Review and Assessment of Literature on Deep Decarbonization in the United States: Importance of System Scale and Technological Diversity

The NorthBridge Group[1]

April 20, 2021

Overview

This literature review summarizes and interprets results from over 40 studies released over the five-year period between late 2015 and early 2021, including several at the end of 2020 or early 2021, that examine the technological and economic feasibility of deeply decarbonizing the U.S. economy, with a focus on the need to expand the electric system and the importance of a diverse generation mix including firm clean energy technologies.

These studies are in general agreement on several broad issues: 1) achieving very deep levels of decarbonization or net-zero GHG emissions on an economy-wide basis is technically and economically feasible, 2) the electric sector will be the foundation for decarbonizing major portions of other sectors of the economy, 3) there are multiple technological pathways to decarbonize the electric sector, all relying on gains in energy efficiency, demand management, variable renewables (primarily wind and solar), and new transmission, but varying with respect the mix of other electric generation resources including nuclear, fossil with carbon capture and sequestration, and zero-carbon fuel technologies, and 4) the substantial declines in the cost of wind, solar and battery technologies achieved in recent years point to those resources playing a very large role in all deep decarbonization pathways.

These studies also show, with remarkable consistency across analyses, modeling platforms and dates of publication, that deep decarbonization requires:

1) Rapidly Scaling the U.S. Electric System
    - Deeply decarbonizing the national economy will likely require more than a doubling of electric generation, which corresponds to a rate of growth three times higher than that experienced in the U.S. over the last several decades.
    - This increased demand for generation is expected to result in a tripling of electric generating capacity, which points to a rate of growth in capacity that is four to five times higher than recent decades.
    - The increase in electric supply is expected to require a doubling or tripling of the nation's electric transmission system.

2) Substantial Firm Clean Electric Capacity and Energy as Part of a Diverse Supply Portfolio

[1] Bruce Phillips, Neil Fisher, Anjie Liu.

- A substantial amount of firm capacity, close to the total amount of electric capacity in place today, is needed to maintain reliable service even in an electric system where variable renewable energy provides a very large or dominant share of total energy.
- Firm clean energy generation is needed as part of a diverse supply portfolio to minimize the overall cost of net-zero decarbonization, avoiding what would otherwise be, in rough terms, a 50% to 100% cost premium.
- Firm clean energy technologies also provide flexibility to address economic and deployment uncertainties – such as the siting and permitting of renewable generation and transmission, rapidly adopting new forms of demand management, further gains in energy efficiency and retaining existing zero-carbon electric capacity over the next several decades – thereby increasing the likelihood that deep decarbonization goals will be met.
- Firm clean energy technologies are particularly important in regions of the country where wind and solar resources are relatively less competitive, and essential for decarbonizing some non-electric sectors of the economy.
- To ensure firm clean energy technologies are commercially available at scale in a timely way given the limited period before mid-century and the path dependency of fully decarbonized electric systems, efforts are needed to extend the operating lives of today's firm low-carbon resources and demonstrate, deploy and commercialize a range of advanced technologies and associated infrastructure.

Review and Assessment of Literature on Deep Decarbonization in the United States: Importance of System Scale and Technological Diversity

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In recent years, as the focus of climate policy goals has shifted to achieving net-zero greenhouse gas emissions on an economy-wide basis by mid-century or earlier, a large and growing number of techno-economic analyses have been conducted to evaluate alternative pathways to meeting this goal.

This literature review summarizes and interprets studies examining this issue in the United States that have been released over the last five years,[3] with a particular focus on the implications for expanding the electric system and the role of a diverse mix of electric generating technologies.

In all, over 40 public studies (reports, academic papers, white papers, and presentations) of original analysis were reviewed.[4] These studies present work from a diverse group of analysts at consulting firms, universities and research organizations using an array of modeling platforms and analytic techniques. All the studies examine the continental United States or a major region of the country and model deep levels of decarbonization (considered here as emission levels 80% to 100% below historical levels, including both zero and net-zero emission goals). Most studies also examine the impacts of electrifying other sectors of the economy ("beneficial electrification") including portions of the transportation, building and industrial sectors, and assess multiple technological pathways including ones that rely exclusively or primarily on variable renewable generating technologies and others that rely on a more diverse mix including both variable and firm technologies. The period of years covered by this review is a time when deep decarbonization analyses have increasingly examined more stringent economy-wide emission reduction targets, assessed multi-sector approaches to reducing emissions, and examined the impact of declining costs for wind, solar and battery storage technologies.

These studies are in general agreement on several broad points: 1) achieving very deep levels of decarbonization or net-zero GHG emissions on an economy-wide basis is technically and economically feasible with recent studies estimating annual costs will be modestly higher than reference cases without deep decarbonization and equal to or less than historical spending levels in real dollar terms, 2) the electric sector will, through beneficial electrification, be the foundation for decarbonizing major

[2] Bruce Phillips, Neil Fisher, Anjie Liu.

[3] From late 2015 to early 2021.

[4] See complete list of studies at the end of this document. Several studies of note released late in 2020 or early 2021 include Net-Zero America by Eric Larsen and others from Princeton University, America's Zero-Carbon Action Plan by Jeffrey Sachs and others associated with the Zero Carbon Consortium, Carbon Neutral Pathways for the United States by James Williams and others, and Insights from Modeling the Decarbonization of the United States Economy by Christopher Clack of Vibrant Energy.

portions of other sectors of the economy, 3) there are multiple technological pathways to decarbonize the electric sector, all including gains in energy efficiency, demand management, variable renewables (e.g., wind and solar), and new transmission, but varying with respect the mix of variable renewables, fossil-fired generation with carbon capture and sequestration, nuclear and zero-carbon fuels such as hydrogen for electric generation,[5] and 4) the substantial declines in the cost of wind, solar and battery technologies achieved in recent years point to those resources playing a very large role with commensurate reductions in the overall cost of decarbonizing the economy.[6]

With respect to expansion of the electric system and the role of diverse generating technologies, these studies consistently point to two main conclusions:

- Deeply decarbonizing the national economy is expected to require more than a doubling of electric generation and tripling of electric capacity relative to today's levels, and substantial expansion of the transmission system, implying a rate of infrastructure development several times higher than that seen over the last 30 years.
- A diverse portfolio of clean energy technologies, including variable renewables (primarily wind and solar) and firm electric generating technologies, is needed to maintain reliable low-cost electric service, provide flexibility to overcome important economic and deployment uncertainties, achieve decarbonization goals in regions of the country where variable renewable technologies are less competitive and decarbonize non-electric sectors of the economy.

These main conclusions are explained more fully in the following points.[7]

Deeply decarbonizing the national economy will likely require more than a doubling of U.S. electric generation, which corresponds to a rate of growth three times higher than that experienced in the U.S. over the last several decades.

Driven largely by partial electrification of other sectors of the economy (primarily transportation, building and industry), fifteen cases from nine studies reporting nationwide results estimate total U.S. electric generation in 2050 would be 21% to 335% higher than today, with an average increase of 137% – more than doubling current U.S. electric generation.[8] These results are shown in the figure at the top of the following page.

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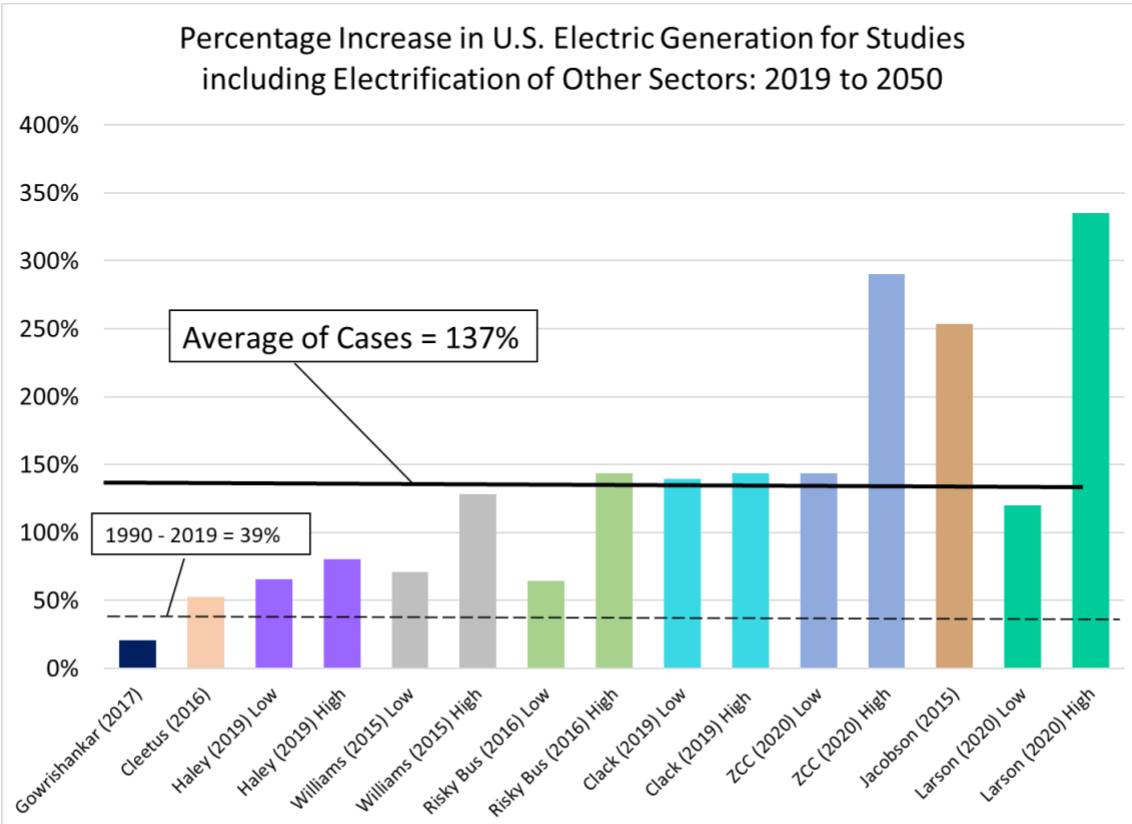
5 Along with other technologies such as hydropower, geothermal, bioenergy with CCS (BECCS), long duration thermal energy storage and direct air capture which may be used to offset residual electric sector emissions.

6 For example, the Zero Carbon Consortium (2020) study reports that, "At 0.4 percent of 2050 GDP, the incremental cost of decarbonization for the *central scenario* is a remarkable decline, given that a few years ago, analysts were calculating a net cost of about 2 percent of GDP for less aggressive emission reductions (80 percent by 2050)." (p. 40). The central scenario results in net-zero greenhouse gas emissions by 2050.

7 In the charts that follow, some data come directly from that reported numerically in the cited studies and some is approximated from graphs and similar figures.

8 Studies that only examine single regions or states, do not account for beneficial electrification, have terminal study dates before 2050 or do not report electric generation results have not been included in this figure.

Figure 1



The range of results across these studies is driven in large part by differing assumptions regarding the level of decarbonization in and out of the electric sector, the magnitude of future energy efficiency improvements, and the degree of electrification in non-electric sectors of the economy. The average increase of 137% relative to today points to a rate of growth three times higher than that experienced in the U.S. over the last three decades.

The increase in generation is expected to result in a tripling of electric capacity, which points to a rate of growth in capacity that is four to five times higher than recent decades.

As shown in the following figure, the nine cases from six studies that report total system capacity results on a comparable basis estimate that U.S. electric capacity would increase between roughly 81% and 630% with an average of 278%., almost three times current capacity.[9] The large increase in capacity relative to the increase in energy is primarily due to wind and solar facilities, which are expected to provide a larger share of total generation over time and typically operate at lower capacity factors than some of the carbon-emitting technologies they are expected to replace.

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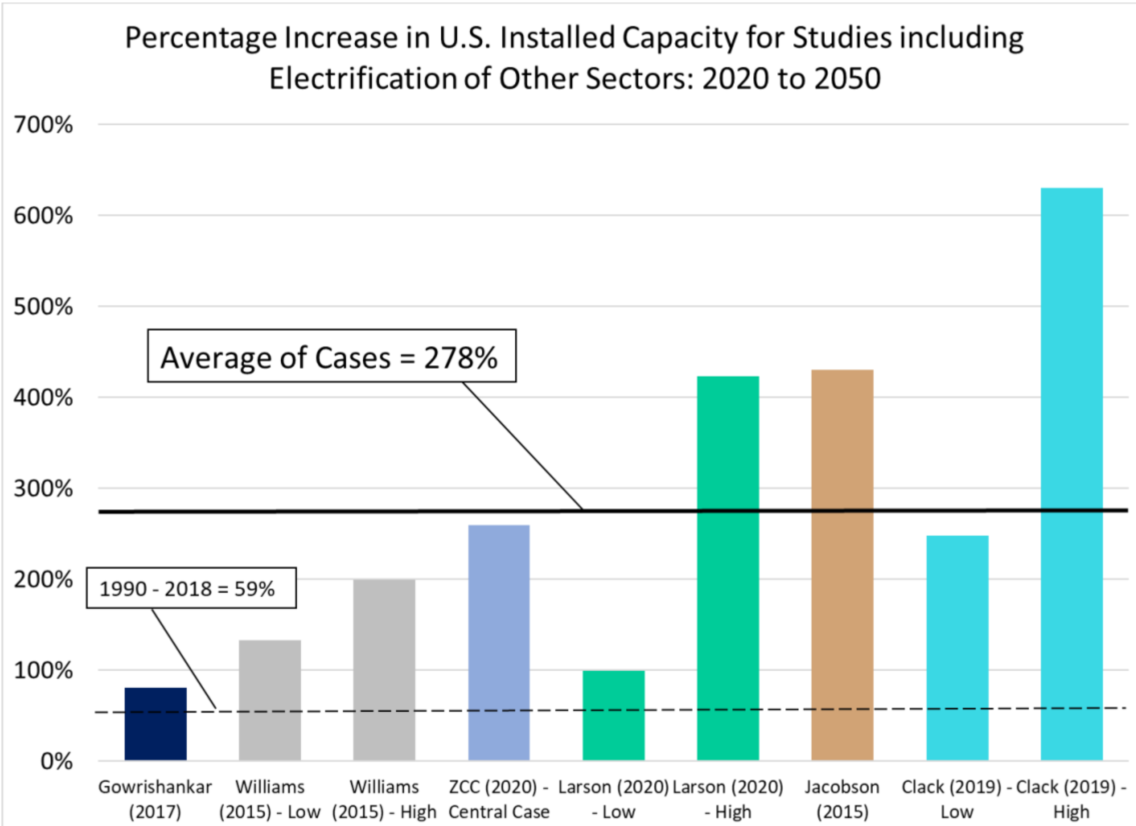
[9] Not all the studies referenced in Figure 1 report the capacity results needed to be included in Figure 2.

Figure 2



The 278% average estimated increase in U.S. electric capacity over the next three decades is comparable to the 59% increase in U.S. electric capacity realized over the last three decades,[10] meaning the estimated increase is almost five times the average seen in recent decades.

The increase in electric supply is expected to require a doubling or tripling of the nation's electric transmission system.

With the increase in electric capacity and generation, new transmission capacity will be needed to connect generating resources and load centers, and to secure the reliability and economic benefits of regional diversity. Studies quantifying the need for new transmission on a national basis with deep decarbonization and electrification have concluded this need will be substantial. As shown in the table below, the base cases from three recent studies estimated transmission will need to be expanded by roughly 150% to 200% relative to today. Further if the electric generating system is exclusively or primarily renewables, the transmission system would need to be expanded by 200% to 300%, much

[10] In 1990, U.S. Total Net Generating Capacity was 690 GW. (Table 2, Electric Power Annual 1994 – Volume 1, DOE/EIA). In 2018, U.S. Electricity demand was 1,095 GW, a 59% increase.

more than under the base cases.[11] This is due to the variability, low energy density, and remoteness of many wind and solar resources.

Percentage Increase in U.S. Transmission Capacity Through 2050								
Study	Reported Metric	Current Baseline	Base Case in 2050			High Case in 2050		
			Case	Total	% Increase	Case	Total	% Increase
Larsen (2020)	Transmission Capacity (GW-km)	320,000	Hi Elec	1,011,000	216%	Hi Elec & 100% RE	1,382,000	332%
ZCC (2020)	High Voltage Inter-Regional Transmission (GW)	80	Central	200	150%	High	300	275%
Williams (2021)	Interstate Transmission Capacity (GW-Mile)	145	Central	368	154%	100% RE	462	219%

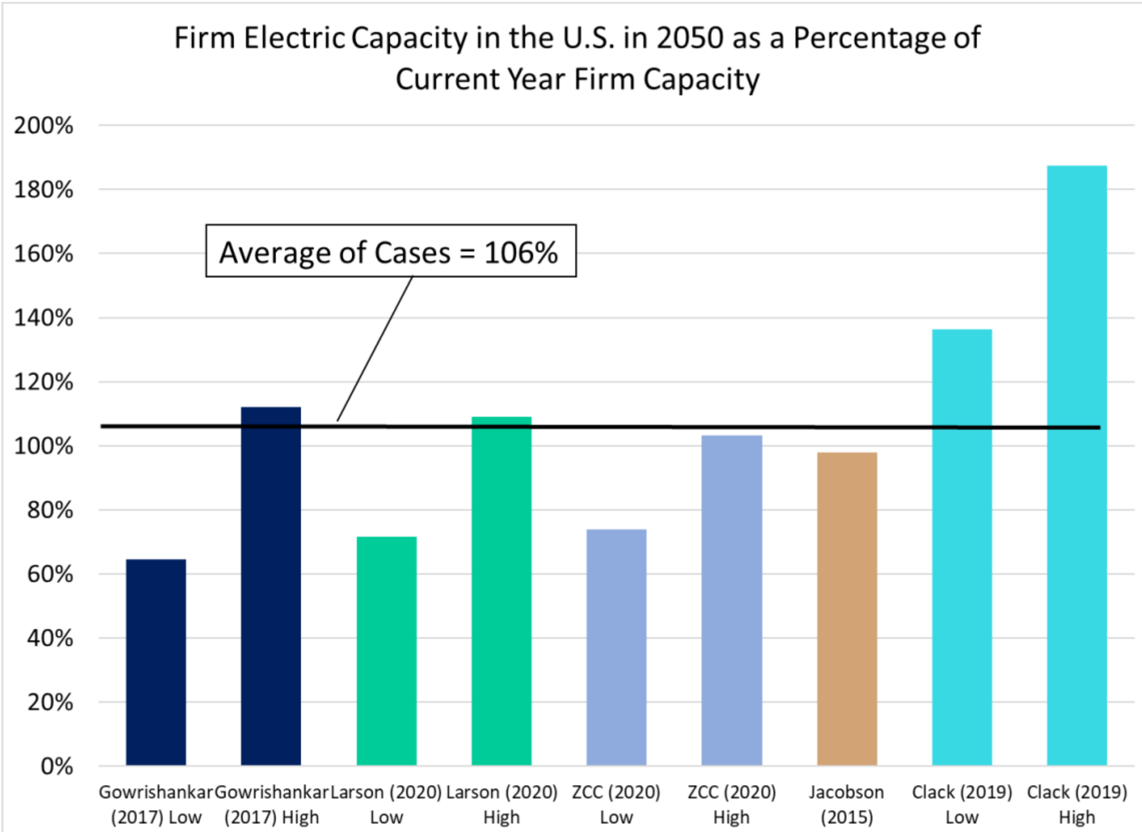
A substantial amount of firm electric capacity, close to the amount in place today, is needed to maintain reliable service even in an electric system where variable renewable energy provides a very large or dominant share of total energy.

Much of the anticipated electric load growth in the transportation, building and industrial sectors – which comes from vehicle charging, electrolysis for hydrogen production, electric boilers for industrial process heat, heat pumps, water heaters, direct air capture, and charging battery storage among other uses – is expected to be curtailable when adequate electric generation is not available to serve all those needs. This controllable load allows variable renewable generation to be a larger source of supply than would otherwise be the case because these loads can be curtailed if needed and so do not require additional firm generating capacity to serve them reliably. At the same time, other types of residential, commercial, and industrial demand are expected to remain firm, as they are in today's electric system. Serving this firm demand will require reliable electric generating capacity (which is provided by resources that are dependably available on demand over extended periods of weeks and months throughout the year) inter-regional transmission, and long-duration electric storage capacity. These types of resources help ensure reliable electric service during seasons of the year when variable renewable supplies are expected to be less available and during "dark doldrum" periods of several days to weeks at a time when wind and solar production may decline more substantially because of prolonged weather patterns that do not support large amounts of wind and solar production.

The following figure at the top of the next page shows the amount of firm capacity estimated by five studies to be needed as a percent of the total amount of firm capacity currently in place. On average across these cases, somewhat more than 100% of today's firm capacity is expected to be required. The wide range of results, varying between 65% and 168% of current firm capacity is likely driven by the level of energy efficiency improvements, degree of electrification and amount of flexible load assumed in these studies.

Figure 3

[11] The results from these studies are directionally consistent with other national transmission studies.



Firm clean energy generation is needed as part of a diverse supply portfolio with variable renewable energy to minimize the overall cost of net-zero decarbonization, avoiding what would otherwise be, in rough terms, a 50% to 100% cost premium.

Despite the decline in the cost of wind, solar and battery technologies, and the reduction in forecasted low-carbon electric system costs expected through time, relying exclusively on variable renewables to supply the energy needed to achieve very high or net-zero levels of decarbonization is expected to substantially raise system costs relative to more diverse portfolios that also include firm clean energy generation.

The first table below compares the results from four studies of the electric sector that report costs for cases that rely exclusively or very heavily on variable renewables and battery storage[12] with alternative cases that have a more diverse mix of resources including both variable renewables and firm clean energy generation.[13] While the design of the cases and reported cost metrics vary across the studies, the results show that pathways relying exclusively or very heavily on variable renewables cost roughly 40% to 150% more than more diverse portfolios, with an approximate average cost premium of 90%.

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12 Some cases also include limited amounts of other resources such as hydro and transmission.

13 Other studies in this literature review do not report results for comparable cases.

Cost Premium of High Variable Renewable (VRE) Cases Compared to Cases with a More Diversified Generation Mix: Electric Sector Studies				
Study	**Reported Cost Metric**	**Cases (% Wind & Solar TWhs)**	**Costs**	**Cost Premium**
Sepulveda (2018)	Annual Energy System (Mid-pt #s) (Range reflects two regions)	VRE and Storage only (100%) Low-C Firm Resources (20% - 40%)	\$160 - \$215/MWh \$100 - \$105/MWh	60% - 105%
Clack (2019)	Annual Electric Cost	Renewables Only (100%) 100% Carbon Free (65%)	\$155/MWh \$95/MWh	63%
Baik (2021)	Annual Electric Cost Cents/KWh	Variable RE + Batteries (N/A%) All Options (N/A%)	12.9 - 15.0 c/KWh 7.1 - 9.4 c/KWh	37% - 111%
Blanford (2021)	Incremental NPV of Cumulative Energy Services Costs (\$T)	100% Renewables by 2050 (95%) Net-Zero by 2050 (55%)	\$0.75 T \$0.3 T	150%

The next table shows similar results for five economywide studies. While the modeling platforms, case definitions and study assumptions differ from the studies in the previous table, and the cost results reflect changes in non-electric sectors of the economy, cases relying exclusively or heavily on variable renewables cost 40% to 125% more, with an approximate average cost premium of 65%.

Cost Premium of High Variable Renewable (VRE) Cases Compared to Cases with a More Diversified Generation Mix: Economywide Studies				
Study	**Reported Cost Metric**	**Cases (% Wind & Solar TWhs)**	**Costs**	**Cost Premium**
Williams (2015)	Annual Energy System (mid-point of range)	High RE (78%) Mixed Case (50%)	\$625 B \$375 B	67%
Risky Business (2016)	Cumulative Energy System	Renewable-Heavy (77%) Mixed Resources (51%)	\$7 T \$5 T	40%
Larsen (2020)	Cumulative Energy System	High electrification, 100% RE (98%) High electrification, med. VRE (85%)	\$6 T \$4 T	50%
ZCC (2020)	Annual Energy System Percent of GDP	100% RE (97%) Central Case (92%)	0.90% 0.40%	125%
Williams (2021)	Net E&I System Cost (NPV)	100% Renewables (98%) Central Scenario (91%)	\$2,644 B \$1,728 B	53%

Including firm clean energy generation in an electric supply portfolio reduces overall system-wide costs when it avoids more expensive variable renewable, storage, and transmission investments. Solar and wind facilities generate electricity on a variable basis, not only from hour to hour during a day as is widely recognized, but also on a seasonal basis and during periods of dark doldrums.[14] To serve firm electric demand and maintain system reliability, decarbonization paths relying exclusively on variable renewables require complementary energy storage and long-distance transmission. Today's battery storage technologies, however, while providing important economic value to the grid, are designed to discharge stored electricity over a period of just a few hours, typically four hours today. Because of this, they are not a complete solution to the longer supply deficits arising from seasonal variability and dark doldrums. While technical and commercial advances will undoubtedly be made in future years, today's battery technology is not a cost-effective way to store electricity over a period of weeks or months. Similarly, while long distance transmission can be a valuable means to increase transfer capacity from solar and wind rich regions to load centers and can capture the benefits of regional diversity in the time

14 For illustrations of the seasonal patterns of wind and solar output in three regions of the United States, see Columbia SIPA CGEP (2021)

patterns of wind and solar output, long distance transmission can be difficult to site and permit, especially at the substantial scale as noted earlier.[15]

From an overall system cost perspective, as more wind, solar, storage and transmission are built to overcome supply deficits associated with seasonal variability and dark doldrums, surplus generation is produced during other hours and seasons of the year when solar and wind output is particularly high relative to electric loads. This overbuilding to cover deficit periods leads to curtailment of wind and solar generation during periods of peak output and surplus supply, reduces the effective utilization of solar and wind resources, increases the marginal cost of adding renewables, storage and transmission, and raises total electric system costs. At increasingly high levels of solar and wind market penetration, this dynamic builds on itself, often causing system costs to rise sharply.

In contrast to variable renewable technologies, firm clean energy technologies can more reliably produce energy up to the capacity rating of the facility for extended periods of time during any season of the year. With adequate fuel supplies, they can generate electricity in all regions of the country. These characteristics allow firm clean energy technologies to produce generation on a reliable basis during periods of low solar and wind output, in any region of the country, thereby overcoming seasonal variability and dark doldrum deficits. When the combined cost of new wind, solar, batteries and transmission investments at high levels of market penetration (and low rates of utilization) exceeds the cost of a mix of variable renewables and firm clean generation, a diverse portfolio starts to become lower cost on an overall system basis.

Analyzing decarbonization pathways on an economywide basis is more complex than the electric sector alone since aggregate economywide cost estimates reflect changes in non-electric sectors, and the economics of building low-carbon technologies like CCS and some negative emission technologies are linked across applications in multiple sectors. Nevertheless, the economywide studies summarized in the earlier table point to higher costs for variable renewable-heavy paths than more diversified paths.

The economic tradeoff between a variable renewable-centric system and one that has a mix of variable and firm clean energy generating resources is situation- and fact-specific. The availability and cost of each competing technology, consumer and industrial acceptance of new load management programs and many other factors make a difference. But at very deep or net-zero levels of decarbonization, the literature on this subject over the five-year period covered in this literature review consistently indicates that employing a diverse mix of clean energy resources (i.e., both variable renewables and firm generation) would achieve deep decarbonization goals with materially lower costs.

Firm energy-producing technologies, in addition to bolstering reliability and reducing system costs, also provide flexibility to address important economic and deployment uncertainties – such as the siting of renewables and transmission, adoption of new demand management programs, achieving

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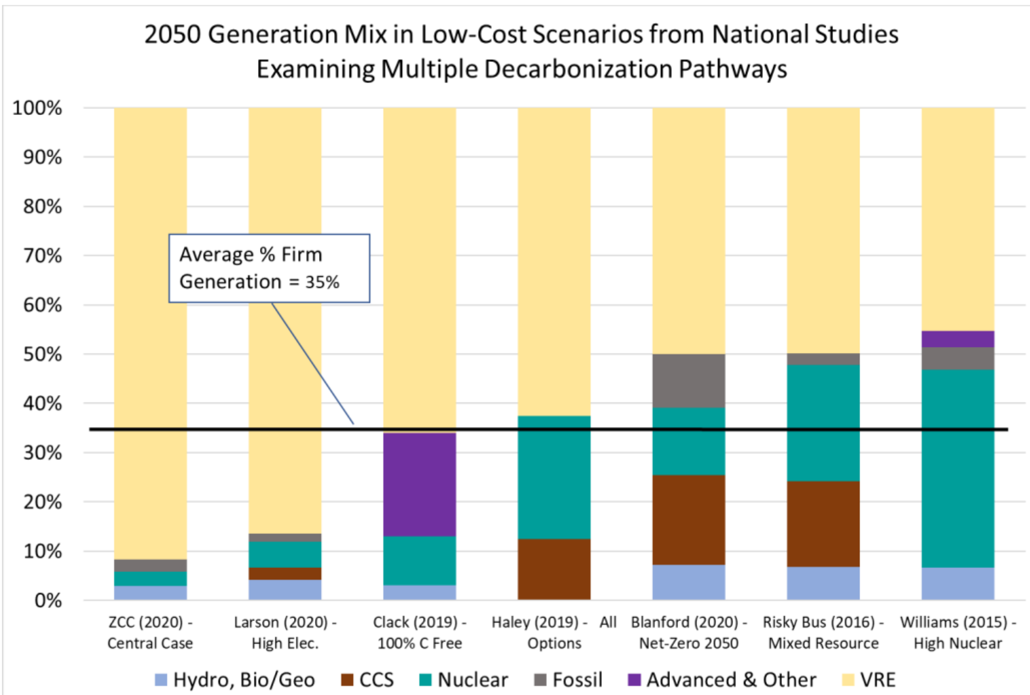
[15] As explained earlier, studies show that achieving deep decarbonization in an electric system composed exclusively or primarily of variable renewable generation would require a transmission system roughly 50% larger than what would otherwise be needed.

future efficiency gains and retaining existing low-carbon generating capacity – thereby increasing the likelihood that decarbonization goals will be met.

All transition pathways, whether they rely primarily on variable renewables or firm clean energy technologies, are subject to considerable uncertainty and implementation challenges. Some of these issues are explicitly captured in the techno-economic modeling studies covered in this literature review and others are not. In the six national studies that analyze multiple decarbonization pathways for the U.S. and allow for a diverse mix of clean energy technologies, the cases with the lowest system costs within a single study generally show a wide range of generation mixes. This can be seen in the figure below.

Figure 4



Of the studies in this figure, two of the most recent ones show very high energy shares for solar and wind, between 86% and 92% (and a total of 8% to 14% for firm technologies). This reflects the substantial cost declines for solar and wind technologies in recent years and expectations for the future. At the same time, other national studies published in recent years point to the possibility of larger energy shares for firm clean energy technologies ranging between 34% and 55%. And for all the cases in this figure, the average share of firm energy is 33%. Similarly, studies conducted for single regions of the country (not shown in this figure) point to firm clean energy shares ranging between 35% and 80%[16] and another recent national study points to a firm clean energy share of roughly 50% driven in part by

[16] CETI (2019), Sepulveda (2018) Mettetal (2020), Kwok (2020).

assumed commercialization and deployment of small modular nuclear reactors and molten salt reactors.[17]

Collectively, the range of these modeling results highlights the importance of technology assumptions (both on an expected basis and with successful innovation), modeling platforms and case structure, as well as the potential for a wide range of outcomes to unfold over the coming decades.

The decarbonization pathways examined in these studies are also subject to numerous uncertainties that are, by design, not explicitly considered in the techno-economic studies, further expanding the range of potential outcomes. The studies reviewed here typically focus on technological and economic questions, often with a single reference policy case and one or more sensitivity cases that examine discrete and sometimes relatively modest changes from the reference case. They are for the most part not designed to examine a comprehensive set of uncertainties and decarbonization pathways. For example, in the technology pathway with 80% to 90% or more variable renewable energy that emerges from several studies, the remaining 10% to 20% of energy and the necessary capacity is largely sourced from existing nuclear, hydropower and natural gas-fired electric capacity, the last of these operated at capacity factors that average just 3% to 10%.[18] Taken as a whole, this high-variable renewable pathway rests on several important assumptions including:

- Substantially increasing the efficiency with which energy is used by consumers (in one study, this is reported as a 40% reduction in per capita energy use or two-thirds reduction in energy intensity of GDP),[19]
- Being able to manage and control the new electric loads associated with transportation, industry, and buildings to the extent and at the costs assumed in these studies, with consumers and industry accepting these demand management programs and variability of electric supplies,
- Doubling electric generation and tripling electric capacity as described earlier which requires rates of project siting, permitting and construction three to five times higher than in recent decades, and a 2- to 3-fold increase or more in national transmission capacity; and recognizing that variable renewable heavy systems require total capacity to be roughly twice that of more diverse systems[20] with commensurately larger land use impacts,[21] and
- Retaining much or most of the existing firm electric capacity currently in place (nuclear, hydropower and thermal natural gas); and operating the gas transportation and gas-fired electric generation systems at utilization rates of just 3% to 10%.[22]

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17 Clack (2021).
18 For example, Zero Carbon Consortium (2020), Williams (2021) among others.
19 Zero Carbon Consortium (2020).
20 Clack (2019).
21 See Larsen (2020) for an assessment of land use impacts. From slide 172, for their high electrification case, "Total area spanned by onshore wind and solar farms is ~590,000 sq-km, an area roughly equal to the size of IL, IN, OH, KY, TN, MA, CT and RI put together." From slide 137, for the same case, total U.S. transmission capacity more than triples.
22 Zero Carbon Consortium (2020).

For these reasons, while these studies are well-structured for their intended purposes, the cases presented studies do not reflect all the uncertainty associated with achieving ambitious climate goals. This may inadvertently lead to the impression that single decarbonization pathways (or a narrow set of closely related pathways) are more certain than they in fact are.

It is also important to recognize that all deep decarbonization pathways and technologies are subject to their own uncertainties. Because of this, adopting approaches to decarbonization that diversify risk exposure would provide flexibility and increase the likelihood of meeting climate goals. Complementing variable renewable technologies with firm clean energy technologies in a diversified portfolio can increase the odds of success. In the event any of the uncertainties highlighted earlier – gains in energy efficiency, controllable loads, siting and permitting renewables, and retaining existing capacity – come into play, additional firm clean energy resources could be required to achieve decarbonization goals. In one study for instance, constraining the development of wind and solar leads to an outcome where advanced nuclear and gas with carbon capture and sequestration combine to provide roughly half of system energy, several times that expected under the central policy case.[23] Given the relatively similar costs of the cases across studies with diverse resource mixes including firm clean energy, the availability of multiple firm clean energy technologies can act as a low cost hedge against the types of risks listed earlier.

Firm clean energy technologies are expected to be particularly important in regions of the country where wind and solar resources are less competitive, and essential for decarbonizing several non-electric sectors of the economy.

Firm clean energy technologies are forecasted to be a relatively large portion of electric sector generation in regions of the country where less strong wind or solar resource endowments, the ready availability of other natural resources (hydropower, biomass, access to geologic sequestration etc.), and existing electric and energy infrastructure (production, storage, and transport of fuels) may combine to make wind and solar less competitive than alternative clean energy technologies. From the studies covered in this literature review, examples of these include the Pacific Northwest with its existing hydropower resource, the Southeast with its relatively limited wind resource, the Northeast and the Great Lakes regions. [24]

Technologies to capture and geologically sequester carbon dioxide are also often considered essential to achieving deep decarbonization goals outside of the electric sector and sometimes cited as one of several foundational "pillars" of deep decarbonization.[25] This is because of their ability to remove carbon dioxide from various industrial processes and the lack of alternative low-cost technology options in those sectors. For example, carbon capture and sequestration technologies may be used in the production of zero-carbon or carbon-negative fuels (that rely on biomass feedstocks or natural gas reformation to hydrogen), industrial production of cement, and direct capture of carbon from the

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[23] Larsen (2020) p. 88. Also see Williams (2021).
[24] CETI (2019), Kwok (2020), Mettetal (2020), Larsen (2020) p.91.
[25] Two recent examples are Larsen (2020) and ZCC (2020)

atmosphere.[26] The economic advantages of these technologies are likely a contributing factor to the lower costs associated with diverse technology pathways in the economy wide studies shown earlier.

To ensure firm clean energy technologies are commercially available at scale in a timely way and the path dependency of fully decarbonized electric systems, efforts are needed to extend the operating lives of today's firm resources and demonstrate, deploy and commercialize a range of advanced technologies and associated infrastructure.

While a large majority of the clean generation deployed in the U.S. over the next decade is expected to be wind and solar, achieving deep economy wide decarbonization by mid-century or earlier also rests on early-year efforts to advance firm clean energy technologies. This is in part because many years are typically needed to demonstrate, commercialize and deploy any type of new electric technology at scale as has been the case for wind, solar and battery storage among many other new technologies. This will be particularly important for new technologies requiring large physical networks for production, transportation and storage as with carbon dioxide and zero-carbon fuels. Early year efforts to demonstrate and commercialize advanced firm technologies are also valuable because knowledge about the characteristics of the technologies most likely to complement variable renewables will influence the eventual mix of variable and firm generation through time and the odds of decarbonizing in a low-cost manner. Because the electric sector operates as an integrated system composed of long-lived assets and there is limited time before mid-century, pursuing deep decarbonization in a sequential manner, one step at a time, is unlikely to lead to the lowest cost outcome.

This suggests the importance of initiatives to extend the operating lives and increase the capacity of existing firm clean energy technologies such as nuclear and hydropower; to explore how existing natural gas infrastructure might be life-extended and used in a deeply decarbonized electric sector; to demonstrate, deploy and commercialize a range of firm clean energy technologies including carbon capture and sequestration, zero-carbon fuels for electric generation, advanced nuclear, geothermal and long-duration storage; and to build out production, transport and storage infrastructure networks for carbon dioxide and zero-carbon fuels.[27]

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26 Larsen (2020), Zero Carbon Consortium (2020), Jones (2020), Williams (2021).

27 See Larsen (2020), Zero Carbon Consortium (2020), Williams (2021), and Clack (2021) for elements of this.

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