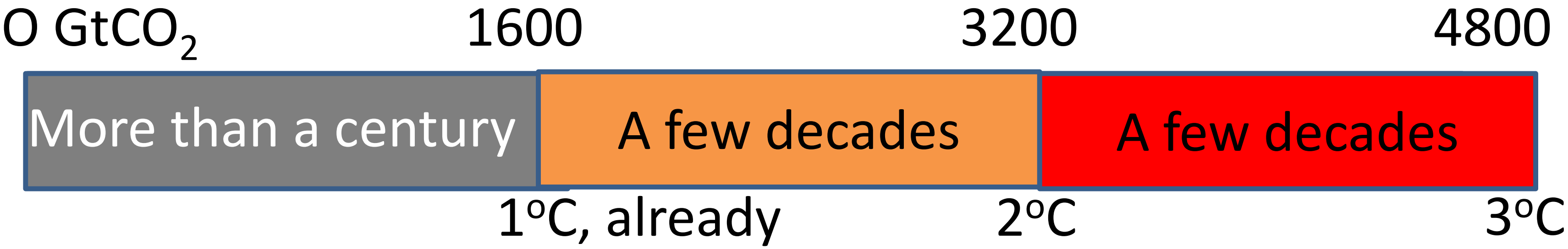
2°C results from future emissions equaling historic emissions.
It is the most discussed target.

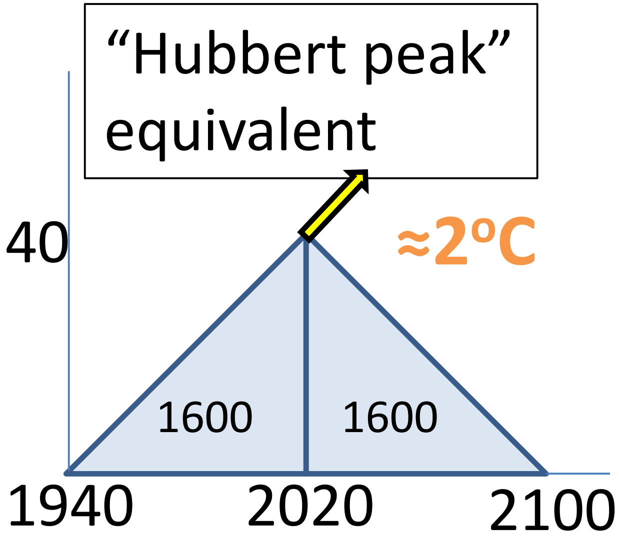
3°C will result from roughly tripling the historical total.

The probability is about 1/6 for both:

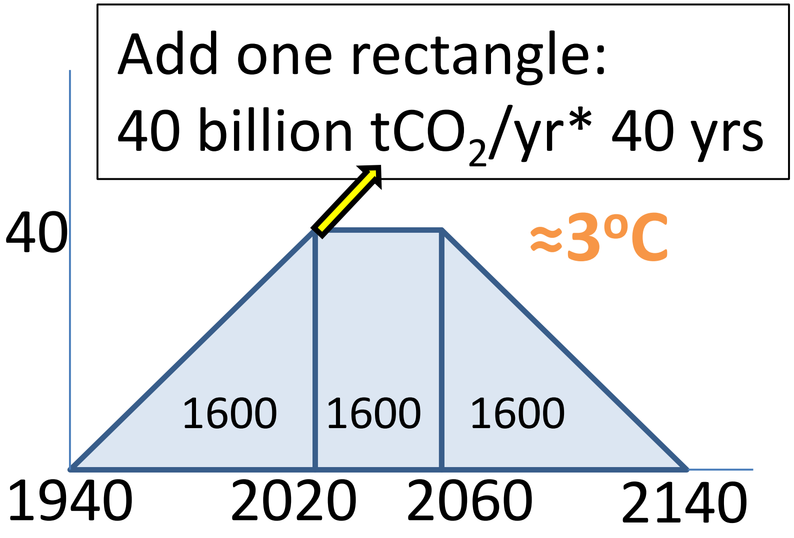
getting 3°C while aiming for 2°C (being unlucky)
getting 2°C while aiming for 3°C (being lucky).

Carbon budgets




“Hubbert peak” equivalent

≈2°C


Add one rectangle:
40 billion tCO$_2$/yr* 40 yrs

≈3°C

↗ If we were not confronting climate change, the era of fossil fuels (coal, oil, and gas) could last hundreds of years.

Budgets demand choices

The budget concept leads inexorably to choices about which fossil fuels to extract and which to leave in the ground:

When?
Whose?
Used where?
For what purpose?
Which fossil fuels?

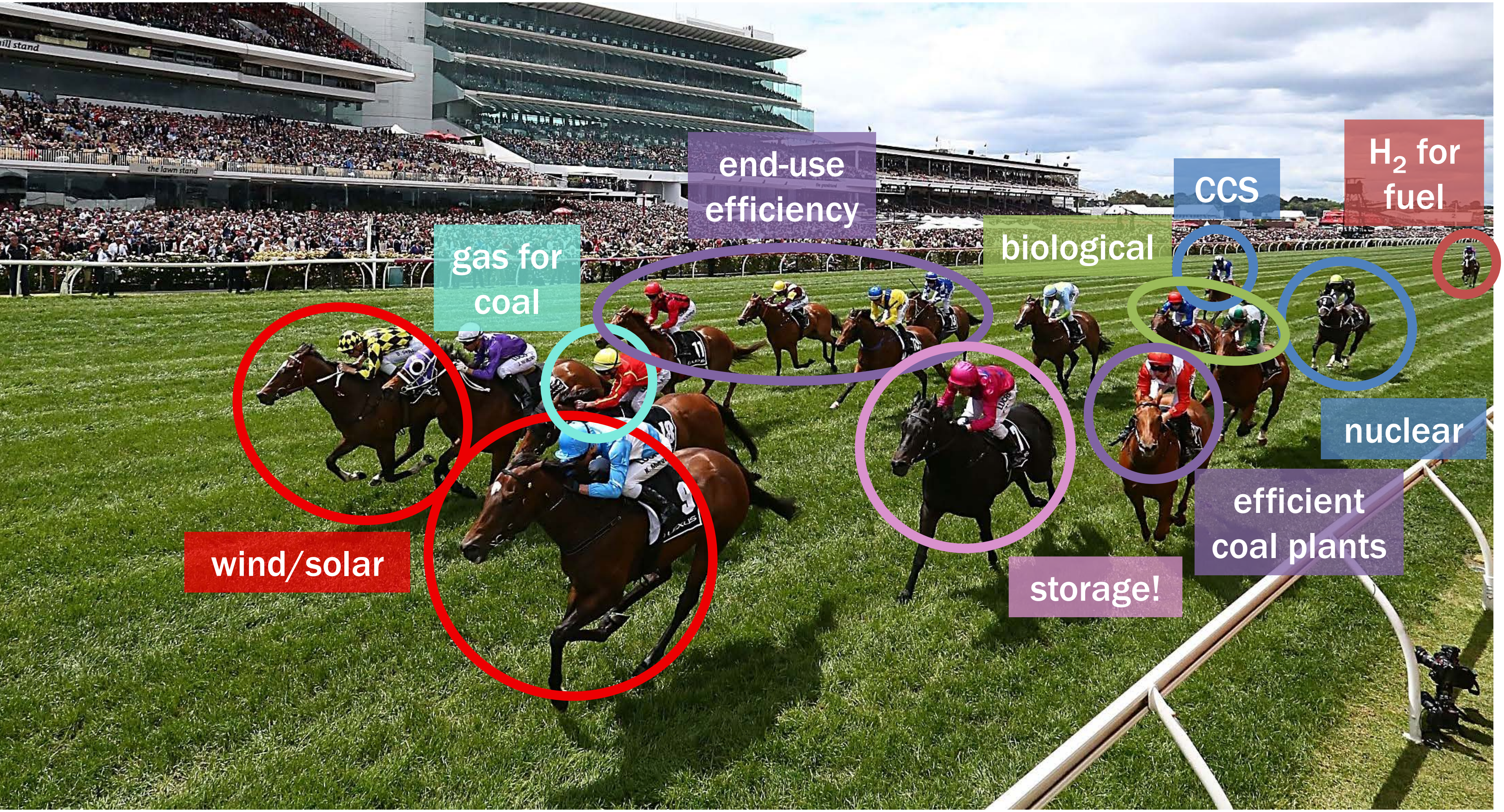
Better options someday?
Geopolitical stability
“Fairness”
Who judges?
Those with the highest H/C ratio?

Judgments about which fossil fuels are “unburnable” have no precedents.

Stabilization wedges… in 2004

2011 Kentucky Derby, AP Photo/Matt Slocum. https://www.cbsnews.com/pictures/2011-kentucky-derby/7

Stabilization wedges… in 2018



Melbourne Cup, The Foreign Correspondents‘ Club, Hong Kong. https://www.fcchk.org/event/melbourne-cup

SOLAR AND WIND

Plummeting costs are the most exciting development in the past decade. The world placed a big bet, and it paid off. A swap of the current fossil fuel system for an energy system dominated by solar and wind no longer seems fanciful.

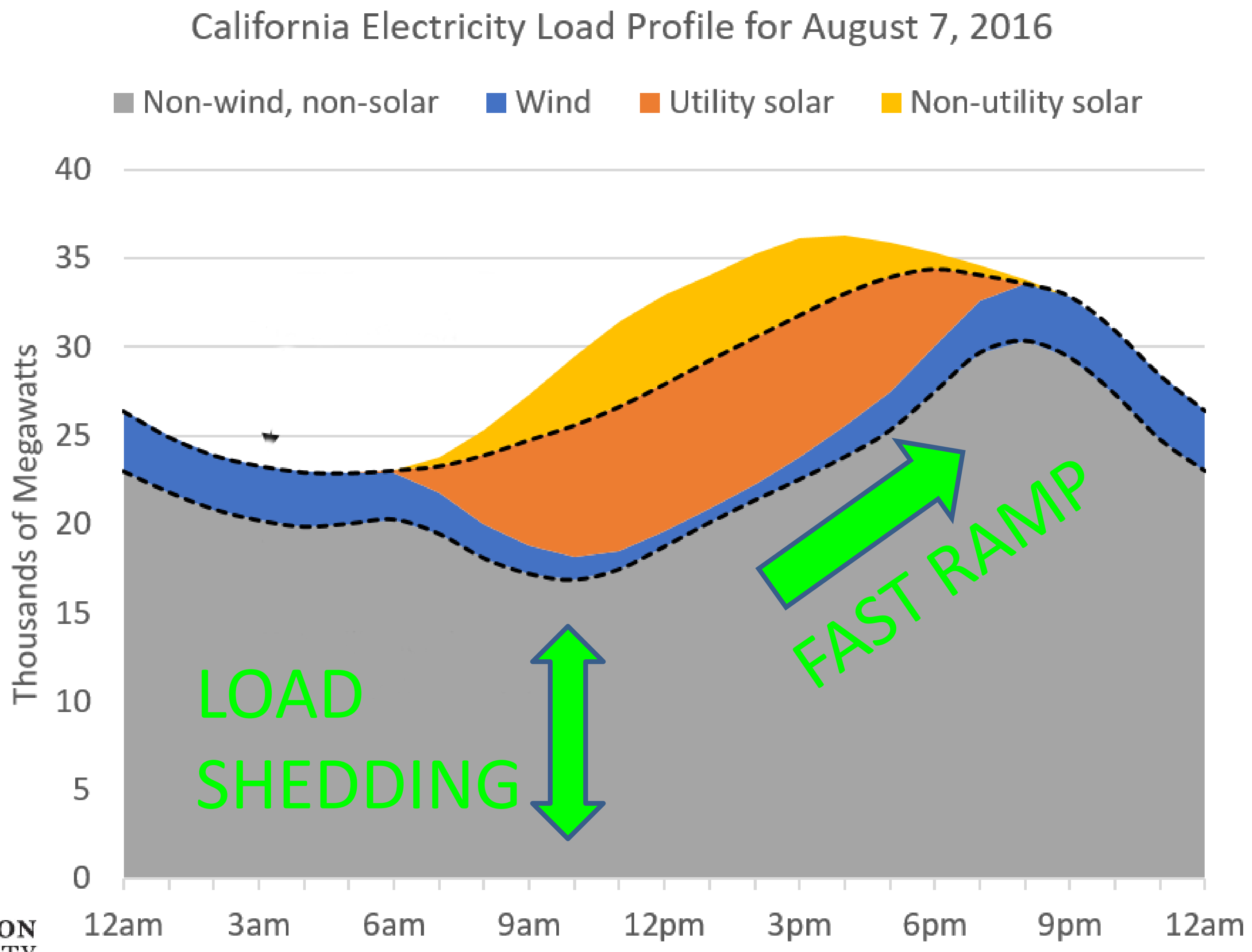
Obstacles:

1. **Ramping requirements**
2. **Intermittency and unpredictability**
3. **Long periods of low power output (long lulls).**

Solutions:

1. **Demand-side management**
2. **Transmission investments**
3. **Back-up power**
4. **Storage**

Solar power helps the summer peak, but…



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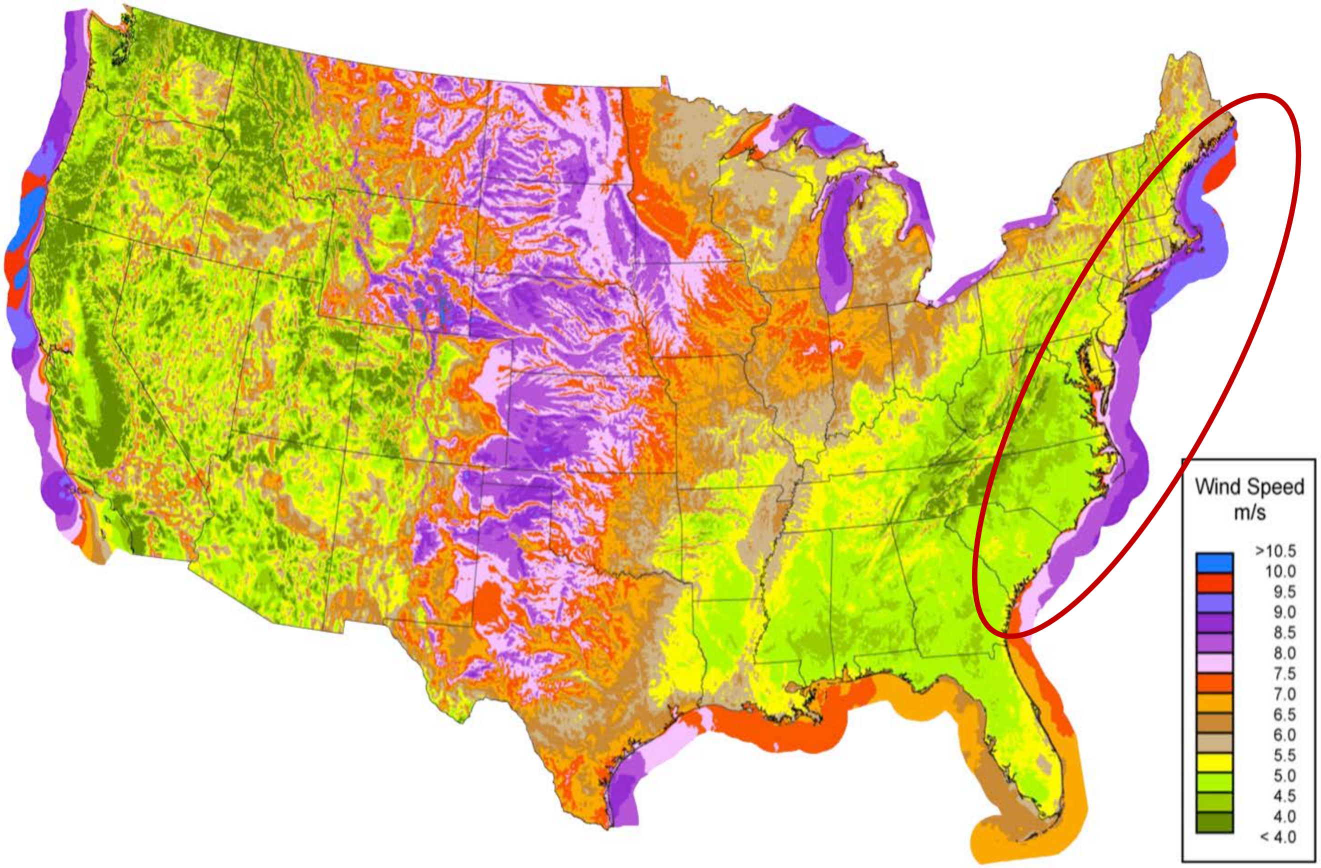
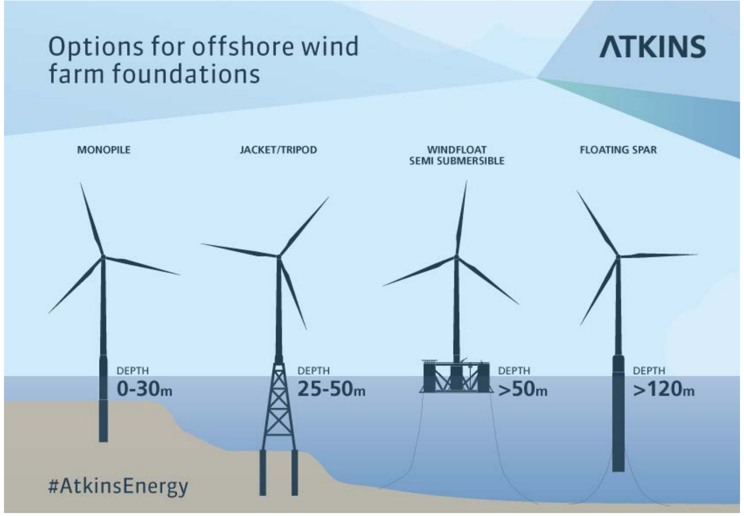
Off the Atlantic shore

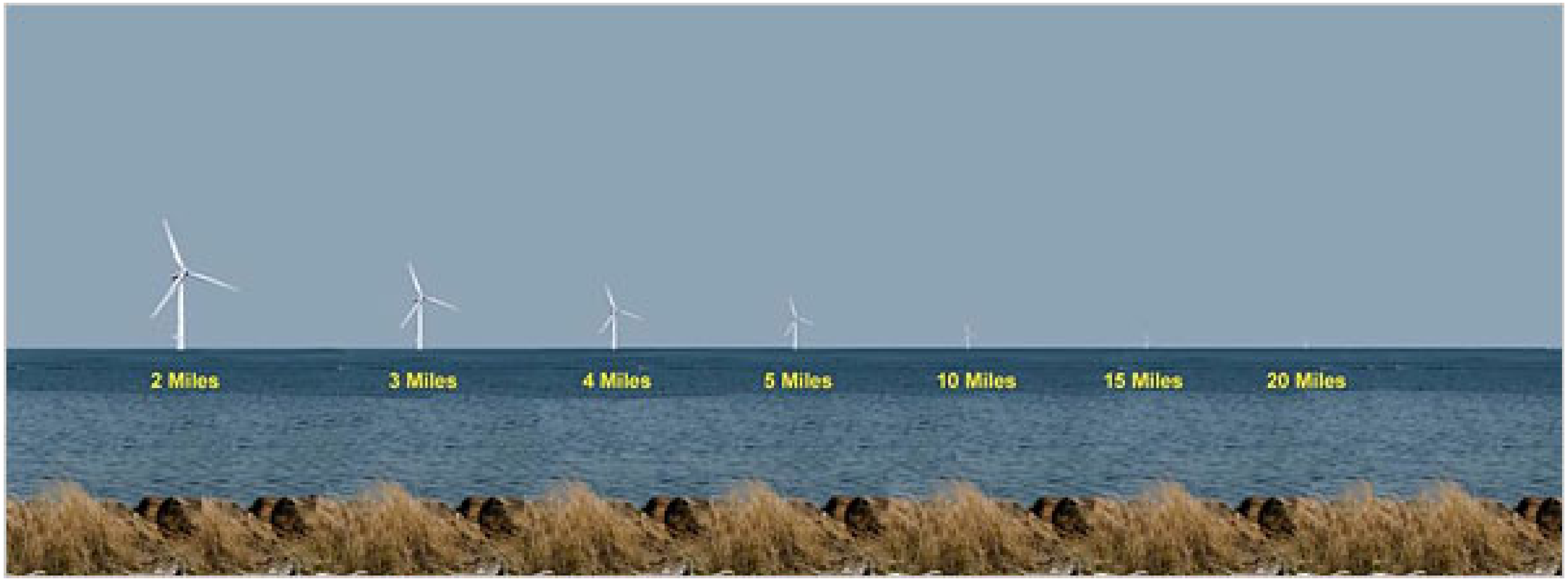


Plan regionally. E.g., promote offshore trunk lines.
Avoid boom and bust by too fast a rush.
Bottlenecks are everywhere and can be avoided.

What’s ahead


Options for offshore wind farm foundations
ATKINS
MONOPILE
JACKET/TRIPOD
WINDFLOAT SEMI SUBMERSIBLE
FLOATING SPAR
DEPTH 0-30m
DEPTH 25-50m
DEPTH >50m
DEPTH >120m
#AtkinsEnergy

Wind farms out of sight



Offshore New Jersey: 96 turbines, 346 MW, 16 to 20 miles from coast. $1 billion project. Power “starting in 2013.”

Source: http://www.nytimes.com/2008/10/04/nyregion/04wind.html?ref=nyregion, *New York Times*, October 3, 2008.

LOW-CARBON FOSSIL FUEL

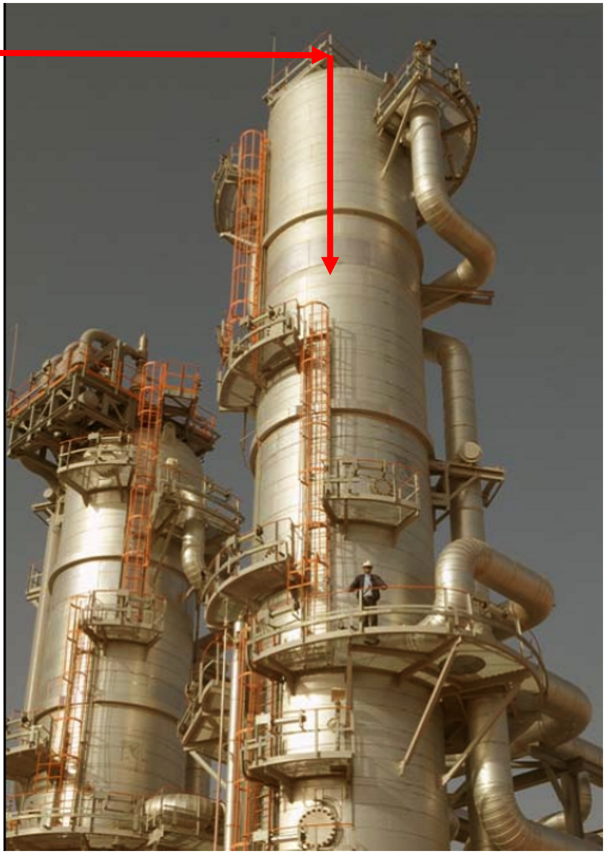
Encourage Carbon Capture and Storage (CCS), which expands CO_2 emission budgets

Resist ideological opposition to fossil fuels.
The great is the enemy of the good.

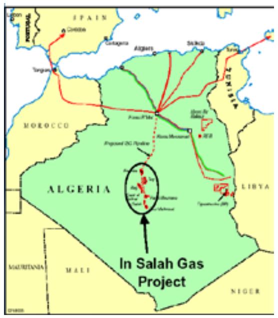
The new federal subsidy, “45Q,” will stimulate CCS.

CCS is already well known


BP’s CCS Project in In Salah, Algeria


Amine contactor towers

Natural gas purification by CO_2 removal, then CO_2 pressurization for nearby injection



“45Q,” a new U.S. subsidy: EOR (\$35/tCO_2), aquifer-CCS (\$50/tCO_2).

EFFICIENCY

Major gains are possible in every sector.

Residential and commercial buildings and their appliances have particularly large potential.

1. **Measure! It’s the key to learning.**
2. **Protect the poor via lifeline rates (low unit cost for first block).**
3. **Use spot-market prices to enable “smart” residential and commercial buildings everywhere.**
4. **Pursue deep retrofits of public housing.**
5. **Upgrade the appliance stock (cash for clunkers).**
6. **Don’t be distracted by “net-zero” buildings.**

Efficiency and Conservation

transport

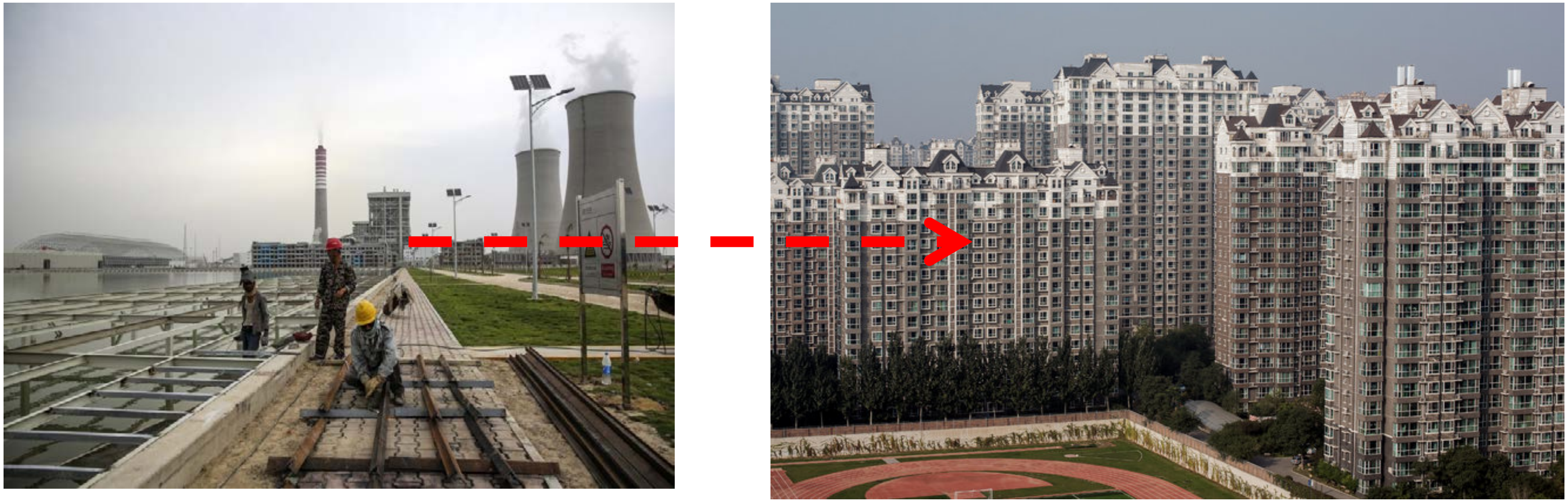
buildings

industry

information

power

In the U.S., 70% of power-plant electricity goes to buildings.



Shown: Yanjiao, China

Less demand for heating, cooling, appliances – fewer power plants.

Most new “committed emissions” are in the developing world.

INFRASTRUCTURE

Assure that the national priority of “infrastructure” gives significant priority to electricity and natural gas.

1. Electricity

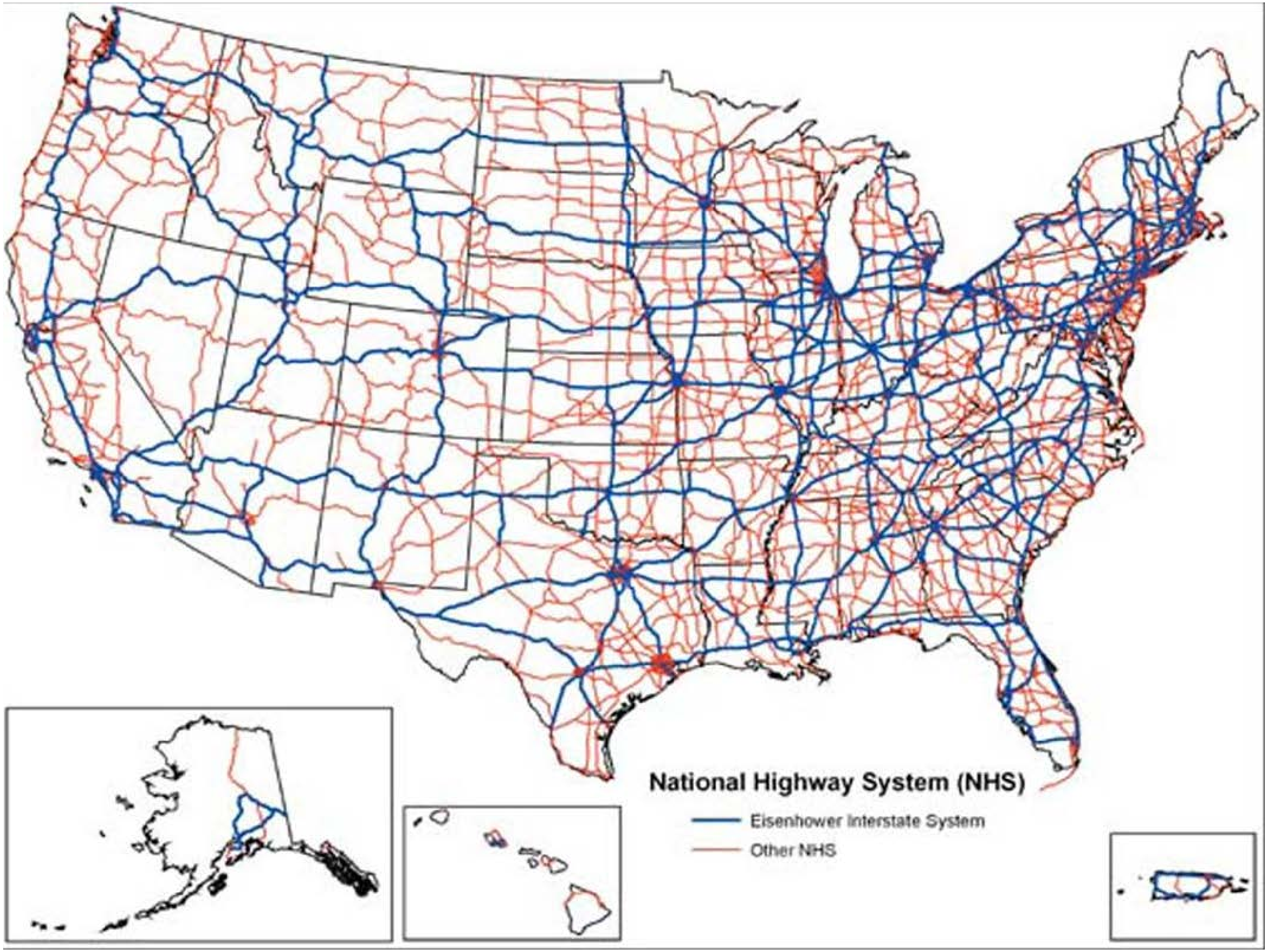
  a. Encourage the smart grid.
  b. Anticipate the demand for charging stations.

2. Natural gas

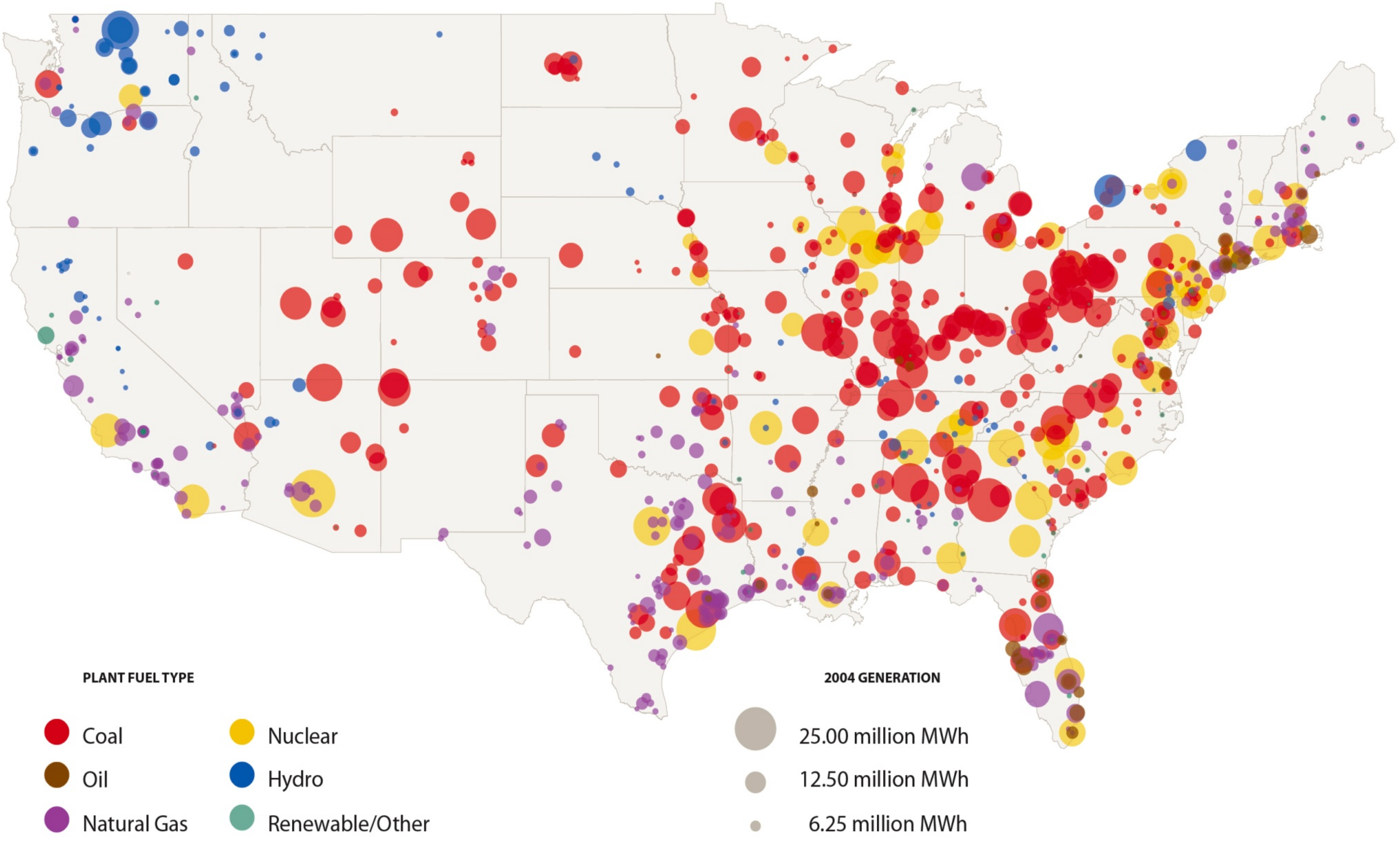
  a. Plan regionally
  b. Find the leaks – in distribution systems and buildings.*

*** Natural gs is mostly methane, the #2 greenhouse gas.**

Legacy: National Highway System

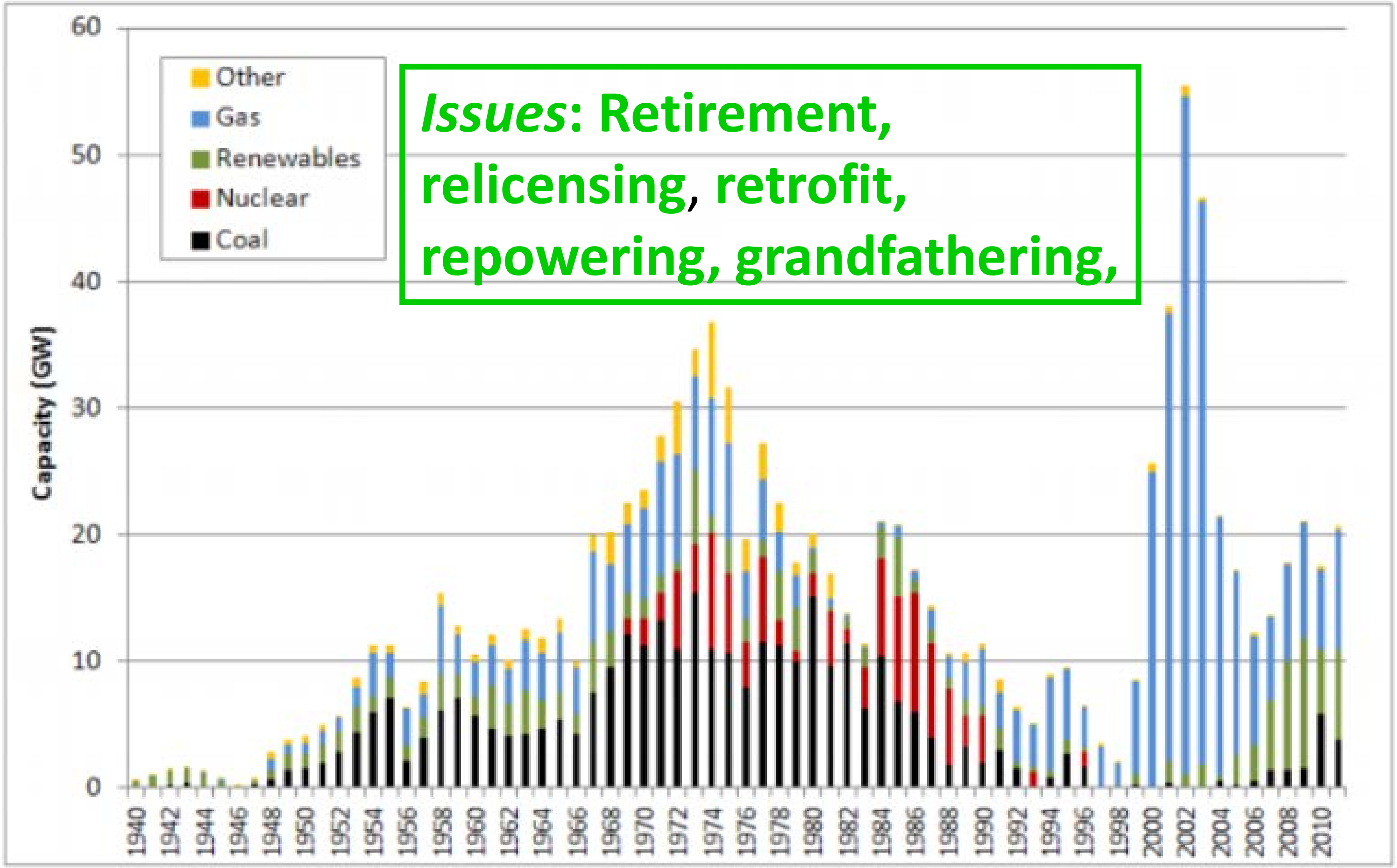


Legacy: U.S. Power Plants



Source: *Benchmarking Air Emissions*, April 2006. The report was co-sponsored by CERES, NRDC and PSEG.

U.S. power plants are old



***Issues*: Retirement, relicensing, retrofit, repowering, grandfathering,**

Figure 5-1. Historical U.S. Power Plant Capacity Additions, by Technology, 1940-2011

Source: Form EIA-860 (2011)

Note: Renewables include hydro, geothermal, biomass, solar, and wind energy technologies.

NUCLEAR POWER

It’s about aging plants:

1. **“Too big to fail,” but they will be closed and, it seems, not replaced. So states must plan!**
2. **Aggressive use of dry-cask storage needs to be required to reduce risks of accidents at spent-fuel storage in pools**
3. **They age differently from all other facilities because neutron bombardment embrittles metals. Demand third-party inspection of all plants that close.**

Fission Power – with Dry Cask Storage

Site: Surry station, James River, VA; 1625 MW since 1972-73,. *Credit*: Domi

CARBON PRICES

Pay attention to how big the prices are, whether via a tax or cap-and-trade.

Resist tokenism: a lot of effort and a very low price.

The point is to drive action.

A carbon price of $\$100/tCO_2$

Upstream, the impacts are particularly dramatic. **$\$100/tCO_2$** is:

$40/barrel of oil
$5/million Btu of natural gas
$200/ton of high-quality coal.

Downstream, percent increases in prices are smaller. **$\$100/tCO_2$** is:

$0.80/U.S. gallon of gasoline
$0.08/kWh electricity from coal
$0.04/kWh electricity from natural gas.

WORK TOGETHER

1. **The wonderful briefing document I was sent made me feel like Alexander Hamilton.**

   So many independent actors!

2. **Share best practices, much as the world's nations are committing to do as they implement the Paris Agreement.**

   A pot-luck dinner: bring your best dishes, look at what others bring and copy what you like. A race to the top.

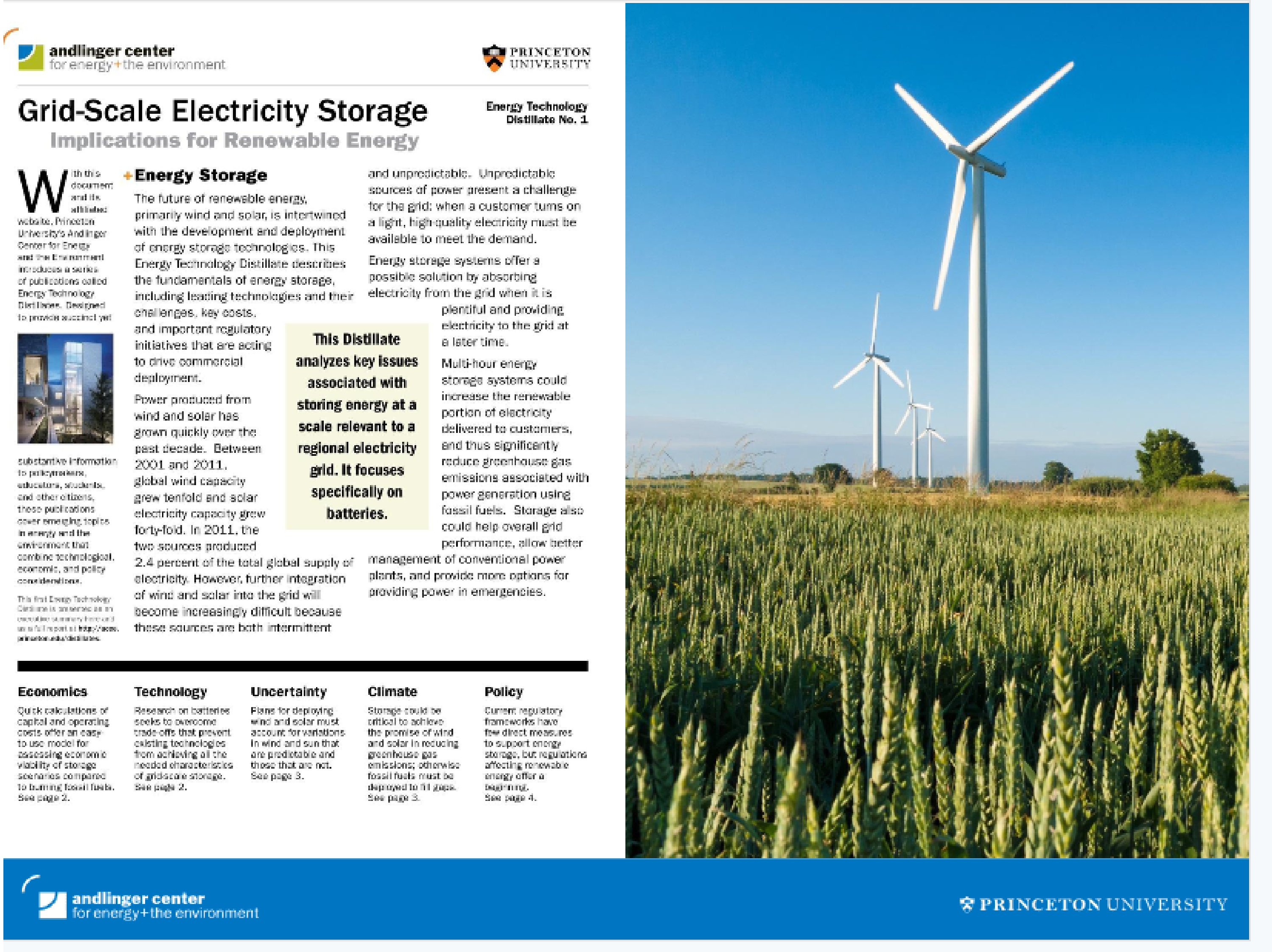
3. **Protect what's special: wilderness, landscapes,…**

Recommendations

1. Efficiency, efficiency, efficiency
2. Use spot-market prices to enable “smart” residential and commercial buildings everywhere.
3. Assure that the national priority of “infrastructure” features the smart electricity grid.
4. Act collectively to prevent boom and bust for off-shore wind. Expect it to be big.
5. Plan ahead for the closing of nuclear plants.
6. Require investments at nuclear plants for spent-fuel safety.
7. Think regionally.

DISTILLATES

The Andlinger Distillates:
#1 Grid-scale storage



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Grid-Scale Electricity Storage

Implications for Renewable Energy

Energy Technology
Distillate No. 1

With this document and its affiliated website, Princeton University's Andlinger Center for Energy and the Environment introduces a series of publications called Energy Technology Distillates. Designed to provide succinct yet substantive information to policymakers, educators, students, and other citizens, these publications cover emerging topics in energy and the environment that combine technological, economic, and policy considerations.

This first Energy Technology Distillate is presented as an executive summary here and as a full report at http://acee.princeton.edu/distillates.

+Energy Storage

The future of renewable energy, primarily wind and solar, is intertwined with the development and deployment of energy storage technologies. This Energy Technology Distillate describes the fundamentals of energy storage, including leading technologies and their challenges, key costs, and important regulatory initiatives that are acting to drive commercial deployment.

Power produced from wind and solar has grown quickly over the past decade. Between 2001 and 2011, global wind capacity grew tenfold and solar electricity capacity grew forty-fold. In 2011, the two sources produced 2.4 percent of the total global supply of electricity. However, further integration of wind and solar into the grid will become increasingly difficult because these sources are both intermittent and unpredictable. Unpredictable sources of power present a challenge for the grid: when a customer turns on a light, high-quality electricity must be available to meet the demand.

Energy storage systems offer a possible solution by absorbing electricity from the grid when it is plentiful and providing electricity to the grid at a later time.

Multi-hour energy storage systems could increase the renewable portion of electricity delivered to customers, and thus significantly reduce greenhouse gas emissions associated with power generation using fossil fuels. Storage also could help overall grid performance, allow better management of conventional power plants, and provide more options for providing power in emergencies.

This Distillate analyzes key issues associated with storing energy at a scale relevant to a regional electricity grid. It focuses specifically on batteries.

Economics

Quick calculations of capital and operating costs offer an easy-to-use model for assessing economic viability of storage scenarios compared to burning fossil fuels. See page 2.

Technology

Research on batteries seeks to overcome trade-offs that prevent existing technologies from achieving all the needed characteristics of grid-scale storage. See page 2.

Uncertainty

Plans for deploying wind and solar must account for variations in wind and sun that are predictable and those that are not. See page 3.

Climate

Storage could be critical to achieve the promise of wind and solar in reducing greenhouse gas emissions; otherwise fossil fuels must be deployed to fill gaps. See page 3.

Policy

Current regulatory frameworks have few direct measures to support energy storage, but regulations affecting renewable energy offer a beginning. See page 4.

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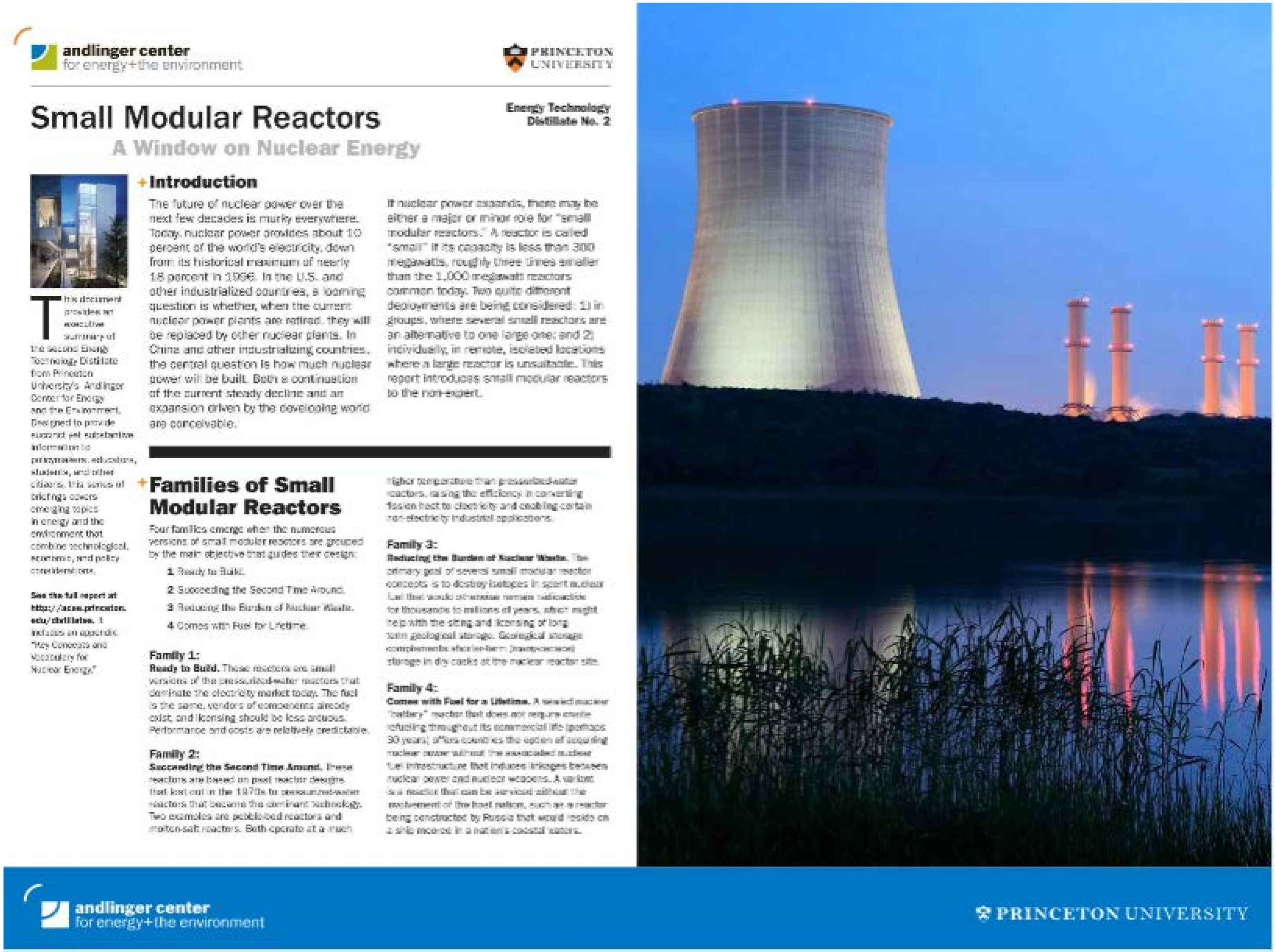
The Andlinger Distillates:
#2 Small Modular Nuclear Reactors



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Small Modular Reactors

A Window on Nuclear Energy

Energy Technology
Distillate No. 2

This document provides an executive summary of the second Energy Technology Distillate from Princeton University's Andlinger Center for Energy and the Environment. Designed to provide succinct yet substantive information to policymakers, educators, students, and other citizens, this series of briefings covers emerging topics in energy and the environment that combine technological, economic, and policy considerations.

See the full report at http://acee.princeton.edu/distillates. It includes an appendix, "Key Concepts and Vocabulary for Nuclear Energy."

Introduction

The future of nuclear power over the next few decades is murky everywhere. Today, nuclear power provides about 10 percent of the world's electricity, down from its historical maximum of nearly 18 percent in 1996. In the U.S. and other industrialized countries, a looming question is whether, when the current nuclear power plants are retired, they will be replaced by other nuclear plants. In China and other industrializing countries, the central question is how much nuclear power will be built. Both a continuation of the current steady decline and an expansion driven by the developing world are conceivable.

If nuclear power expands, there may be either a major or minor role for "small modular reactors." A reactor is called "small" if its capacity is less than 300 megawatts, roughly three times smaller than the 1,000 megawatt reactors common today. Two quite different deployments are being considered: 1) in groups, where several small reactors are an alternative to one large one; and 2) individually, in remote, isolated locations where a large reactor is unsuitable. This report introduces small modular reactors to the non-expert.

Families of Small Modular Reactors

Four families emerge when the numerous versions of small modular reactors are grouped by the main objective that guides their design:

1 Ready to Build.
2 Succeeding the Second Time Around.
3 Reducing the Burden of Nuclear Waste.
4 Comes with Fuel for Lifetime.

Family 1:
Ready to Build. These reactors are small versions of the pressurized-water reactors that dominate the electricity market today. The fuel is the same, vendors of components already exist, and licensing should be less arduous. Performance and costs are relatively predictable.

Family 2:
Succeeding the Second Time Around. These reactors are based on past reactor designs that lost out in the 1970s to pressurized-water reactors that became the dominant technology. Two examples are pebble-bed reactors and molten-salt reactors. Both operate at a much higher temperature than pressurized-water reactors, raising the efficiency in converting fission heat to electricity and enabling certain non-electricity industrial applications.

Family 3:
Reducing the Burden of Nuclear Waste. The primary goal of several small modular reactor concepts is to destroy isotopes in spent nuclear fuel that would otherwise remain radioactive for thousands to millions of years, which might help with the siting and licensing of long-term geological storage. Geological storage complements shorter-term (many-decade) storage in dry casks at the nuclear reactor site.

Family 4:
Comes with Fuel for a Lifetime. A sealed nuclear "battery" reactor that does not require onsite refueling throughout its commercial life (perhaps 30 years) offers countries the option of acquiring nuclear power without the associated nuclear fuel infrastructure that induces linkages between nuclear power and nuclear weapons. A variant is a reactor that can be serviced without the involvement of the host nation, such as a reactor being constructed by Russia that would reside on a ship moored in a nation's coastal waters.

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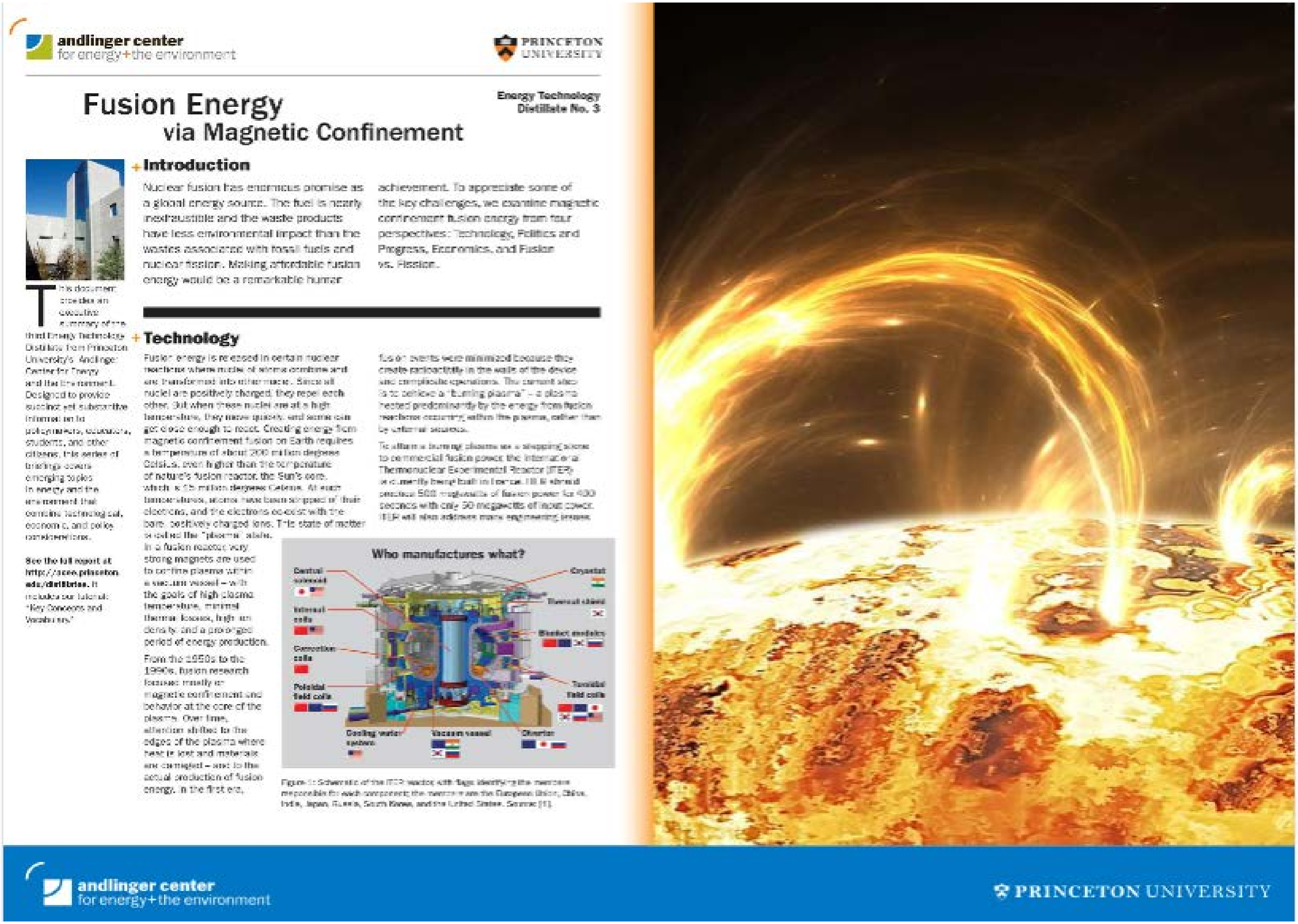
The Andlinger Distillates:
#3 Nuclear Fusion



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Energy Technology
Distillate No. 3

Fusion Energy
via Magnetic Confinement

This document provides an executive summary of the third Energy Technology Distillate from Princeton University's Andlinger Center for Energy and the Environment. Designed to provide succinct yet substantive information to policymakers, educators, students, and other citizens, this series of briefings covers emerging topics in energy and the environment that combine technological, economic, and policy considerations.

See the full report at http://acee.princeton.edu/distillates. It includes our tutorial: "Key Concepts and Vocabulary."

+ Introduction

Nuclear fusion has enormous promise as a global energy source. The fuel is nearly inexhaustible and the waste products have less environmental impact than the wastes associated with fossil fuels and nuclear fission. Making affordable fusion energy would be a remarkable human achievement. To appreciate some of the key challenges, we examine magnetic confinement fusion energy from four perspectives: Technology, Politics and Progress, Economics, and Fusion vs. Fission.

+ Technology

Fusion energy is released in certain nuclear reactions where nuclei of atoms combine and are transformed into other nuclei. Since all nuclei are positively charged, they repel each other. But when these nuclei are at a high temperature, they move quickly and some can get close enough to react. Creating energy from magnetic confinement fusion on Earth requires a temperature of about 200 million degrees Celsius, even higher than the temperature of nature's fusion reactor, the Sun's core, which is 15 million degrees Celsius. At such temperatures, atoms have been stripped of their electrons, and the electrons co-exist with the bare, positively charged ions. This state of matter is called the "plasma" state.

In a fusion reactor, very strong magnets are used to confine plasma within a vacuum vessel – with the goals of high plasma temperature, minimal thermal losses, high ion density, and a prolonged period of energy production.

From the 1950s to the 1990s, fusion research focused mostly on magnetic confinement and behavior at the core of the plasma. Over time, attention shifted to the edges of the plasma where heat is lost and materials are damaged – and to the actual production of fusion energy. In the first era, fusion events were minimized because they create radioactivity in the walls of the device and complicate operations. The current step is to achieve a "burning plasma" – a plasma heated predominantly by the energy from fusion reactions occurring within the plasma, rather than by external sources.

To attain a burning plasma as a stepping stone to commercial fusion power, the International Thermonuclear Experimental Reactor (ITER) is currently being built in France. ITER should produce 500 megawatts of fusion power for 400 seconds with only 50 megawatts of input power. ITER will also address many engineering issues.

Who manufactures what?

Figure 1: Schematic of the ITER reactor with flags identifying the members responsible for each component; the members are the European Union, China, India, Japan, Russia, South Korea, and the United States. Source: [1].

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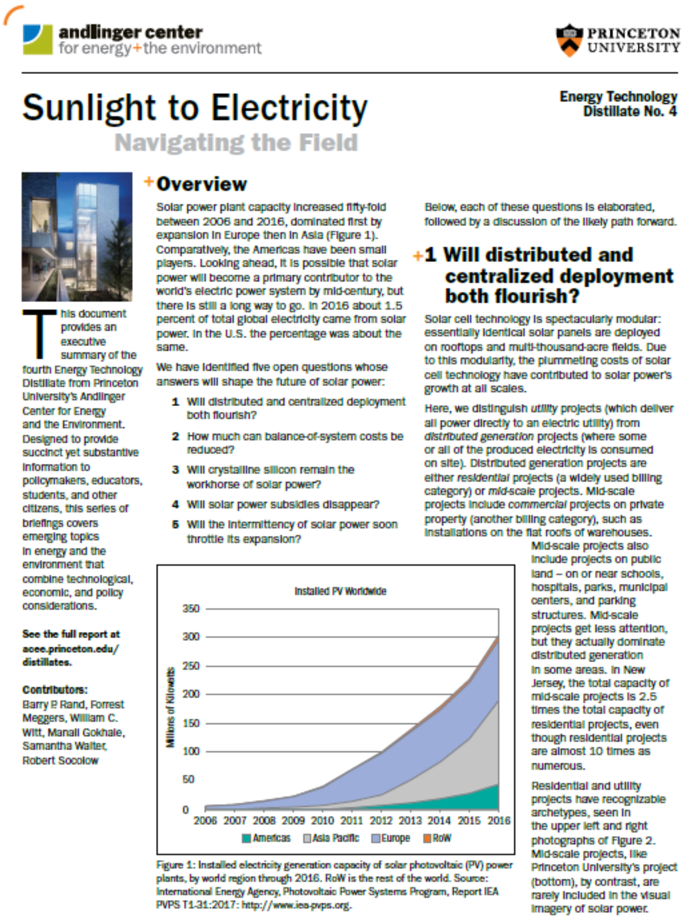
The Andlinger Distillates
#4 Solar Power



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Sunlight to Electricity
Navigating the Field

Energy Technology
Distillate No. 4

This document provides an executive summary of the fourth Energy Technology Distillate from Princeton University's Andlinger Center for Energy and the Environment. Designed to provide succinct yet substantive information to policymakers, educators, students, and other citizens, this series of briefings covers emerging topics in energy and the environment that combine technological, economic, and policy considerations.

See the full report at acee.princeton.edu/distillates.

Contributors:
Barry P. Rand, Forrest Meggers, William C. Witt, Manali Gokhale, Samantha Walter, Robert Socolow

+Overview

Solar power plant capacity increased fifty-fold between 2006 and 2016, dominated first by expansion in Europe then in Asia (Figure 1). Comparatively, the Americas have been small players. Looking ahead, it is possible that solar power will become a primary contributor to the world's electric power system by mid-century, but there is still a long way to go. In 2016 about 1.5 percent of total global electricity came from solar power. In the U.S. the percentage was about the same.

We have identified five open questions whose answers will shape the future of solar power:

1 Will distributed and centralized deployment both flourish?

2 How much can balance-of-system costs be reduced?

3 Will crystalline silicon remain the workhorse of solar power?

4 Will solar power subsidies disappear?

5 Will the intermittency of solar power soon throttle its expansion?

Figure 1: Installed electricity generation capacity of solar photovoltaic (PV) power plants, by world region through 2016. RoW is the rest of the world. Source: International Energy Agency, Photovoltaic Power Systems Program, Report IEA PVPS T1-31:2017: http://www.iea-pvps.org.

Below, each of these questions is elaborated, followed by a discussion of the likely path forward.

+1 Will distributed and centralized deployment both flourish?

Solar cell technology is spectacularly modular: essentially identical solar panels are deployed on rooftops and multi-thousand-acre fields. Due to this modularity, the plummeting costs of solar cell technology have contributed to solar power's growth at all scales.

Here, we distinguish *utility* projects (which deliver all power directly to an electric utility) from *distributed generation* projects (where some or all of the produced electricity is consumed on site). Distributed generation projects are either *residential* projects (a widely used billing category) or *mid-scale* projects. Mid-scale projects include *commercial* projects on private property (another billing category), such as installations on the flat roofs of warehouses. Mid-scale projects also include projects on public land – on or near schools, hospitals, parks, municipal centers, and parking structures. Mid-scale projects get less attention, but they actually dominate distributed generation in some areas. In New Jersey, the total capacity of mid-scale projects is 2.5 times the total capacity of residential projects, even though residential projects are almost 10 times as numerous.

Residential and utility projects have recognizable archetypes, seen in the upper left and right photographs of Figure 2. Mid-scale projects, like Princeton University's project (bottom), by contrast, are rarely included in the visual imagery of solar power.