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COMMENTARY

Getting to Zero Carbon Emissions in the Electric Power Sector

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The electric power sector is widely expected to be the linchpin of efforts to reduce greenhouse gas (GHG) emissions. Virtually all credible pathways to climate stabilization entail twin challenges for the electricity sector: cutting emissions nearly to zero (or even net negative emissions) by mid-century, while expanding to electrify and consequently decarbonize a much greater share of global energy use.[1,2] In light of this fact, a flurry of recent studies has outlined and explored pathways to "deep decarbonization" of the power sector, defined here as an 80%–100% reduction in carbon dioxide (CO_2) emissions from current levels. Here we review and distill insights from 40 such studies published since the most recent Intergovernmental Panel on Climate Change review in 2014 (summarized in Table 1).

Despite differing methods, scopes, and research questions, several consistent insights emerge from this literature. The studies collectively outline and evaluate two overall paths to decarbonize electricity: one that relies primarily (or even entirely) on variable renewable energy sources (chiefly wind and solar power) supported by energy storage, greater flexibility from electricity demand, and continent-scale expansion of transmission grids; and a second path that relies on a wider range of low-carbon resources including wind and solar as well as "firm" resources such as nuclear, geothermal, biomass, and fossil fuels with carbon capture and storage (CCS) (see Sepulveda et al. in the November 2018 issue of this journal[3]).

Whichever path is taken, we find strong agreement in the literature that reaching near-zero emissions is much more challenging—and requires a different set of low-carbon resources—than comparatively modest emissions reductions (e.g., CO_2 reductions of 50%–70%). This is chiefly because more modest goals can readily employ natural gas-fired power plants as firm resources. Pushing to near-zero emissions requires replacing the vast majority of fossil fueled power plants or equipping them with CCS.

Given the long-lived nature of power sector capital equipment and long gestation period for R&D efforts, it is critical to examine the distinct challenges inherent to deep decarbonization today; a policy of "muddling through" is unlikely to produce optimal outcomes. The literature outlines potentially feasible decarbonization solutions, but also clarifies several challenges that must be overcome along each path to a zero-carbon electricity system. In light of these challenges, and the considerable technological uncertainty facing us today, we conclude that a strategy that seeks to improve and expand the portfolio of available low-carbon resources, rather than restrict it, offers a greater likelihood of affordably achieving deep decarbonization.

Failing to Affordably Decarbonize Electricity Could Imperil Global Climate Efforts

Studies considering economy-wide GHG reduction goals consistently envision the power sector cutting emissions further and faster than other sectors of the economy, achieving close to zero (or net negative) emissions in 2050.[2] Because electricity is technically easier and less costly to decarbonize than other sectors,[4] economy-wide studies rely upon expanded generation of carbon-free electricity to meet greater shares of energy demand for heating, industry, and transportation. Across global decarbonization

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Table 1. Review of Electricity Deep Decarbonization Studies

	Authors	Year	Title	Publication	Geographic Scope	Sectors	Methodology	Strictest CO_2 Limit	Firm Resources Considered (Selected in Lowest CO_2 Cases)	Long-Duration Storage	Transmission	Flexible Demand
1	Akashi et al.	2014	Halving global GHG emissions by 2050 without depending on nuclear and CCS	*Climatic Change*	Global	W	I	50% below 2010 economy-wide (>80% in electricity sector)	bio, bio CCS, coal, coal CCS, gas, gas CCS, nuc, oil, oil CCS	N	N	N
2	Amorim et al.	2014	Electricity decarbonization pathways for 2050 in Portugal: a TIMES (The Integrated MARKAL-EFOM System) based approach in closed versus open systems modeling	*Energy*	Portugal	E	O	zero CO_2	coal, gas, res. hydro (existing), oil, bio	N	L	N
3	Becker et al.	2014	Features of a fully renewable US electricity system: optimized mixes of wind and solar PV and transmission grid extensions	*Energy*	Continental USA	E	O, S	zero CO_2	none	Y	Y	Y
4	Bibas and Méjean	2014	Potential and limitations of bioenergy for low carbon transitions	*Climatic Change*	Global	W	I	98% below business as usual in 2050, 99.3% in 2100	bio CCS, coal, coal CCS, gas, gas CCS, nuc, oil	N	N	N
5	Boston and Thomas	2015	Managing flexibility whilst decarbonizing the GB electricity system	The Energy Research Partnership	UK	E	O, S	~80% below 1990 (50g CO_2/kWh)	bio (existing), coal CCS, gas (existing), gas CCS, nuc	S	S	S
6	Brick and Thernstrom	2016	Renewables and decarbonization: Studies of California, Wisconsin and Germany	*The Electricity Journal*	California, Wisconsin, and Germany	E	S	80% renewable portfolio standard	gas CCS, nuc	N	N	N

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Table 1. Continued

	Authors	Year	Title	Publication	Geographic Scope	Sectors	Methodology	Strictest CO_2 Limit	Firm Resources Considered (Selected in Lowest CO_2 Cases)	Long-Duration Storage	Transmission	Flexible Demand
7	Brown et al.	2018	Synergies of sector coupling and transmission reinforcement in a cost-optimized, highly renewable European energy system	*Energy*	Europe	E, T, H	O	95% below 1990	gas, res. hydro (existing)	Y	Y	Y
8	Connolly and Mathiesen	2014	A technical and economic analysis of one potential pathway to a 100% renewable energy system	*I.J. Sustainable Energy Planning and Management*	Ireland	E, T, H	S	net zero CO_2 (renewables only, including biofuels)	bio, CHP	Y	N	Y
9	Connolly et al.	2016	Smart Energy Europe: The technical and economic impact of one potential 100% renewable energy scenario for the European Union	*Renewable and Sustainable Energy Reviews*	EU-28	E, T, H	S	net zero CO_2 (renewables only, including biofuels)	bio, CHP	Y	N	Y
10	de Sisternes et al.	2016	The value of energy storage in decarbonizing the electricity sector	*Applied Energy*	Texas ERCOT-like system	E	O	90% below 2016	gas, nuc	N	N	N
11	Després et al.	2016	Storage as a flexibility option in power systems with high shares of VRE sources: a POLES-based analysis	*Energy Economics*	EU-28, Norway and Switzerland	E	O	~80% below 1990 (EU 2°C policy)	bio, coal, coal CCS, gas, gas CCS, res. hydro (existing), nuc, oil	N	N	Y

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Table 1. Continued

	Authors	Year	Title	Publication	Geographic Scope	Sectors	Methodology	Strictest CO_2 Limit	Firm Resources Considered (Selected in Lowest CO_2 Cases)	Long-Duration Storage	Transmission	Flexible Demand
12	Elliston et al.	2014	Comparing least cost scenarios for 100% renewable electricity with low emission fossil fuel scenarios in the Australian National Electricity Market	*Renewable Energy*	Australia National Energy Market (NEM)	E	S	net zero CO_2 (renewables only, including biofuels)	bio, coal, coal CCS, gas, gas CCS, res. hydro (existing)	N	L	N
13	Fernandes and Ferreira	2014	Renewable energy scenarios in the Portuguese electricity system	*Energy*	Portugal	E	S	net zero CO_2 (renewables only, including biofuels)	bio, res. hydro (existing), CHP	Y	Y	N
14	Frew et al.	2016	Flexibility mechanisms and pathways to a highly renewable US electricity future	*Energy*	Continental USA	E	O	zero CO_2 (100% renewable portfolio standard)	geo, res. hydro (existing)	Y	Y	Y
15	Heal	2016	What would it take to reduce US greenhouse gas emissions 80% by 2050?	National Bureau of Economic Research	USA	E	A	80% below 2005	bio, coal, gas, geo, hydro, nuc, oil	N	Y	N
16	Heuberger et al.	2017	A systems approach to quantifying the value of power generation and energy storage technologies in future electricity networks	*Computers & Chemical Engineering*	UK	E	O	zero CO_2	coal CCS, gas, gas CCS, nuc	N	L	N
17	Heuberger et al.	2017	Power capacity expansion planning considering endogenous technology cost learning	*Applied Energy*	UK	E	O	80% below 1990	bio CCS, coal CCS, gas, gas CCS, nuc	N	L	N

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Table 1. Continued

	Authors	Year	Title	Publication	Geographic Scope	Sectors	Methodology	Strictest CO_2 Limit	Firm Resources Considered (Selected in Lowest CO_2 Cases)	Long-Duration Storage	Transmission	Flexible Demand
18	Jacobson et al.	2014	A roadmap for repowering California for all purposes with wind, water, and sunlight	*Energy*	California	W	S	zero CO_2	geo, res. hydro (existing)	Y	Y	Y
19	Jacobson et al.	2015	100% clean and renewable wind, water, and sunlight (WWS) all-sector energy roadmaps for the 50 United States	*Energy & Environmental Science*	USA	W	S	zero CO_2	geo, res. hydro (existing)	Y	Y	Y
20	Jacobson et al.	2015	Low-cost solution to the grid reliability problem with 100% penetration of intermittent wind, water, and solar for all purposes	*PNAS*	Continental USA	W	S	zero CO_2	geo, res. hydro (existing)	Y	Y	Y
21	Kim et al.	2014	Nuclear energy response in the EMF27 study	*Climatic Change*	Global	W	R	~80%–100% below 2000 (450 ppm CO_2e)	multiple models with different firm resource options and choices regarding storage, transmission, and flexible demand. In all 18 models, **nuc** was selected in most stringent decarbonization scenarios			
22	Knorr et al.	2014	Kombikraftwerk 2	German Federal Ministry for the Environment	Germany	E	S	Net zero CO_2 (renewables only, including biofuels)	**bio, geo, res. hydro (existing)**	Y	Y	Y
23	Koelbl et al.	2014	Uncertainty in carbon capture and storage (CCS) deployment projections: a cross-model comparison exercise	*Climatic Change*	Global	W	R	~80%–100% below 2000 (450 ppm CO_2e)	multiple models with different firm resource options and choices regarding storage, transmission, and flexible demand. In all 18 models, a combination of coal CCS and gas CCS was selected in most stringent decarbonization scenarios			

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Table 1. Continued

	Authors	Year	Title	Publication	Geographic Scope	Sectors	Methodology	Strictest CO_2 Limit	Firm Resources Considered (Selected in Lowest CO_2 Cases)	Long-Duration Storage	Transmission	Flexible Demand
24	Krey et al.[1]	2014	Getting from here to there – energy technology transformation pathways in the EMF27 scenarios	*Climatic Change*	Global	W	R	~80%–100% below 2000 (450 ppm CO_2e)	multiple models with different firm resource options and choices regarding storage, transmission, and flexible demand. Bio, coal CCS, and gas CCS are selected in most abundance in lowest cost decarbonization scenarios			
25	Kriegler et al.[2]	2014	The role of technology for achieving climate policy objectives: overview of the EMF 27 study on global technology and climate policy strategies	*Climatic Change*	Global	W	R	~80%–100% below 2000 (450 ppm CO_2e)	multiple models with different firm resource options and choices regarding storage, transmission, and flexible demand. Bio, coal CCS, gas CCS, and nuc are selected in most stringent decarbonization scenarios			
26	Lenzen et al.	2016	Simulating low-carbon electricity supply for Australia	*Applied Energy*	Australia	E	O	net zero CO_2 (renewables only, including biofuels)	bio, res. hydro (existing)	N	Y	N
27	MacDonald et al.[10]	2016	Future cost-competitive electricity systems and their impact on US CO_2 emissions	*Nature Climate Change*	Continental USA	E	O	80% below 1990	gas, res. hydro (existing), nuc. (existing)	N	Y	N
28	Mai et al.	2014	Envisioning a renewable electricity future for the United States	*Energy*	Continental USA	E	O	80% renewable portfolio standard	bio, coal, gas, geo, res. hydro (existing), nuc (existing)	N	Y	Y
29	Mai et al.[7]	2014	Renewable electricity futures for the United States	*IEEE Trans. Sustainable Energy*	Continental USA	E	O	80% renewable portfolio standard	bio, coal, gas, geo, res. hydro (existing), nuc (existing)	N	Y	Y
30	Mathiesen et al.	2015	IDA's Energy Vision 2050: a smart energy system strategy for 100%	Aalborg University	Denmark	W	S	net zero CO_2 (renewables only, including biofuels)	bio, geo	Y	N	Y

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Table 1. Continued

	Authors	Year	Title	Publication	Geographic Scope	Sectors	Methodology	Strictest CO_2 Limit	Firm Resources Considered (Selected in Lowest CO_2 Cases)	Long-Duration Storage	Transmission	Flexible Demand
			renewable Denmark									
31	Mileva et al.	2016	Power system balancing for deep decarbonization of the electricity sector	*Applied Energy*	US Western Electricity Coordinating Council (WECC)	E	O	85% below 1990	bio, coal, gas, res. hydro (existing), **geo, nuc**	Y	Y	S
32	Pleßmann and Blechinger[8]	2017	How to meet EU GHG emission reduction targets? A model based decarbonization pathway for Europe's electricity supply system until 2050	*Energy Strategy Reviews*	EU-28	E	O	>95% below 2015 (24 Mt CO_2e/yr)	coal, gas, res. hydro (existing), nuc	Y	Y	Y
33	Riesz et al.	2015	Assessing "gas transition" pathways to low-carbon electricity—an Australian case study	*Applied Energy*	Australia National Energy Market (NEM)	E	O	>80% below 2010	coal, gas, res. hydro (existing)	N	N	N
34	Safaei and Keith	2015	How much bulk energy storage is needed to decarbonize electricity?	*Energy & Environmental Science*	Texas ERCOT-like system	E	O	zero CO_2	dispatchable-zero-carbon source (a proxy for any combination of bio, coal CCS, geo, gas CCS, or nuc), gas	N	N	N
35	Schlachtberger et al.	2017	The benefits of cooperation in a highly renewable European electricity network	*Energy*	Europe	E	O	95% below 1990	gas, res. hydro (existing)	Y	Y	N
36	Schlachtberger et al.[9]	2018	Cost optimal scenarios of a future highly renewable	*Energy*	Europe	E	O	zero CO_2	res. hydro (existing)	Y	Y	N

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Table 1. Continued

	Authors	Year	Title	Publication	Geographic Scope	Sectors	Methodology	Strictest CO_2 Limit	Firm Resources Considered (Selected in Lowest CO_2 Cases)	Long-Duration Storage	Transmission	Flexible Demand
			European electricity system									
37	Sepulveda, et al.[3]	2018	The role of firm low-carbon resources in deep decarbonization of electricity generation	*Joule*	New England, Texas	E	O	zero CO_2	bio, gas CCS, nuc	S	S	S
38	Sithole et al.	2016	Developing an optimal electricity generation mix for the UK 2050 future	*Energy*	UK	E	O	~zero CO_2 (1.9 g/kWh)	bio, bio CCS, coal, coal CCS, gas, gas CCS, res. hydro (existing), nuc	N	N	N
39	White House	2016	United States mid-century strategy for deep decarbonization	United States White House	USA	W	R	≥80% below 2005	bio, bio CCS, coal, coal CCS, gas, gas CCS, geo, nuc	N	Y	Y
40	Williams et al.	2014	Pathways to deep decarbonization in the United States	Sustainable Development Solutions Network	USA	W	S	80% below 1990 (<1,080 $MtCO_2e$/yr)	bio, coal, coal CCS, gas, gas CCS, geo, nuc	N	N	N

Sectors: E, electricity; T, transport; I, industry; H, heat; W, economy-wide; Methodologies: O, techno-economic cost optimization; I, integrated climate-economic-energy cost optimization; S, scenario-based simulation; A, accounting-based; R, review or inter-model comparison; Long-duration storage, transmission, flexible demand: N, not in any cases; Y, yes in all cases; S, in some sensitivity cases; L, limited interconnection with neighboring region only.To be included in our review, studies had to be published in English and feature one or more scenarios in which the electricity sector reduced CO_2 emissions by more than 80% below contemporary levels. While this review focuses on the electricity sector, we also included a subset of 15 multi-sector or economy-wide studies in order to survey insights regarding the role of the electricity sector within broader mitigation efforts. This is not an exhaustive catalog of all research on this topic, but spans a wide range of studies and is intended to be broad enough to capture the critical insights from recent research.

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scenarios produced by 18 modeling groups, for example, electricity demand increases 20%–120% by 2050 (median estimate of 52%) and 120%–440% by 2100; electricity supplies 25%–45% of total energy demand by mid-century and as much as 70% by 2100.[1] In the United States, electricity use could increase 60%–110% by 2050 as electricity (and fuels produced from electricity, e.g., hydrogen) expand from around 20% of final energy demand at present to more than 50% by 2050.[5]

In short, scholars agree that the electricity sector must not only decarbonize but also steadily increase its end-use market share through mid-century and beyond. It follows that a failure to deeply decarbonize the power sector would imperil climate mitigation efforts across the broader economy. At the same time, costly routes to decarbonization that substantially increase the price of electricity would make low-carbon electricity a less attractive substitute for oil, natural gas, and coal in transportation, heating, and industry. Finding feasible and affordable routes to decarbonize the power sector thus takes on outsized importance in global climate mitigation efforts.

Renewables May Drive Decarbonization, but Challenges Increase Sharply as Variable Renewable Energy Penetration Approaches 100%

Multiple studies indicate that achieving deep decarbonization primarily or even exclusively with variable renewable energy (VRE) sources may be technically possible. Despite a diversity of contexts and analytical methods, these studies also exhibit a high degree of agreement on several key features of VRE-centric power systems that must fall into place for this decarbonization pathway to be feasible and affordable. Most of these features arise from the need to manage the variable nature of wind and solar power, which are the predominant renewable energy sources in most studies because they offer the most abundant resource potential. Importantly, challenges associated with the variability of wind and solar increase nonlinearly as the share of energy from these sources rises. As a result, issues that may be manageable at more modest penetration levels can quickly become significant barriers as VRE shares approach 100% of generation.[6]

Continent-Scale Transmission Expansion

First, in order to smooth renewable energy variation across wider regions, high-VRE scenarios routinely entail a continent-scale expansion of long-distance transmission capacity. To reach 80% renewable electricity in the United States (with only 50% from wind and solar), for example, a National Renewable Energy Laboratory study proposes a 56%–105% increase in long-distance transmission capacity.[7] Other studies envision tens of thousands of miles of new high-voltage direct-current transmission linking all regions in the United States, while two renewables-focused studies for the European Union see interconnection capacity between EU nations expanding 4- to 9-fold by 2050.[8,9] The necessary long-distance transmission capacity reported in these studies typically does not include the additional transmission lines needed *within* each region to access renewable energy sites. As transmission makes up a relatively small share of the cost of delivered electricity in most regions, even a large-scale transmission build-out may have modest impacts on total system costs.[10] However, grid expansion of this magnitude would need to overcome persistent challenges related to siting and cost allocation that frequently prevent (or severely delay) planned transmission infrastructure.

Flexible Demand

In most of the populated regions of the world, the availability of wind and solar energy varies substantially not just on a daily cycle but over weekly, monthly, and seasonal periods. As a result most scenarios highly reliant on wind and solar assume that sources of electricity consumption will become much more flexible and responsive to power system needs in the future. To varying degrees, these scenarios envision reshaping demand to match variable supply, rather than shaping supply to match variable demand, as is commonplace in all power systems today. Electrification of transportation, heating, and industry will increase demand for electricity, as discussed above, but some of these new sources of demand could also become flexible resources that help manage power systems. For example, electric vehicles must be ready when drivers need them, but they are parked most of the time. Smart controls could modulate charging rates (or return power to the grid) to help balance supply and demand while lowering costs for vehicle owners. Thermal inertia in buildings and water tanks can also shift the timing of heating and cooling to some extent without affecting occupancy comfort.[11] The demand flexibility considered in these studies typically helps address daily fluctuations in wind and solar output, rather than multi-week and seasonal resource deficits; the ability and willingness of businesses or households to curtail demand for multi-day periods, weeks, or months are as yet untested.

Inefficient Utilization Requires Very-Low-Cost Wind and Solar to Make Overcapacity Economical

Due to their intrinsic variability, relying on very high shares of wind or solar to achieve deep decarbonization involves overbuilding total installed capacity (relative to peak demand) to produce sufficient energy during periods when available wind or solar output is well below average (Figure 1). As a corollary, during periods of the year when

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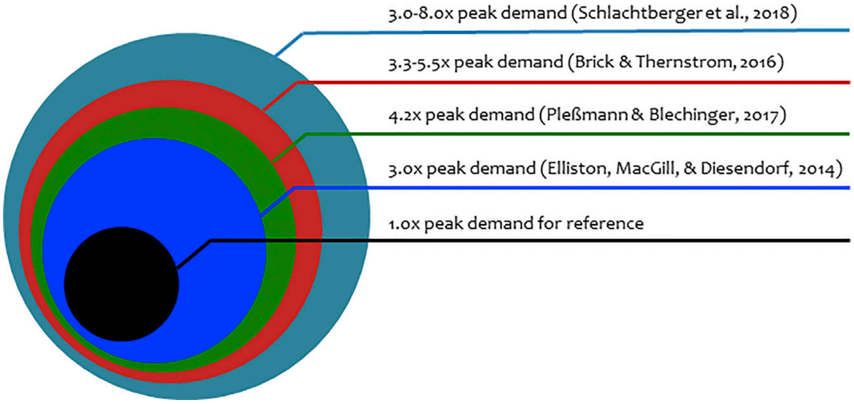

Figure 1. Total Installed Generation and Storage Capacity in Selected High-Renewables Scenarios

wind or solar is abundant, available electricity production exceeds total demand in these scenarios. This excess generation must either be curtailed (wasted) or stored for later use. While overgeneration and curtailment are manageable at lower penetration levels, the challenge increases significantly as VRE supply reaches high levels. For example, one study finds that curtailment is negligible if the share of renewables is held to 60% or below, but rises nonlinearly at higher penetrations (Figure 2). At 100% renewables, curtailment wastes enough energy (in this study) to meet at least 40% of current annual United States electricity demand, even after assuming continent-scale transmission expansion, flexible demand (in the form of controllable electric vehicle [EV] charging), and widespread deployment of battery energy storage.

Overbuilding capacity and wasting a large fraction of available energy to curtailment results in low utilization rates for wind and solar capacity, especially the marginal capacity installed to reach greater than 80% energy shares. As such, total system costs also rise nonlinearly as renewable energy shares increase toward 100% (Figure 2). To counteract this escalation in total costs and keep VRE-dominant routes to electricity decarbonization affordable, capital costs for wind and solar must therefore fall much further than in scenarios where they share the market with a mix of other low-carbon resources.

Either "Firm" Generation or "Seasonal" Storage Is Needed to Ensure Reliability in Wind- and Solar-Dominated Scenarios

While overgeneration arises during periods of abundant supply, periods of scarce wind or solar production are the flip side of the variability challenge. Prolonged periods of calm wind speeds lasting days or weeks during winter months with low solar insolation are particularly challenging for VRE-dominated systems. These sustained lulls in available wind and solar output are too long to bridge with shorter-duration batteries or flexible demand.

Power systems with high VRE shares consequently require sufficient capacity from reliable electricity sources that can sustain output in any season and for long periods (weeks or longer). This "firm" capacity[3] is often provided by augmenting wind and solar with dispatchable generation—e.g., natural gas plants, geothermal, hydropower with large reservoirs, nuclear power, or bioenergy. In high-VRE scenarios, however, these firm resources suffer from a lower utilization rate than they do in more balanced scenarios. This means that resources with low capital costs and high variable costs (e.g., bioenergy, hydrogen, or natural gas fueled power plants) are economically better suited to pair with high wind and solar shares.

Other studies partially or fully replace firm generation with one or more energy storage media capable of sustained output over weeks or longer and suited to low annual utilization rates. No such energy storage options exist at large scale today. Even at $100 per kWh of installed energy capacity (less than a third of today's costs), enough Li-ion batteries to store one week of United States electricity use would cost more than $7 trillion, or nearly 19 years of total United States electricity expenditures. Scenarios that eschew firm generation therefore must rely upon one or more long-term energy storage technologies with an order-of-magnitude lower cost per kWh, including thermal energy storage, production of hydrogen from electrolysis and storage in underground salt caverns or pressurized tanks, or conversion of electrolytic hydrogen to methane. Considerable uncertainty remains about the real-world cost, timing, and scalability of these storage options.

Firm Low-Carbon Resources Can Lower Decarbonization Costs

Most of the challenges associated with very high shares of wind or solar energy can be avoided by adopting a more balanced portfolio of resources. Across decarbonization scenarios that harness variable renewables alongside firm low-carbon generation resources—including nuclear power, coal or natural gas plants with CCS, and greater shares of firm renewable resources such as bioenergy or geothermal power plants—total installed capacity is more closely sized to peak demand, all resources enjoy higher asset utilization, and substantial curtailment of renewable energy output is avoided. None

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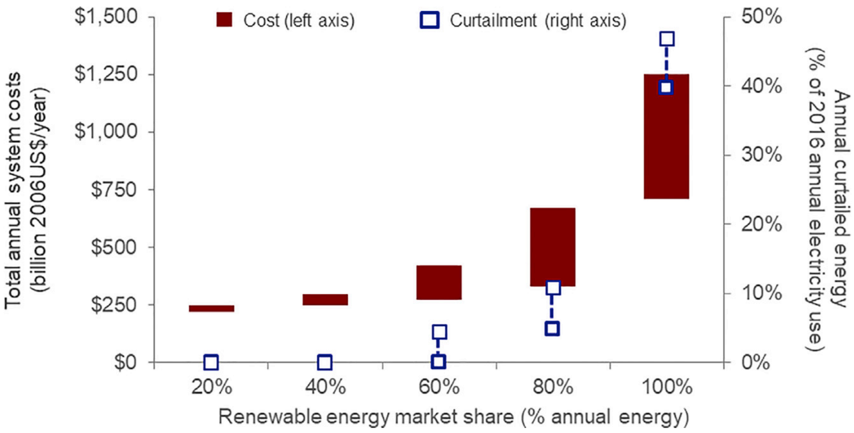

Figure 2. Nonlinear Increases in Total Annual Electricity System Cost and Curtailed Wind and Solar Energy as Renewable Energy Share Increases

Graphic is authors' with data from Frew et al. (2016), see Table 1 for full citation. Low cost and curtailment correspond to "Agg. PEV" scenario (with continent-wide transmission, flexible EV charging) and high cost and curtailment correspond to "Indep. PEV" scenario (limited transmission, flexible EV charging). Curtailment is converted to percentage of 2016 annual electricity use based on U.S. EIA, *Electric Power Annual*, Table 2.2: "Sales and Direct Use of Electricity to Ultimate Customers."

of these scenarios require the long-duration "seasonal" storage technologies discussed above. Moreover, while all scenarios benefit from cost-effective demand flexibility and transmission expansion, these features have less impact on the cost of decarbonization in more technology-diversified scenarios.

Twenty of the studies surveyed employ techno-economic optimization or integrated assessment modeling techniques to find the most affordable path to deep decarbonization and considered one or more scalable, firm low-carbon resources (beyond geothermal energy and existing reservoir hydropower, which are severely constrained in most models due to available sites suitable for expansion). Notably, all of these studies include a substantial share of firm low-carbon generation in their lowest cost resource portfolio (see Table 1). In other words, firm low-carbon resources are a consistent feature of the most affordable pathways to deep decarbonization of electricity.

However, all currently available firm low-carbon energy sources face challenges that may impede adoption at the scale or pace desired for climate stabilization.[12] Worldwide, deployment of new nuclear power is barely keeping pace with retirement of aging reactors, while high-profile cost overruns and bankruptcies have plagued nuclear construction in the United States and Europe. Carbon-capture technologies continue to make progress at the demonstration scale, but commercial deployment remains nearly nonexistent. Furthermore, while solid biomass use is rapidly increasing, driven particularly by renewable energy policies in Europe, researchers have raised serious questions about the net life-cycle greenhouse gas benefits of biomass from both managed forests and dedicated energy crops. Reservoir hydropower systems are mature, but new construction is geographically limited and entails substantial environmental impact, including the release of methane.[13] Conventional geothermal energy technologies are constrained to locations with ideal geological conditions, while enhanced or engineered geothermal systems, which could unlock widespread resource potential, are pre-commercial.

Expanding and Improving the Low-Carbon Electricity Portfolio Increases Chances of Affordable Decarbonization

Given the challenges now facing available firm low-carbon resources, it is tempting for policymakers, socially conscious businesses, and research efforts to bet exclusively on today's apparent winners: solar photovoltaics (PV), wind, and battery energy storage. That would be a mistake.

As this review indicates, several obstacles must be overcome to cost-effectively decarbonize electricity regardless of whether wind and solar are expected to deliver the vast majority of electricity or we pursue a more diverse portfolio of resources. We cannot assume that public opposition and siting challenges for new, continent-spanning transmission networks can be overcome; that flexible demand will be unlocked at sufficient scale; that wind and solar PV will continue deep and sustained cost declines; or that order-of-magnitude cheaper "seasonal" storage technologies will become widely scalable. Any one of these things may well happen, but it is far less likely all will be simultaneously achieved.

Assume hypothetically that each of these four key outcomes (grid expansion, flexible demand, very-low-cost wind and solar, and seasonal storage) has the same odds as rolling a dice and not coming up with a 1. Despite this five-out-of-six chance for each individual outcome, the joint probability of all four occurring (0.833^4) would be just 48%—effectively a coin flip.

Given the high stakes, it would be prudent to expand and improve a wide set of clean energy resources, each of which may fill the critical niche for firm, low-carbon power should other technologies falter. For example, nuclear power, CCS, bioenergy, and enhanced geothermal energy each have the ability to fill the firm role in

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a low-cost, low-carbon portfolio. Assume that each resource has only a 50% probability of becoming affordable and scalable within the next two decades. If all four options are pursued, however, the odds that *at least one* succeeds ($1–0.5^4$) would be 94%. A strategy that supported the development of all low-carbon options, both firm and variable, would raise the chance of success of at least one affordable pathway to decarbonize electricity to 97% (using the hypothetical odds given above).

These examples are purely illustrative, but the logic is critical. Eschewing the development of firm low-carbon technologies because they face challenges today would amount to betting the planet on the assumption that *all* of the conditions needed for an affordable wind and solar-centered path to decarbonize electricity will fall into place. Supporting an expanded and diversified portfolio of clean energy options that can substitute for one another hedges the risk of technology failure and substantially improves the chances of achieving a zero-carbon energy system.

Obstacles remain along any path to zero-carbon electricity, and the true probabilities of success are unknowable. It is therefore vitally important that decision makers identify and pursue prudent strategies to improve the odds of feasible and cost-effective decarbonization.

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