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DEEP DECARBONIZATION OF THE ELECTRIC POWER SECTOR
INSIGHTS FROM RECENT LITERATURE

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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?

This paper reviews recent literature on the deep decarbonization of the electric power sector, defined here as 80-100% reduction in carbon dioxide (CO_2) emissions. To capture insights from recent research, this review encompasses 30 deep decarbonization studies published since 2014.[1] These studies employ a variety of methods, including detailed power system optimization models, higher-level energy-economic and integrated assessment models, and scenario-driven exercises. They also span different scopes, from the regional to national to global, and they entail different research objectives. Despite this diversity of parameters, the recent literature presents a set of clear and consistent insights. This review seeks to synthesize these key insights and present these findings in a policy-relevant manner.

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-CO_2 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 and costly than pathways that employ a diverse portfolio of resources. In particular, including dispatchable low-carbon resources in the portfolio, such as nuclear energy or fossil energy with carbon capture and storage (CCS), would significantly reduce the cost and technical challenges of deep decarbonization.

We summarize the evidence for each of these findings in the remainder of this document.

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[1] This sample is not statistically representative, but is extensive in scope. 2014 was selected to coincide with the publication of the Intergovernmental Panel on Climate Change's Fifth Assessment Report (IPCC 2014), which extensively reviews previously published literature. In addition to the 30 papers directly reviewed, this literature review also covers other review articles (Cochran, Mai, and Bazilian 2014; Morrison et al. 2015) that summarize findings from an additional 21 previously published studies, as well as Kriegler et al. (2014) and Krey et al. (2014), which describe results from a detailed inter-model comparison exercise involving 18 energy-economic and integrated assessment models. While this sample may not be comprehensive, we believe it is sufficiently extensive and current to provide valid insights into the state of the literature.

1. Power sector CO_2 emissions must fall nearly to zero by 2050 to achieve climate policy goals.

Studies considering economy-wide greenhouse gas emissions reduction goals consistently envision the power sector cutting emissions further and faster than other sectors of the economy, such as transportation, heating, agriculture, and industry (Kriegler et al. 2014; White House 2016; Morrison et al. 2015; Williams et al. 2015; Krey et al. 2014). Kriegler et al. (2014) and Krey et al. (2014) summarize results from a detailed comparison of global decarbonization research performed by 18 modeling groups, and conclude that across all scenarios, "the electricity sector is decarbonized first with close to zero or net negative emissions in 2050."[2] Similarly, Morrison et al. (2015) compare nine models of deep carbon reductions in the California economy and find that "because some sectors cannot be electrified or are difficult to decarbonize (e.g., aviation, marine, heavy duty road freight, agricultural fertilizer, etc.), GHG emissions from the electricity grid will likely need to be reduced beyond 80%" below 1990 levels by 2050. Williams et al. (2015) likewise propose 90-97% reductions in power sector emissions by 2050 as part of efforts to decarbonize the U.S. economy. There is no disagreement on the question of prioritizing the power sector in decarbonization scenarios.

2. A low-carbon power sector must expand to electrify and decarbonize greater shares of transportation, heating, and industrial energy demand as part of a strategy for economy-wide emissions reductions.

Due to the availability of several low- and zero-carbon sources of electricity, including renewable energy, nuclear power, and fossil fuels (or biomass) with carbon capture and storage (CCS), each of the economy-wide studies reviewed envisions electricity supplying greater shares of heating, industry, and transportation energy demand by 2050 (Kriegler et al. 2014; White House 2016; Morrison et al. 2015; Williams et al. 2015; Jacobson, Delucchi, Bazouin, et al. 2015). Total demand for electricity use therefore grows under all deep decarbonization scenarios, even as total primary energy use overall remains relatively flat in developed countries and grows more modestly globally. Electricity increases end-use market share, either by direct electrification of end-uses (including expansion of electric vehicles and efficient electric heat pumps for heating and cooling) or by creating electrolytic hydrogen or synthetic natural gas for use as a heating or transport fuel, or as an industrial feedstock.

The global decarbonization scenarios summarized by Krey et al. (2014) envision global electricity demand rising roughly 35-150% by 2050, with electricity supplying 20-50% of energy demand by midcentury. Across four possible U.S. scenarios outlined by Williams et al. (2015), electricity use roughly doubles (+60-110%) by 2050. Use of electricity and fuels produced from electricity increases from around 20% of U.S. energy demand at present to more than 50% by 2050 in these scenarios. By 2050, White House (2016) envisions about 60% of passenger vehicle miles travelled will be fueled by electricity or hydrogen, 50% of industrial energy demand will be supplied by electricity (up from 20% today), and electricity will supply most space and water heating needs. In eight of nine models reviewed by Morrison et al. (2015), electricity demand in California increases 8-226% by 2050. The ninth study reviewed, Jacobson et al. (2014), considers a scenario where 100% of California end-use energy demand is met by electricity or hydrogen produced by electricity. In that case, electricity demand grows more than five-fold (+465%) by 2050. Jacobson et al. (2015) outlines a similar scenario for the U.S. as a whole, wherein electricity demand more than triples by 2050.

3. Deep decarbonization of the power sector is significantly more difficult than more modest emissions reductions.

Many studies conclude that reducing power sector CO_2 emissions by one-half to two-thirds can be achieved with a mix of commercially available technologies—namely, by displacing existing coal-fired generation with natural gas combined cycle power plants, increasing the share of wind and solar energy, and maintaining existing nuclear and hydropower capacity (White House 2016; de Sisternes, Jenkins, and Botterud 2016; Williams et al. 2015; Morrison et al. 2015; Gillespie, Grieve, and Sorrell 2015; Elliston, MacGill, and Diesendorf 2014; MacDonald et al. 2016; Riesz, Vithayasrichareon, and MacGill 2015).

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[2] Negative emissions are achieved in some scenarios by employing carbon capture and storage at biomass-fired power plants.

By contrast, reaching near-zero emissions will require virtually all unabated coal and gas-fired power plants to be replaced by zero-emissions sources. This would necessitate a substantial increase in variable renewable energy from wind and solar, an expansion of nuclear power capacity (even as all existing nuclear reactors retire between now and 2050), significant penetration of coal or gas with CCS (with nearly 100% CO_2 capture rates), or some combination thereof. The pace of emissions reductions and zero-carbon power capacity build-out would also need to increase to reach deep decarbonization by 2050 (Williams et al. 2015; White House 2016; Krey et al. 2014).

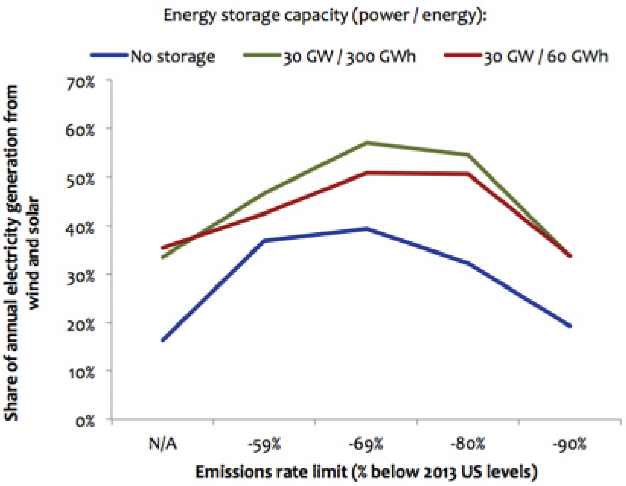
4. Deep decarbonization may require a significantly different mix of resources than more modest goals; long-term planning is important to avoid lock-in of suboptimal resources.

It is important to emphasize that the lowest-cost portfolio of resources suited to achieving moderate emissions reductions may differ dramatically from the portfolio needed to efficiently reach deep decarbonization goals. For example, de Sisternes, Jenkins, and Botterud (2016) use a detailed power system optimization model to find the least-cost portfolio of electricity generation resources in a Texas-like power system under different emissions limits. The authors conclude that the optimal share of wind and solar is greatest under emissions limits roughly 60-80% below current levels (reaching a maximum of 40% of annual generation without energy storage, and up to 51-57% if significant energy storage capacity is available; see figure 1). The optimal share of renewables then shrinks as emissions limits tighten to achieve deep decarbonization, falling to just 19% without storage and up to 34% with substantial storage (equal to roughly 30% of peak demand for 2-10 hours of storage duration).

Similar results are found for lower-emissions fossil fueled power plants. Riesz, Vithayasrichareon, and MacGill (2015) explore the role of natural gas in a low-carbon transition for Australia's National Electricity Market region. The authors conclude that an energy mix dominated by natural gas (supplying 95% of annual energy) could reduce CO_2 emissions 30-50% below current levels in the Australian power system. Gas-fired capacity and energy shares fall steadily as emissions goals become more stringent, however. A generation mix with 80% gas and 20% renewables can cut CO_2 by 50-65%, the authors find. Gas's optimal share then falls to 45% as emissions limits tighten to approximately 65-75% below current levels, then declines further to less than 22% to achieve emissions reductions of 88% or greater.

Figure 1. Optimal Share of Wind and Solar in Texas-Like Power System under Increasingly Stringent Emissions Limits (with and without energy storage)

Data from de Sisternes, Jenkins, and Botterud (2016)



Similarly, if CO_2 capture rates for gas- or coal-fired plants with CCS are not close to 100%, then fossil plants with CCS can contribute to more modest emissions reduction goals (e.g. 60-80%), but to reach a fully decarbonized system, either capture rates must increase or those plants must be phased out (Elliston, MacGill, and Diesendorf 2014).

These conclusions suggest that if power generation resources are built out without considering long-term decarbonization objectives, costly "lock-in" of a suboptimal resource portfolio is possible. Installed capacities of wind, solar, uncontrolled natural gas, and low-capture-rate CCS plants that are suitable for achieving mid-term objectives could all exceed their optimal share for substantially decarbonized power systems. Policy measures and power sector planning should therefore consider the long-term transition to a CO_2-free power system and avoid incremental and short-sighted targets or capacity build-outs that may perversely make deep decarbonization more challenging.

5. Achieving deep decarbonization primarily (or entirely) with renewable energy may be theoretically possible but it would be significantly more challenging and costly than pathways employing a diverse portfolio of low-carbon resources.

Multiple studies explore 100% renewable electricity systems that achieve deep decarbonization goals (Becker et al. 2014; Jacobson, Delucchi, Bazouin, et al. 2015; Jacobson, Delucchi, Cameron, et al. 2015; Elliston, MacGill, and Diesendorf 2014; Frew et al. 2016; Lenzen et al. 2016), or include scenarios with very high shares (80% or greater) of renewables (Cochran, Mai, and Bazilian 2014; Mai, Mulcahy, et al. 2014; Mai, Hand, et al. 2014; Riesz, Vithayasrichareon, and MacGill 2015; Brick and Thernstrom 2016; Akashi et al. 2014; Amorim et al. 2014; Gillespie, Grieve, and Sorrell 2015; Heal 2016; Mileva et al. 2016; MacDonald et al. 2016; Pleßmann and Blechinger 2017).

These studies indicate that achieving deep decarbonization primarily with renewable energy sources (chiefly wind and solar) may be technically possible.[3] However, despite a diversity of contexts and analytical methods, these studies find a high degree of agreement on several key features of renewables-centric power systems that are likely to make these systems more costly and challenging than balanced low-carbon power systems employing a diverse portfolio of resources:

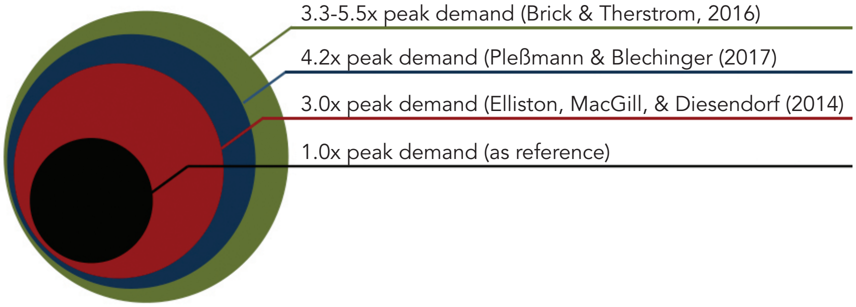
Decarbonized power systems dominated by variable renewables such as wind and solar energy are physically larger, requiring much greater total installed capacity.

Due to the variability of wind and solar energy, power systems with high shares of these resources have much greater overall installed capacity than more diversified power systems, and must maintain significant dispatchable capacity to ensure demand can be met at all times. For example:

- Pleßmann and Blechinger (2017) present a scenario for decarbonizing the European power system by 2050 (achieving 98.4% below 1990 emissions levels) that relies heavily on an expansion of wind and solar energy. Total installed capacity in this scenario is 4.2-times larger than the peak demand.
- Similarly, a 100% renewable electricity scenario for Australia outlined by Elliston, MacGill, and Diesendorf (2014) features total capacity roughly three times the peak demand in the system.
- Brick and Thernstrom (2016) likewise conclude that total installed capacity is 3.5 to 5.5 times larger for wind and solar-dominated power systems than more balanced systems.
- Total U.S. generating capacity is roughly double today's installed capacity in a set of 80% renewable electricity scenarios described by Mai, Mulcahy, et al. (2014).

Greater required installed capacity and the lower energy-density of wind and solar resources also significantly increases the land use consequences of power systems dominated by variable renewable resources.

Figure 2. Total Installed Capacity in High-Renewables Scenarios as a Multiple of Peak Demand



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[3] This section focuses on results from studies envisioning power systems reliant primarily on wind and solar energy supplemented by other renewables. Regions with significant endowments of geothermal and/or hydroelectric power may more readily achieve very high renewable energy shares. However, these resources are highly constrained in most locations.

Wind and solar-heavy power systems require substantial dispatchable power capacity to ensure demand can be met at all times. This amounts to a "shadow" system of conventional generation to back up intermittent renewables.

The renewables-heavy EU scenario presented by Pleßmann and Blechinger (2017) maintains sufficient capacity from hydro, gas, and energy storage to exceed peak demand. Elliston, MacGill, and Diesendorf (2014)'s 100% renewable system for Australia also retains dispatchable capacity exceeding the system's peak demand (with capacity provided by biogas, hydro, and concentrating solar power with 15-hours of thermal energy storage). The 80% renewable electricity portfolios for the U.S. described by Mai, Mulcahy, et al. (2014) includes 400 GW of total coal, gas, and nuclear capacity, roughly 100 GW of biomass, and an additional 200 GW of hydro and concentration solar power with thermal energy storage. This is in addition to 100-152 GW of storage and 24-48 GW of curtailable demand. Relatively dispatchable resources thus total 825-900 GW, or approximately equal to peak demand.

Without a fleet of reliable, dispatchable resources able to step in when wind and solar output fade, scenarios with very high renewable energy shares must rely on long-duration seasonal energy storage.

Becker et al. (2014) determine the optimal mix of wind and solar capacity to supply 100% of U.S. electricity while minimizing energy storage requirements. The authors conclude that the minimal storage capacity necessary to ensure demand is reliably met would be sufficient to store 15-30% of U.S. annual electricity demand, or roughly 8-16 weeks of storage.

The total energy storage capacity envisioned by Jacobsen et al. (2015)'s 100% renewable energy scenario for the United States is equivalent to 37.8 Billion Tesla Power Wall 2.0 home energy storage systems.

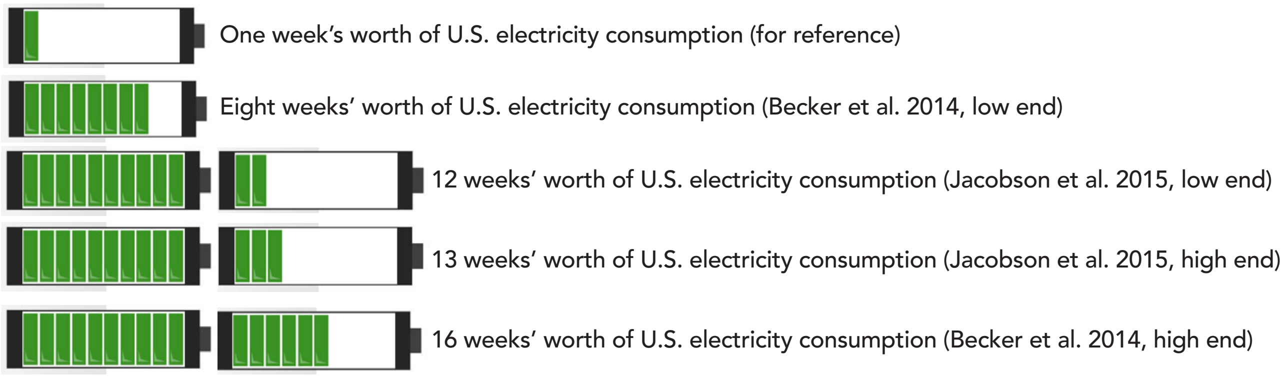
The "100% wind, water, solar" scenario for the U.S. described in Jacobson, Delucchi, Bazouin, et al. (2015) and Jacobson, Delucchi, Cameron, et al. (2015) also envisions total energy storage with a power capacity that is two and a half times the current U.S. installed generating capacity, with a collective capability to store more than seven weeks worth of total U.S. electricity consumption. This is in addition to substantial power-to-hydrogen production and the capacity to store enough hydrogen to meet another 5-6 weeks' of current U.S. electricity demand.

Gillespie, Grieve, and Sorrell (2015) also find that variation in wind, solar, and electricity demand in the United Kingdom can lead to persistent power supply deficits lasting 2-3 weeks in a 100% renewable power system.

Looking at similar results for renewables-heavy systems Brick and Thernstrom (2016) conclude that "wind and solar output exhibit seasonal episodes of both sustained oversupply and undersupply that overwhelm any conceivable storage strategy."

Battery storage is infeasible for such long duration seasonal storage. For comparison, the total storage capacity envisioned by Jacobson et al. is equivalent to 37.8 billion Tesla Power Wall 2.0 home energy storage systems—320 Power Walls per U.S. household.

Figure 3. Energy Storage Capacity Required in 100% Renewable Electricity Scenarios



Alternatively, to put the weeks' worth of energy storage envisioned in these studies in perspective, consider that the ten largest pumped hydro storage facilities in the U.S. are collectively capably of storing a total of just 43 minutes worth of U.S. energy consumption (DOE, 2016).

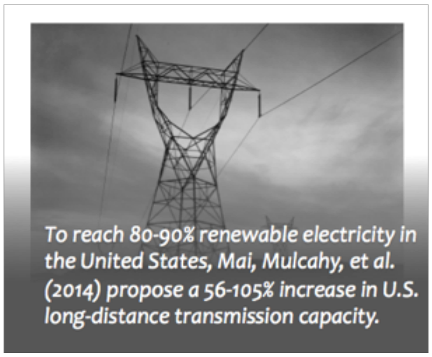
In addition, studies envisioning long-duration storage inevitably rely on one or more technologies that remain unproven at such large scales, including underground thermal energy storage, electrolytic hydrogen production, and/or production of synthetic natural gas.

Very high shares of wind and solar entail significant curtailment—even with energy storage, transmission, or demand response.

Due the variability of wind and solar production, achieving very high energy shares requires significantly over-building total installed capacity (as discussed above). In addition to contending with prolonged lulls in output, high renewable energy systems must also face periods when available wind and solar production exceeds total demand. Excess generation must either be curtailed (that is, wasted) or stored for later use.

For example, Frew et al. (2016) find that curtailment of wind and solar rises sharply as renewable energy shares increase in the United States. Even with significant energy storage or demand-side flexibility (in the form of flexible EV charging), at a 60% renewable energy share, wasted energy output is sufficient to supply 5% of all 2015 U.S. electricity generation. Wasted output rises to nearly 12% of annual U.S. generation at 80% renewable energy share, and as high as 48% of 2015 annual U.S. generation in a 100% renewable energy power system. With a major expansion of long-distance transmission interconnection to smooth renewable energy variation across the continent, curtailment falls to negligible levels—if the share of renewables is held to 60%—but at 80% renewables it still amounts to 5% of total U.S. generation, and 37-48% of annual generation at 100% renewables.

Similarly, Mai, Mulcahy, et al. (2014) find that curtailed renewable output would be sufficient to supply 6-9% of 2015 U.S. electricity generation across a range of 80% renewable scenarios, despite positing nearly 200 GW of energy storage capacity and a major build-out of U.S. long-distance transmission capacity.



To reach 80-90% renewable electricity in the United States, Mai, Mulcahy, et al. (2014) propose a 56-105% increase in U.S. long-distance transmission capacity.

High renewable energy scenarios also envision a significant expansion of long-distance transmission grids.

In order to smooth renewable energy variation across wider regions, most high-renewable scenarios include plans for much greater long-distance transmission capacity. To reach 80-90% renewable electricity in the United States, Mai, Mulcahy, et al. (2014) propose a 56-105% increase in U.S. long-distance transmission capacity. MacDonald et al. (2016) envision approximately 20,000 miles of new high-voltage direct-current transmission lines linking all regions in the United States, while transmission interconnection between EU regions expands 4.5-fold by 2050 in the renewables-dominated scenario in Pleßmann and Blechinger (2017). Importantly, these figures do not include additional transmission lines needed within each region to access renewable energy resource zones.

High renewables scenarios are more costly than other options, due to the factors outlined above.

Frew et al. (2016) finds that a fully renewable U.S. power system costs at least twice as much as an 80% renewables system, and 2.8-times the cost of a system with 20% renewables, even after building an expanded, nationwide high-voltage power grid. The same study finds that a 100% renewable power system for California costs 2.1 to 2.8-times as much as an 80% renewable system, and 3 to 8-times more than a 20% renewable system.

Brick and Thernstrom (2016) find that 80% renewable energy portfolios in Wisconsin, California and Germany would be 1.5 to 2.5-times costlier than a diversified low-carbon portfolio. Furthermore, the authors find that an 80% renewable portfolio only achieves a roughly 70% reduction in CO_2 emissions. To achieve the same deep emissions reductions as a diversified portfolio (81-87%), a renewables-heavy portfolio costs 3.2 to 4-times more under baseline cost assumptions from the U.S. Energy Information Administration and 30-115% higher under a low-cost renewables/high-cost nuclear sensitivity case.

Williams et al. (2015) similarly find that a high-renewables pathway for deep decarbonization of the U.S. economy costs 1.6 times more than a diversified portfolio and 3.25 to 4-times higher than high-CCS and high-nuclear pathways.

6. Including dispatchable base resources (such as nuclear or CCS) reduces the cost and technical challenge of achieving deep decarbonization.

The challenges associated with high-renewable energy scenarios described above strongly suggest that harnessing dispatchable baseload resources (nuclear, biomass, or fossil fuels with CCS) that could form the foundation of a low-carbon power system would significantly decrease the cost and challenge of reaching deep decarbonization goals.

It is notable that, of the 30 papers surveyed here, the only deep decarbonization scenarios that do not include a significant contribution from nuclear, biomass, hydropower, and/or CCS exclude those resources from consideration a priori. Every paper employing least-cost optimization techniques includes significant shares of dispatchable base resources in the decarbonized power portfolio (de Sisternes, Jenkins, and Botterud 2016; Safaei and Keith 2015; Gillespie, Grieve, and Sorrell 2015; Mai, Hand, et al. 2014; Mai, Mulcahy, et al. 2014; Mileva et al. 2016; Lenzen et al. 2016; Kriegler et al. 2014; as well as several of the scenarios in Morrison et al. 2015).

For example:

- In a least-cost electric generation portfolio reducing Texas emissions by roughly 90%, de Sisternes, Jenkins, and Botterud (2016) find that nuclear supplies 52-68% of annual generation, depending on the availability of energy storage.
- Allowing new nuclear to contribute to a least-cost portfolio that reduces emissions 85% (from 1990 levels) in the western United States, Mileva et al. (2016) finds that the dispatchable base resource has a 43% share of annual generation. Furthermore, including nuclear in the generation mix lowers total power system costs by an estimated 23% (relative to a baseline case in which new nuclear construction is prohibited).
- Gillespie, Grieve, and Sorrell (2015) and Brick and Thernstrom (2016) also conclude that the lowest-cost portfolio for deep decarbonization includes significant shares of nuclear and/or CCS.

There is high agreement in the literature that dispatchable base resources are a virtually indispensible part of least-cost pathways to deep decarbonization.

7. A diversified mix of low-carbon resources offers the best chance of affordably achieving deep decarbonization of the power system.

Multiple studies stress the importance of maintaining a diverse mix of low and zero-carbon resources in order to affordably and reliably decarbonize the power system.

Kriegler et al. (2014) survey global decarbonization pathways analyzed by 18 different international modeling groups and find that wind, solar, biomass, nuclear power, and fossil fuels with CCS all play a substantial role in reaching low-carbon goals. If any one of these resources are excluded or unavailable, the cost of decarbonization increases—by up to 30% by 2100 if nuclear or renewables are limited in availability, by as much as 200% if bioenergy availability is restricted, and up to 300% if CCS is unavailable (Kriegler et al. 2014).

Similarly, after drawing on a review of the academic literature, multiple stakeholder listening sessions, and a set of low-GHG pathways developed using up-to-date data and modeling of the energy and land sectors, White House (2016) concluded:

> There are major benefits to supporting a wide range of electricity generation technologies. First, decarbonizing the electricity system does not depend on the success of any single technology, and the capacity additions required from any single technology are lessened due to what other technologies can contribute. Second, supporting a wide range of technologies today through a portfolio approach is likely to lower the costs of decarbonization in the long run, because we do not know today how technologies will progress over many decades; policies should be designed to enable the lowest cost technologies to emerge (while ensuring reliability).

CONCLUSIONS

The recent literature sheds significant light on the challenge of decarbonizing electric power systems. Despite a wide variety of analytical methods, goals, and scopes, there is strong agreement in the recent literature that deep decarbonization—reaching zero or near-zero CO_2 emissions—is best achieved by harnessing a diverse portfolio of low-carbon resources.

In particular, low-carbon dispatchable baseload resources such as nuclear, biomass, hydropower, or CCS, are an indispensible part of any least-cost pathway to deep decarbonization. Recent literature indicates that removing this dispatchable base from the generation portfolio, relying instead entirely or predominately on variable renewable energy resources such as wind and solar, would significantly increase the cost and technical challenge of decarbonizing power systems.

In addition, reaching zero emissions requires a significantly different capacity mix than achieving comparatively more modest goals. This finding implies that policymakers and planning should be wary of lock-in of suboptimal capacity investments, and should consider policy and market mechanisms that incentivize action toward long-term goals.

Future research should also seek to shed more light on efficient and robust pathways to deep decarbonization over time.

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Samuel Thernstrom is the founder and executive director of the Energy Innovation Reform Project, and a senior fellow at the Center for the National Interest.

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