GETTING TO ZERO: PATHWAYS TO ZERO CARBON ELECTRICITY SYSTEMS

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The Decarbonization Challenge

Source: Peters et al. (2017), "Key indicators to track current progress and future ambition of the Paris Agreement," *Nature Climate Change* 7: 118-122
Deep Decarbonization of Electricity

~2x electricity demand

Near-zero CO₂

We Are Falling Behind...

Nuclear energy

Carbon capture & storage

Source: Peters et al. (2017), "Key indicators to track current progress and future ambition of the Paris Agreement," Nature Climate Change 7: 118-122
Santee Cooper, SCE&G pull plug on roughly $25 billion nuclear plants in South Carolina

July 31, 2017

Westinghouse Files for Bankruptcy, in Blow to Nuclear Power

March 29, 2017

Carbon Capture Suffers a Huge Setback as Kemper Plant Suspends Work

June 29, 2017
...Renewable Energy Excepted

Wind & solar energy

Biomass

Source: Peters et al. (2017), "Key indicators to track current progress and future ambition of the Paris Agreement," Nature Climate Change 7: 118-122
Xcel Energy receives shockingly low bids for Colorado electricity from renewable sources

January 17, 2018

Renewable energy will be consistently cheaper than fossil fuels by 2020, report claims

January 13, 2018

The Price of Solar Is Declining to Unprecedented Lows

Despite already low costs, the installed price of solar fell by 5 to 12 percent in 2015

August 27, 2016

Report: Wind And Natural Gas Are Cheapest Power Sources In Most Of The Country

December 9, 2016
Cost reductions since 2008 for selected technologies

Do We Go All In?

Image Source: go100percent.org
DEEP DECARBONIZATION OF THE ELECTRIC POWER SECTOR
INSIGHTS FROM RECENT LITERATURE

JESSE D. JENKINS AND SAMUEL THERNSTROM

MARCH 2017

The electric power sector is widely expected to be the linchpin of efforts to reduce greenhouse gas (GHG) emissions. Most studies exploring climate stabilization pathways envision a decline in global anthropogenic GHGs of 50-90% below current levels by 2050 (IPCC 2014; Loftus et al. 2015). To reach these goals, the power sector would need to cut emissions nearly to zero, while expanding to electrify (and consequently decarbonize) portions of the transportation, heating, and industrial sectors (GEA 2012; IPCC 2014; Krey et al. 2014; McCollum et al. 2014).

Given this challenge, what do we know about potential pathways to decarbonization of the electric power sector?

There is a strong consensus in the literature that reaching near-zero emissions is much more challenging — and may require a very different mix of resources — than comparatively modest emissions reductions (50-70% or less). Planning and policy measures should therefore focus on long-term objectives (near-zero emissions) in order to avoid costly lock-in of suboptimal resources.

In addition, there is strong agreement in the literature that a diversified mix of low-CO₂ generation resources offers the best chance of affordably achieving deep decarbonization. While it is theoretically possible to rely primarily (or even entirely) on variable renewable energy resources such as wind and solar, it would be significantly more challenging
“...there is strong agreement in the literature that a diversified mix of low-CO$_2$ generation resources offers the best chance of affordably achieving deep decarbonization.”
A race to beat fossil fuels on cost...

Levelized cost of electricity ($/MWh)

- Solar $/MWh
- Coal $/MWh
- Gas $/MWh

Global installed solar PV capacity (GW)

The (Flawed) Mental Model
The (Correct) Mental Model

A race between declining cost and declining value...

GenX: Power System Optimization

- Highly configurable
- Detailed operating constraints
- Hourly resolution
- Transmission & distribution networks
- Distributed energy resources

Enhanced Decision Support for a Changing Electricity Landscape: The GenX Configurable Electricity Resource Capacity Expansion Model

An MIT Energy Initiative Working Paper
Revision 1.0
November 27, 2017

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Declining Value: Four Mechanisms

1. Declining “fuel-saving” value (energy substitution)
2. Decreasing “capacity value” (capacity substitution)
3. Increasing “curtailment” (wasted generation when supply exceeds demand)
4. (Increasing reserve requirements and transmission network costs)
CO₂ Limit

100 t/GWh

Energy (GWh)

Hour of the Day

Nuclear
Gas CCGT
Wind
Solar
Gas CT
Storage discharging
Demand shifting satisfied
Demand curtailment
Storage charging
Demand shifting delayed
Wind curtailment
Solar curtailment

Net demand peak moved to February evening

Annual Energy Share (%)

Annual Marginal Curtailment (%)
Net demand peak moved to February evening

Annual Energy Share (%)

Annual Marginal Curtailment (%)
The role of flexible base resources in deep decarbonization of power systems

with Nestor Sepulveda, Richard Lester, Charles Forsberg, & Fernando de Sisternes, *Joule* (revise and resubmit)
What We Find

“Fuel saving” variable resources
- Wind
- Solar PV
- Solar thermal
- Run-of-river hydro

“Flexible base” resources
- Nuclear
- Coal and gas w/CCS
- Geothermal & biomass
- Seasonal storage?

“Fast burst” resources
- Energy storage
- Demand response
- Biogas CTs
A Balanced Portfolio
1 g/kWh CO₂ emissions limit (99.9% decline)

Energy (GWh)

Hour of the Day

Nuclear
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Demand shifting satisfied
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- Fast Burst Resources
- Fuel Saving Resources
- Flexible Base Resources
Without Flexible Base Resources
1 g/kWh CO₂ emissions limit (99.9% decline)

Note 2x increase in y-axis scale

Fast Burst Resources

Fuel Saving Resources

- Nuclear
- Wind
- Solar
- Gas CT
- Gas CCGT
- Storage discharging
Very high shares of wind and solar entail significant curtailment (even with storage and flexible demand...)

Graphic is author’s with data from: Frew et al. 2016. Flexibility mechanisms and pathways to a highly renewable US electricity future. *Energy* 101: 65-78. Data from Fig. 9 for Indep. PEV scenarios.
Very high shares of wind and solar entail significant curtailment (...and trans-continental power grid expansion)

Graphic is author's with data from: Frew et al. 2016. Flexibility mechanisms and pathways to a highly renewable US electricity future. *Energy* 101: 65-78. Data from Fig. 9 for Agg. PEV scenarios.
To reach 90% renewable electricity in the United States, NREL’s Renewable Energy Futures study (Mai, et al. 2014) propose a doubling of U.S. long-distance transmission...
...MacDonald, Clack et al. 2016 envision a continent-spanning HVDC “supergrid” to link all US regions...

...as does Frew et al. 2016.
The Importance of Flexible Base Resources

Flexible base energy share

Percent cost reduction vs renewable only

Moderate storage cost reduction
(50% below 2016)

Deep storage cost reduction
(75% below 2016)

New England

Texas

Source: Sepulveda, Jenkins et al. (forthcoming), The role of flexible base resources in deep decarbonization of power systems
Flexible Base Options
Energy storage capacity required in 100% renewable energy scenarios for U.S. deep decarbonization

- One week’s worth of U.S. electricity consumption (for reference)
- Eight weeks’ worth of U.S. electricity consumption (Becker et al. 2014, low end)
- 12 weeks’ worth of U.S. electricity consumption (Jacobson et al. 2015, low end)
- 13 weeks’ worth of U.S. electricity consumption (Jacobson et al. 2015, high end)
- 16 weeks’ worth of U.S. electricity consumption (Becker et al. 2014, high end)

For comparison, the ten largest pumped hydro storage facilities in the United States provide enough energy storage capacity to supply average U.S. electricity needs for just 43 minutes.
John W. Keys III Pump-Generating Plant and Banks Lake Reservoir at Grand Coulee Dam: 25 GWh or 3 minutes and 30 seconds of storage.
John W. Keys III Pump-Generating Plant and Banks Lake Reservoir at Grand Coulee Dam: 25 GWh or 3 minutes and 30 seconds of storage.
Storing 2-4 months of US consumption in flow batteries would fill between 9 and 52 of these lakes...
It’s Not a Straight Line to Zero Carbon

**Energy Share**

- **Variable Renewables**
- **Nuclear**
- **Natural Gas**

**Emissions limit (t/GWh)**

**Texas**

**New England**
1. Policy makers should not compare resources using cost; must consider value and distinct roles in a specific system context.
2. Policy support should not exclude nuclear or carbon capture and storage; they play distinct “flexible base” role
3. Technology policy needs to make multiple “bets” in each class of resource, including flexible base resources
4. Not a straight-line path to zero carbon; beware lock-in from myopic policymaking
5. Given uncertainty, policies should, where possible, create and preserve maximum optionality and avoid lock-in and dead ends.
Concluding Thoughts

- Cost
- Land area impact
- Technical and reliability challenges
- Up- & down-stream environmental impacts
- Air pollutants
- Industry scale-up and energy intensity rates
Concluding Thoughts

Hypothetical scoring of balanced solution set

Cost

Land area impact

Technical and reliability challenges

Up- & down-stream environmental impacts

Air pollutants

Industry scale-up and energy intensity rates
Concluding Thoughts

Hypothetical scoring of unbalanced solution set

Cost

- Air pollutants
- Industry scale-up and energy intensity rates
- Up- & down-stream environmental impacts
- Land area impact
- Technical and reliability challenges

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