BETTING ON CLIMATE SOLUTIONS

WHY WE SHOULD SPREAD OUR CHIPS

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CONTENTS

INTRODUCTION

The evidence that climate change is underway grows stronger every year, along with the evidence that it is largely attributable to human activities. To avoid the worst effects of climate change, the United States and the world as a whole must dramatically reduce greenhouse gas emissions over the next 30 years. In the latter half of this century, nations collectively must aim for net *negative* emissions and begin removing carbon dioxide from the air. In the energy sector, CO_2 emissions must be virtually eliminated by mid-century. This will require the "deep decarbonization" of the world's economies, and the transition to a "clean energy economy." An energy transition of this scope will be challenging in many ways, but it is technologically and economically feasible, as are reductions in other greenhouses, including: methane, nitrous oxide and fluorinated gases (IPCC, 2018).

There is widespread agreement among modelers and analysts that a clean energy economy will require three entwined strategies:[1]

1. Aggressive improvements in energy efficiency across all sectors.
2. Electrification of end-uses across all sectors, wherever feasible, and a switch to zero- or low-carbon fuels in other end-uses.
3. Clean generation of electricity from zero- or low-carbon sources.

Despite agreement on these three broad strategies, uncertainties and disagreements remain on details, e.g., over the potential pace of efficiency gains, over which end-uses can be electrified or fuel-switched, and over specific country strategies linked to that country's stage of economic development. One major area of controversy (beyond the scope of this paper) is the role of bioenergy in a future clean energy economy. Bioenergy has the potential to play a major role in electricity generation and/or provision of liquid and gaseous fuels. However, a sharp debate continues over the extent to which a major expansion of bioenergy production would impact food supplies and alter land use in damaging ways.

This paper focuses on the third strategy and the ongoing debate over how to decarbonize the electricity sector. At the most basic level, the debate is over the definition of "clean" generation. Should "clean" mean renewable electricity only (wind, solar, hydro, geothermal, etc.)? Or does "clean" include *all* zero- and low-carbon sources of electricity: renewables, nuclear power, and fossil fuel generation with carbon capture and sequestration (CCS)?

These three categories of electricity generation are all potentially pieces of the solution to the threat of climate change. All face challenges in scaling up to meet the threat. This paper argues that we should use a broad definition of "clean" generation given the challenges and uncertainties that renewables, nuclear power, and CCS still face as they continue to evolve. To use a financial metaphor, a broad definition is analogous to a diversified

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[1] For some developing nations, these strategies can take the form of Low Emission Development Strategies (LEDS). See: LEDS Global Partnership 2019.

investment portfolio, which carries less risk than a narrow portfolio of just a few stocks and bonds.

To use a gambling metaphor, limiting ourselves only to renewables would constitute "betting all our chips" on a narrow portfolio of climate solutions. Given the magnitude of the threat posed by climate change, spreading our chips over a broad portfolio of technologies is the more prudent, lower risk approach given the uncertainties over their future performance and cost.[2] Ultimately, carbon is the problem and should be our focus, not the market share of renewable energy, or RE.

That conclusion is at odds with some in the climate advocacy community who support phasing out use of fossil fuels as quickly as possible, and/or who oppose nuclear power and the use of CCS. Typically, these advocates equate "clean" with "renewable," and have used the call for "100% clean, renewable energy" as a powerful rallying cry and organizing tool.

Ideally, all those committed to preventing dangerous climate change should work toward bridging their differences over how to define clean energy. The stakes are high, and in the U.S., in particular, powerful political forces are currently a roadblock to strong federal action on climate change. More common ground and understanding can help move solutions forward in all policy arenas: at the federal, state, and local government levels; at the regional level via Regional Transmission Organizations and multi-state collaboratives; and in corporate purchasing of "green" electricity. This paper aims to build better understanding of the challenges of 100% renewable scenarios for a clean energy economy, and it offers some observations on the implications for policymaking.[3]

The paper is organized as follows. Section 2 provides a window on the literature on deep decarbonization, using a 2017 synthesis of that literature as a jumping-off point and highlighting recent studies that build on it or contradict it. This section also compares and contrasts models that use a broad versus narrow portfolio of clean generating technologies.

Section 3 focuses on improving understanding of a key challenge in 100% renewable scenarios: the riddle of "low-cost" solar and wind generation but "high-cost" 100% renewable scenarios. It provides a layman's guide to understanding why total electricity system costs increase nonlinearly as the percentage of renewable generation crosses thresholds.

Section 4 describes how various policymakers and policy influencers are staking out positions on strategies for decarbonizing the electricity sector (with regard to supporting 100% renewables versus all zero- and low-carbon options), while some actors in this arena appear to avoid clear positions as a deliberate tactic for coalition-building. The section concludes with some normative recommendations.

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[2] MIT researchers use a similar gambling metaphor to convey the uncertainties in climate change predictions. See: MIT Joint Program on the Science and Policy of Global Change n.d.

[3] There are challenges, of course, in deploying CCS, maintaining existing nuclear reactors, and/or building new nuclear reactors. Those challenges are beyond the scope of this paper but merit equal attention.

A WINDOW ON THE DEEP DECARBONIZATION LITERATURE

There is a burgeoning and expansive literature of deep decarbonization modeling studies stretching all the way back to the 1970s (e.g. Lovins 1976, Sørensen 1975). These studies vary widely across many dimensions:

- Emissions scope (all greenhouse gases, CO_2 only from the energy sector, electricity sector only)
- Geographic scope (global, regional, national, subnational)
- Modeling end year (2030, 2050, 2100) and intermediate years (annual or 5-year increments)
- Model driver (global temperature constraint of 2°C warming, percentage reduction in emissions from a base year, technology scenarios, use of cost optimization)
- Treatment of legacy energy system (modeling of gradual turnover of existing capital stock versus modeling of a "greenfield" energy system of all new capital stock)

Authors of studies vary widely, too:

- Governments (e.g., the U.S. and other governments have submitted "mid-century strategy reports" to the UNFCCC, California and Hawaii have sponsored their own subnational studies)[4]
- Quasi-governmental organizations (e.g., Intergovernmental Panel on Climate Change (IPCC), International Energy Agency (IEA))
- A broad array of non-government actors including:
  - *Research institutes (e.g., National Renewable Energy Lab (NREL), Rocky Mountain Institute) or collaborations among research institutes (e.g., Deep Decarbonization Pathways Project (DDPP), Energy Modeling Forum)*
  - *Nonprofits (e.g., Union of Concerned Scientists, Natural Resources Defense Council, Risky Business Project)*
  - *Academic researchers*
- Private companies (e.g., Shell Oil, BP, Google)

Several synthesizing reviews of recent studies in the deep decarbonization literature provide a good window on this growing body of work. Cochran et al. (2014) provides a meta-analysis of twelve recent studies that evaluate the feasibility of high levels of renewable electricity at the country and regional levels. All of the studies conclude that renewables can supply, on an hourly basis, a majority of electricity demand. Otto K. and C. Breyer (2016) provide a meta-analysis of global and transcontinental scenarios with high shares of renewable electricity generation, noting the key role that expanded transmission systems play in keeping costs reasonable, and the lack of studies that provide good quantitative modeling of the dynamics among continent-wide renewable energy production, transmission grids, and energy storage options.

Jenkins and Thernstrom (2017) take the broadest view, reviewing 30 deep decarbonization studies (some of which look beyond the electricity sector to all energy use or to all greenhouse gases) and several previously published meta-studies.[5] They synthesize the insights from these studies with an eye toward policymaking, and then present them as seven findings:

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[4] The United Nations Framework Convention on Climate Change (UNFCCC) received such reports on scenarios for deep emissions reductions by 2050 from the U.S., Canada, Mexico, and other countries.

[5] This synthesis was extended and expanded to 40 studies in Jenkins et al. (2018) and reached the same conclusions.

FINDINGS FROM JENKINS AND THERNSTROM (2017) DEEP DECARBONIZATION OF THE ELECTRIC POWER SECTOR: INSIGHTS FROM RECENT LITERATURE

1. Power sector CO_2 emissions must fall nearly to zero by 2050 to achieve climate policy goals.
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.
3. Deep decarbonization of the power sector is significantly more difficult than more modest emissions reductions.
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.
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:
    - *Decarbonized power systems dominated by variable renewables such as wind and solar energy are physically larger, requiring much greater total installed capacity.*
    - *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.*
    - *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.*
    - *High renewable energy scenarios also envision a significant expansion of long-distance transmission grids.*
    - *High renewables scenarios are more costly than other options, due to the factors outlined above.*
6. Including dispatchable base resources (such as nuclear or CCS) reduces the cost and technical challenge of achieving deep decarbonization.
7. A diversified mix of low-carbon resources offers the best chance of affordably achieving deep decarbonization of the power system.

Among the mainstream community of modelers and analysts, these insights are widely shared.[6] Generally speaking, if a deep decarbonization model is allowed to draw from *all* zero- and low-carbon electricity options to create a future scenario with much lower emissions, it will produce a scenario with some mixture of renewables, nuclear, and/or CCS. In recent years, as the costs of wind and solar have declined, models have typically produced scenarios with increased percentages of renewable generation, but not 100%. These models are typically relied on by governments and by quasi-governmental bodies such as the IPCC and the IEA, and by major cross-organization collaborations such as the Deep Decarbonization Pathways Project and the Energy Modeling Forum. They are used by a host of nongovernmental actors and by private firms.

However, there is a smaller group of modelers in the nonprofit and academic communities who explicitly create 100% renewable scenarios. Some of these studies aim to show that electricity demand can be met with 100% renewable sources, while others aim

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[6] This statement is based on the author's review of studies and personal communications with modelers.

to show that all economic sectors can rely on 100% renewable energy (via electrification and zero- and low-carbon fuels). They strongly disagree with the insights set forth in Jenkins and Thernstrom (2017) above. As one example, Diesendorf and Elliston (2018) express a sharply divergent view:

> [L]arge-scale electricity systems that are 100% renewable (100RElec), including those whose renewable sources are predominantly variable (e.g. wind and solar PV), can be readily designed to meet the key requirements of reliability, security and affordability. . . We find that the principal barriers to 100RElec are neither technological nor economic, but instead are primarily political, institutional and cultural.

This divergence in views turned into open conflict in 2017. A 2015 study published in the *Proceedings of the National Academy of Sciences* (NAS) set forth a 100% renewable scenario for all U.S. energy use (Jacobson et al. 2015). The study and related work became widely cited as demonstrating the feasibility of an all-renewables approach to decarbonization. In 2017, that study was the subject of a withering critique published in the same journal signed by 20 leading energy modelers and analysts (Clack et al. 2017).

This sparked a series of replies and rebuttals. Lead author Jacobson took the unprecedented step of filing lawsuits against both lead author Clack and the NAS. Jacobson withdrew the lawsuits several months later.[7] This situation exemplifies the dire need to build bridges among competing advocates on how to define clean energy.

MAINSTREAM MODELING

As noted above, mainstream models of deep decarbonization of the U.S. electricity sector include the full portfolio of low- and zero-carbon options to be called on in the model's projected generation mix. Four recent studies of this type, that look out to 2050 and incorporate the declines in the cost of solar and wind, show a generation mix of 36% to 75% variable renewable electricity. Each study includes a reference scenario that assumes no change in current policy regarding climate or energy.

The *U.S. Mid Century Strategy Report* (White House 2016) is an official submission to the UNFCCC made by the Obama Administration in its closing months. The modeling underlying the report aims for an 80% reduction in U.S. greenhouse gas emission by 2050 (from a 2005 baseline) and uses the GCAM model. Across four scenarios, wind and solar generation range from roughly 45% to 60% of total generation in 2050. Nuclear generation ranges from 15% to 25% of the total. Fossil generation with CCS ranges from 20% to 25% in three scenarios and does not play a role in the fourth. Conventional fossil generation ranges from 4% to 10%.

The Risky Business Project (2016) applies the PATHWAYS model to a similar reduction target for the energy sector only and models four scenarios: the first three scenarios each assume a relatively high share of renewables, nuclear, or CCS generation, and a fourth that represents the most balanced mix of the three types. These scenarios produce a range of roughly 36% to 74% wind and solar generation (Figure 1).[8] Nuclear generation varies from 11% to 23% of the total. CCS plays a role only in the High CSS scenario (35%) and the "mixed" scenario (17%). Conventional fossil generation ranges from 3% to 6%.

The Natural Resources Defense Council applies the PATHWAYS model to reductions of 80% below a 1990 emissions baseline—also in the energy sector by 2050 (Gowrishankar and Levin 2017). The study assumes greater emphasis on energy efficiency and renewables, and presents a scenario with roughly: 75% wind and solar, 18% nuclear, gas with CCS, and gas generation; and 7% hydro.

The Union of Concerned Scientists uses the REEDS model to explore scenarios in which the U.S. can reduce electricity sector emissions by 90% by 2050 from a 2005 baseline (Cleetus et al. 2016). The study examines four scenarios. The first three scenarios are each optimistic about the future cost of renewables, nuclear,

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[7] For a summary of the lawsuits, see: Sabin Center for Climate Change Law 2017.

[8] Total generation varies across the four pathways, as the modeling explored generation mix options combined with options for electrification and production of zero-carbon fuels for industry and transportation.

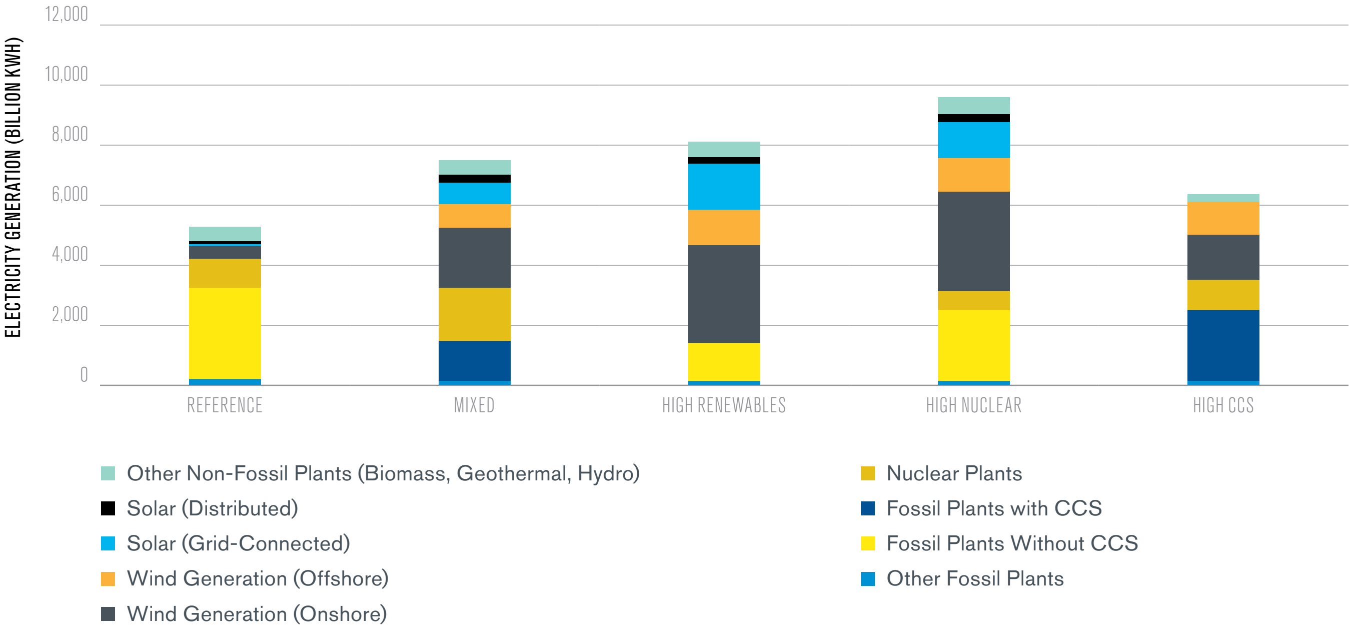
and or CCS generation. The fourth represents a mid-range of future cost assumptions for the three types of generation (Figure 2).[9] The resulting generation mixes have roughly: 62% to 75% wind and solar; 9% to 28% gas generation with CCS; and 3% to 7% conventional gas generation. In the optimistic nuclear scenario, nuclear power retains about 16% of the generation mix (down from a current 20%); in the other three scenarios, nuclear plants are largely retired by 2050.

These four studies are all in the recent "grey literature" (not peer reviewed) and present a range of results across three modeling platforms.[10] Only White House (2016) is part of the Jenkins and Thernstrom (2017) survey, but the other three studies are consistent with the survey findings in two basic themes. First, it is difficult to push the models beyond about 75% wind and solar without encountering reliability challenges or sharp rises in electricity costs (a doubling or more). Second, nuclear and/or CCS generation provide useful complements to wind and solar, along with gas turbines (which can easily follow load to maintain reliability). Noteworthy, too, is the fact that two of these studies were published by environmental groups.

These kind of modeling results are similar to those in recent studies with a global geographic scope. The International Energy Agency's *Energy Technology Perspective 2017* (IEA 2017) presents a "2 degree scenario" (2DS—average temperature increase limited to 2°C above pre-industrial levels). The IEA model covers all the world's economies and all sectors (with current total generation of roughly 25,000 TWh). In the electricity sector, by 2050, the 2DS projects roughly 40% of generation is from wind and solar; hydro and biomass are 26%; nuclear accounts for 16%; fossil with CCS is 9% of the total; and conventional gas is about 6% (Figure 3).

The IPCC publishes modeling of deep decarbonization scenarios approximately every seven years as part of its annual *Assessment Report*, the last being released in 2014 (IPCC 2014). In 2018, the IPCC released a special report on *Global Warming of 1.5°C* (above pre-industrial levels) and related global greenhouse gas emission pathways (IPCC 2018). The report summarizes a large body of modeling scenarios for limiting warming to 1.5°C, and groups them into four illustrative model pathways (P1 to P4) reflecting different assumptions on

FIGURE 1: GENERATION MIX IN 2050 IN RISKY BUSINESS SCENARIOS



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[9] Note: units in vertical access in Figure 2 are terawatt-hours (TWh) which are equal to billions of kilowatt hours, the units used in Figure 1.

[10] The Risky Business and NRDC studies both used the PATHWAYS model.

FIGURE 2: GENERATION MIX IN 2050 IN UNION OF CONCERNED SCIENTISTS SCENARIOS

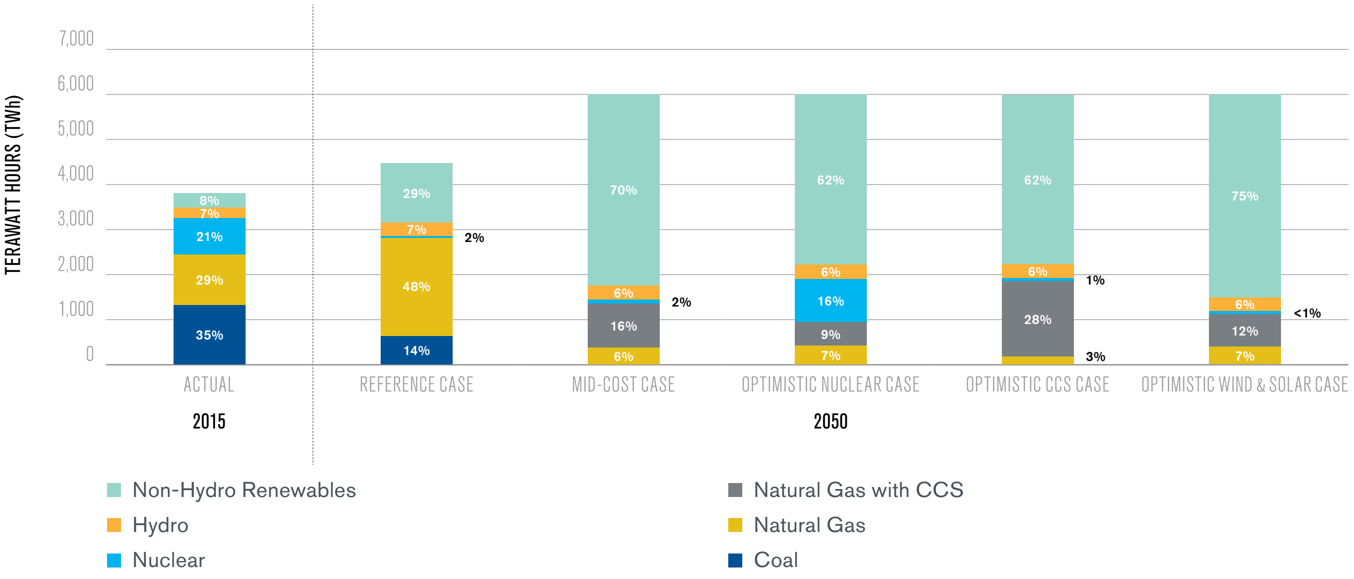
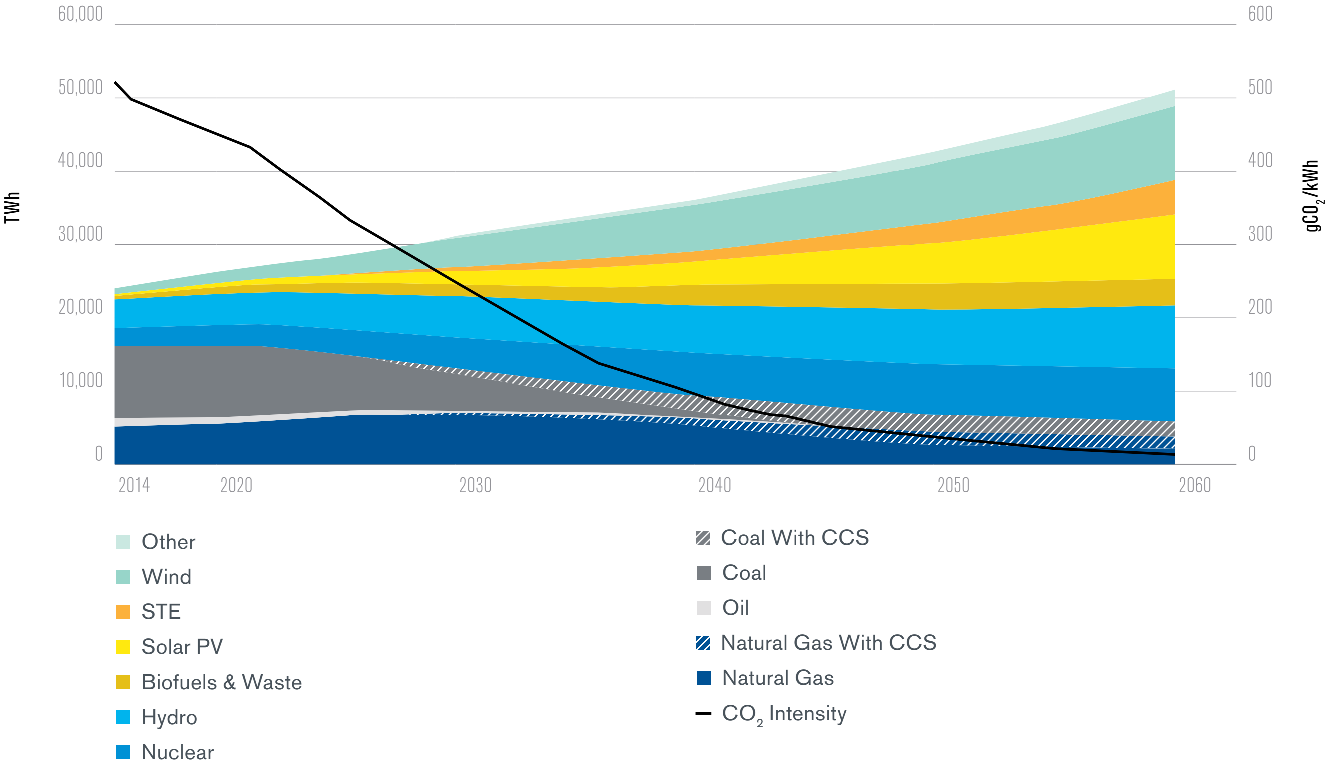


FIGURE 3: GENERATION MIX IN 2050 IN IEA 2DS SCENARIO



growth of overall energy demand and pursuit of broad goals of sustainable development. Across the four illustrative pathways, projections of the global generation mix vary substantially, but all technologies play a role:

- Renewables expand to provide 70% to 85% of global generation by 2050.
- Nuclear generation holds constant at today's levels or increases from two to five fold.
- Natural gas with CCS provides 3% to 11% of total generation.

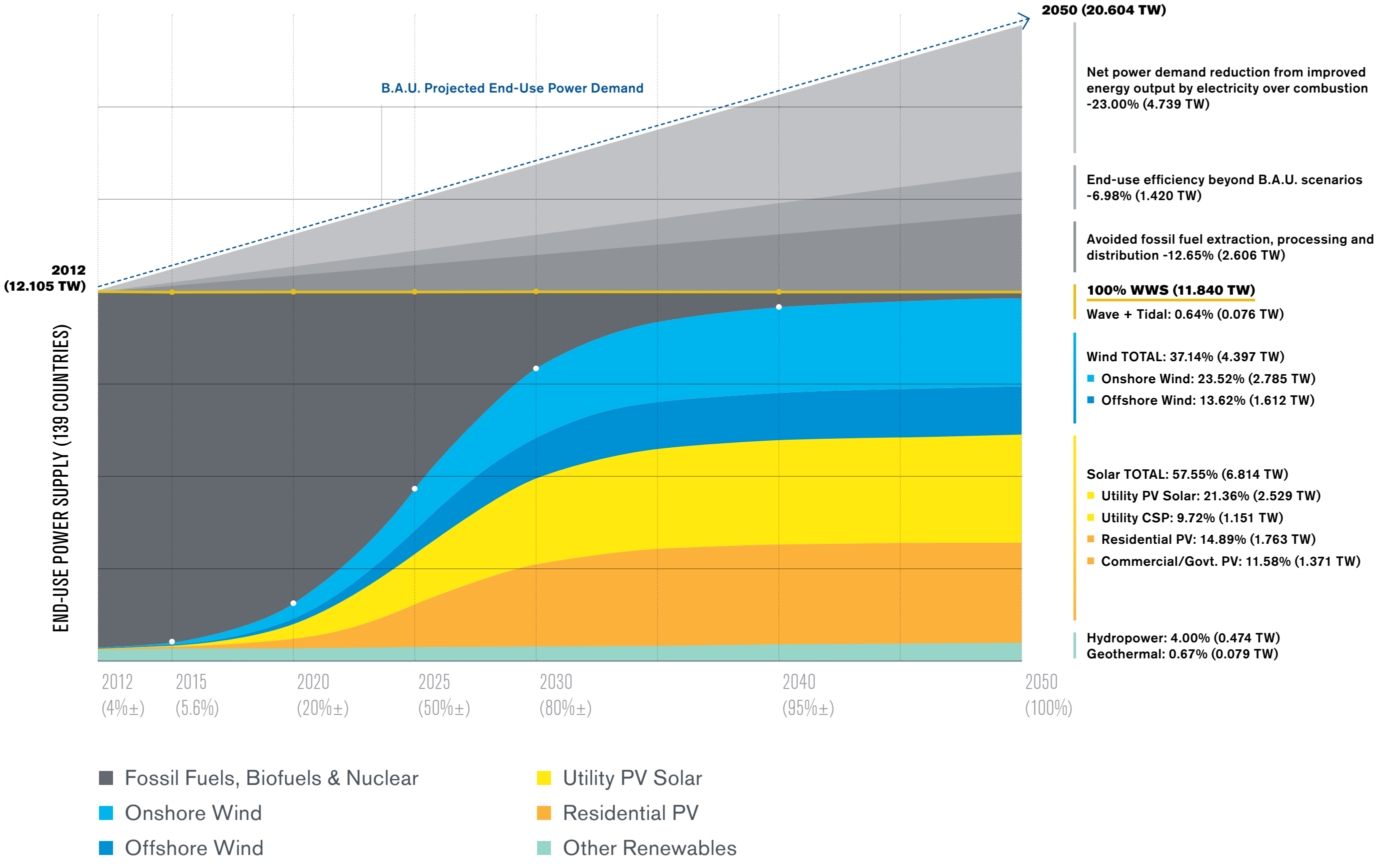
These results are consistent with the *2014 Assessment Report* in not lending credence to the feasibility of a 100% renewable pathway for electricity generation, much less for renewables to fuel the entire energy sector. The results reflect the same conclusion noted earlier for modeling of the U.S.: global models encounter reliability challenges or estimate sharp rises in electricity costs in scenarios of very high renewable penetration.

MODELING OF 100% RENEWABLE SCENARIOS

Nevertheless, as noted earlier, there is a group of modelers in the nonprofit and academic communities who explicitly create 100% renewable scenarios, sometimes for the electricity sector only and sometimes for the energy sector as a whole. Subsequent to the publication of Jenkins and Thernstrom (2017), Jacobson released a study based on the application and expansion of his model (GATOR-GCM-OM) to 139 countries, essentially covering the entire globe (Jacobson et al. 2017). The study's scenario for 2050 excludes all fossil fuels, nuclear, and CCS generation, and all forms of bioenergy (as did Jacobson et al. 2015). The study depicts the resulting generation mix in Figure 4.

Note that Jacobson uses terawatts rather than terawatt-hours as the key unit of measurement, though it is not a measure of energy but rather a measure of the rate of energy consumption (power). Therefore, Figure 3 depicts the sum of 139 countries' "annual averaged

FIGURE 4: GENERATION MIX IN 2050 IN JACOBSON ET AL. 2017



end-use power demand for all purposes (electricity, transportation, heating/cooling, industry, agriculture/fishing/forestry, and other)."

Jacobson projects a scenario in which, by his metrics, total end-use energy demand remains flat despite population and economic growth. He attributes this in the upper right hand of the figure and in the text to: the inherent efficiency of direct use of electricity over combustion; the overall improved end-use efficiency beyond his "business-as-usual" scenario; and the avoided energy demands of fossil fuel extraction, processing, and distribution.

This 139-country study has not been subject to a comprehensive critique in the same manner as Jacobson et al. 2015, however, it would likely draw fire on assumptions previously criticized: deployment of thermal storage at scales never seen, and the use of demand response at scales never seen.[11] Notably, the study also assumes the following:

- By 2020, all new marine freighters are "electrified and/or use electrolytic hydrogen."
- By 2025, all new high-temperature industrial processes are electric.
- By 2025 to 2030, all new heavy-duty trucks and buses are powered by battery or hybrid battery and hydrogen fuel cell.
- The aviation sector transitions completely to battery-powered and hybrid battery/hydrogen-fuel-cell propulsion by 2040.

The study estimates total electricity costs as a weighted average of the Levelized Cost of Energy (LCOE) of all electricity generators, and on a global basis that figure is 8.86 cts/kWh (2013$). Integration costs—the costs of keeping a grid reliable when it is heavily dependent on variable renewable generation—is another source of concern.

Jacobson appears to use a single U.S.-based estimate drawn from his U.S. study and applies it to all countries. And that estimate is a mere 0.8 cents per kWh, and covers expansion of transmission systems, thermal and electrical storage, and hydrogen production, compression, and storage. The study adds this to the weighted LCOE to arrive at a delivered total cost of 9.66 cts/kWh. This estimate of integration costs (roughly 10% of generation costs) is very low compared to the results of mainstream modeling of electricity systems. A detailed discussion of the LCOE metric and integration costs appears in the section below.

Another notable development over the past two years is the emergence of 100% renewable studies by a modeling group at the Lappeenranta University of Technology (LUT) in Finland and the Energy Watch Group. Deploying the LUT Energy System Model, numerous academics have collaborated to create 100% renewable scenarios for the electricity sectors of every region of the world: e.g., North America (Ram et al. 2017), South and Central America (Barbosa et al. 2017), North East Asia (Bogdanov et al. 2016), Southeast Asia (Gulagi et al. 2017a), and South Asia (Gulagi et al. 2017b). In Ram et al. (2017), the results of the regional studies were aggregated into a scenario for 100% renewable electricity for the globe. LUT promises to extend this work to this work to the entire energy sector. The website for this research provides impressive visualization tools.[12]

LUT applies an optimization model to a reference case forecast of electricity demand to estimate a least-cost generation mix to meet that demand. The model solves for hourly balancing of supply and demand. The LUT model excludes nuclear and CCS and relies exclusively on renewable sources, and relies heavily on batteries for diurnal storage, given variable renewable output. The model assumes production of synthetic methane to provide seasonal storage.

Aggregate global results are summarized in Figure 5 on the following page. LUT assumes global power demand will roughly double to 49,000 TWh per year in 2050 (without widespread electrification of end-uses). LUT's generation mix is dominated by solar photovoltaics, or

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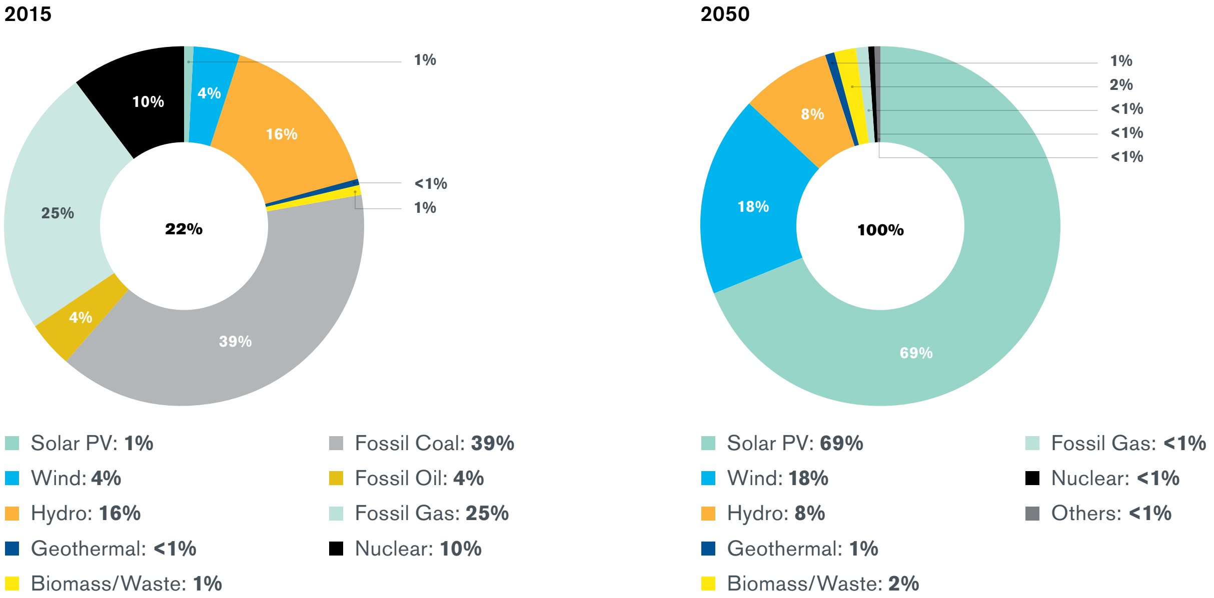
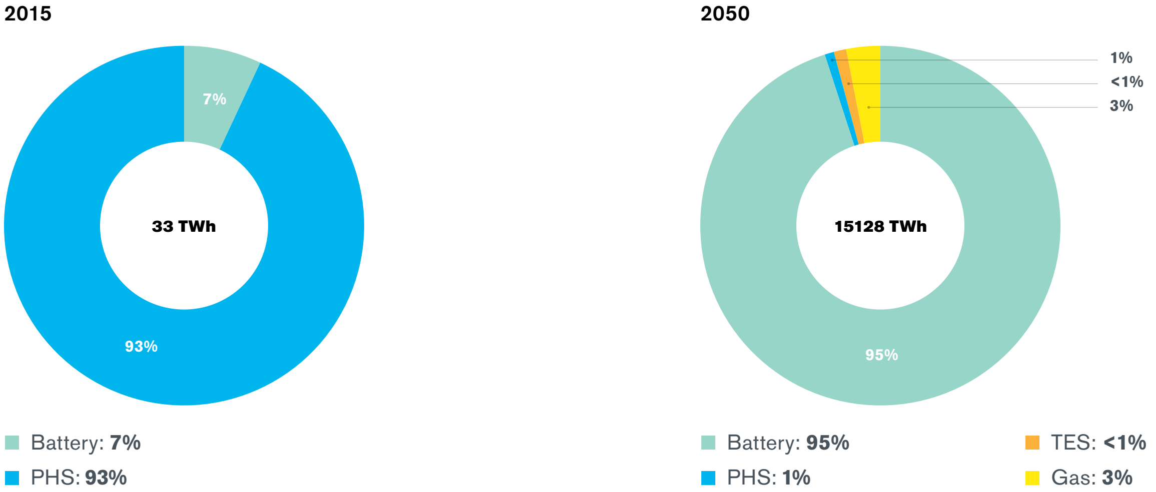
[11] Jacobson describes several methods for maintaining reliability with near total reliance on variable wind and solar, including dispatchable hydro to balance variable renewable output. His 2015 study for the U.S. (Jacobson et al. 2015) was criticized for assuming increases in the peak output of hydroelectric dams without regard to physical constraints or downstream impacts.

[12] See: LUT Lappeenranta University of Technology n.d.

FIGURE 5: GLOBAL ELECTRICITY GENERATION AND STORAGE RESOURCES IN LUT MODELING



Share of electricity generation from renewable sources in 2015 and 2050. Gas capacities in 2050 only use renewable based gas. In 2050, nuclear power still accounts for a negligible 0.3% of the total electricity generation, due to the end of its assumed technical life, but could be phased out earlier.



Share of storage technologies in the overall output in 2015 and 2050. Gas storage in 2050 is based entirely on renewable resources.

PV, at 69% with wind a distant second at 18% of the total. Fossil and nuclear generation are totally eliminated. Battery capacity is equal to 31% of total annual demand, requiring a massive scale-up of storage.

A detailed review of the LUT modeling was beyond the scope of this paper, but some features are apparent. LUT assumes continued major decreases in the costs of solar, wind, and batteries. Aggressive, favorable assumptions for a 100% renewable system include: the lifetime of a solar PV plant pegged at 35 years, and batteries assumed to be cycled 300 times annually for 20 years.[13] Treatment and costing of transmission is not clear. Most importantly, it is unclear how the LUT model results avoid the nonlinear cost increases that occur in mainstream modeling as a system approaches 100% renewable (see The Riddle of Low-Cost Renewables and High-Cost Electricity Systems on page 14).

LUT authors indicate that they will soon go beyond the electricity sector and model the entire energy sector powered by 100% renewables. That is a scenario exercise that few other than Jacobson have taken on, as the challenges are far more daunting than one limited to the electricity sector. However, according to some renewable advocates, the challenges are not technical or economic, but political. In responding to critics of 100% renewable scenarios, Diesendorf and Elliston (2018) not only indicate their strong optimism, but also point to what they believe is the real barrier to achieving their vision:

> The principal barriers that are slowing the transition are the political power of the incumbent fossil fuel, nuclear and electricity industries, bolstered by misinformation disseminated by RE critics, and existing institutions such as market rules that are inappropriate for climate mitigation and discourage RE and flexible, dispatchable power stations.

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[13] NREL currently estimates a 25- to 40-year useful life for solar PV (National Renewable Energy Laboratory n.d.), noting that high temperatures (due to climate or rooftop installation) will likely result in shorter lifetimes (Mow 2018). A recent NREL study of the projected lifetimes of current lithium storage batteries concluded: "Without active thermal management, 7 years lifetime is possible provided the battery is cycled within a restricted 47% DOD [depth-of-discharge] operating range. With active thermal management, 10 years lifetime is possible provided the battery is cycled within a restricted 54% operating range." Thermal management requires keeping battery temperatures at 20 to 30°C year-round. See: Smith et al. 2017. One can expect, of course, technological improvements over time, but the pace and magnitude are always uncertain. The LUT study implicitly asks the reader to invest very heavily in solar PV and to count on the improvements it envisions. That is a narrow, relatively risky portfolio.

THE RIDDLE OF LOW-COST RENEWABLES & HIGH-COST ELECTRICITY SYSTEMS

The notion that the principal barriers to achieving 100% renewable power systems are "political" and "institutional" in nature is rooted in the belief that wind and solar have become the cheapest sources of electricity. This belief is reinforced in much of the climate and clean energy trade press and blogosphere with recent headlines such as "Wind Is Cheapest, Followed by Solar"[14] and "Renewables Can Challenge Existing Coal Plants on Price."[15]

If wind and solar PV are now "the cheapest" sources of electricity, why would one ever want to build another fossil fuel or nuclear plant? This is the riddle of "low-cost" solar and wind generation but "high-cost" 100% renewable scenarios. This section provides a layman's guide to understanding the answer: total electricity system costs increase *nonlinearly* as the percentage of renewable generation crosses certain thresholds. Wider understanding of why this happens is essential to building support for a broad portfolio of low- and zero-carbon energy sources.

But first the good news: through a combination of public and private R&D, supportive policies, and achievement of economies of scale, wind and solar PV costs have decreased dramatically over the past nine years, as measured by the cost metric of "Levelized Cost of Energy" (LCOE). The LCOE per MWh decreased by nearly 70% for wind and by nearly 90% for utility-scale solar photovoltaics (Lazard 2018).

With these decreases, wind and solar PV are now arguably the least expensive incremental source of new electricity in some parts of the United States. Customer demand for renewable or "green" electricity can now be met at a fraction of the cost ten years ago. However, solving the riddle above requires a full understanding of the LCOE metric and its limitations, and how average costs for an individual plant are quite different from the average cost of an electricity system made up of many plants.

LCOE estimates the average cost of a MWh of electricity produced by a generating source. However, LCOE does *not* take into account any interactions with the electricity system as a whole. For example, LCOE doesn't indicate the extent to which a particular technology/fuel resource is dispatched and actually ends up producing electricity at different times of day or seasons of the year.

One of the most widely cited sources of electricity costs is Lazard's *Levelized Cost of Energy Analysis*, published annually since 2008. Lazard's latest LCOE estimates of new plants are (Lazard 2018):

- Wind: $29–$56 per MWh
- Solar PV: $26–$46 per MWh (utility scale)
- Natural Gas Combined Cycle: $41–$74 per MWh (lower than coal or nuclear)

Lazard is always careful to put caveats in its reports on the limitations of the LCOE metric, but these rarely get

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[14] See: Inside Climate News n.d.

[15] See: Bade 2018.

attention in the trade press, especially if the intended narrative is "renewables are the cheapest."

UNDERSTANDING LCOE LIMITATIONS

LCOE is estimated for a "stand-alone" generating source and thus doesn't reflect the system-level cost implications of any technology (nor does it capture externalities such as pollution impacts). For example, LCOE does not take account of how power plants differ in their ability to vary their output to follow load. Baseload coal and nuclear plants have very limited ability to follow load, in contrast to gas plants that can ramp their output up and down far more easily. Wind and solar cannot follow load and have highly variable output depending on time of day and weather. Plants than can follow load provide more value to the system. And this measurement is not captured in the LCOE metric.

For variable renewables, LCOE typically does not include "integration requirements" (or "balancing requirements") that ensure these variable sources of electricity contribute to a reliable grid. Currently, integration is achieved for the most part by dispatching natural gas-powered plants when renewable output falls, though many utilities are beginning to add batteries for storage and for provision of frequency regulation and other ancillary services (taking advantage of their instant dispatch capability).[16]

Other integration methods for variable renewables fall into three main categories:

1. Expansion of transmission systems that effectively pool renewable production from a larger geographic area, hence reducing the variability in output.
2. Load-shifting or "demand response" that moves the load to times when the sun is shining and/or the wind is blowing.
3. Storage of electricity or thermal energy that allows demand to be met regardless of the renewable output at that moment.

Integration requirements depend on many factors including how much renewable energy is already in the system. Integration requirements are minimal at very low penetrations of solar and wind. However, they become very noticeable at just 15% variable renewable penetration, as illustrated by the "Duck Curve" in California.[17] Solar production drops rapidly near sunset, and California must quickly ramp up other generating sources to fill the gap.

All credible modeling indicates that integration requirements increase as the penetration of variable renewables increases, and that the cost of integration requirements turns *non-linear* at some high penetration level. The corollary point is that the *value* of variable renewables decreases as penetration increases, because less and less of the renewables will be supplied during peak hours (and thus cannot contribute to system reliability). This is a "diminishing returns" phenomenon from both an economic and greenhouse gas reduction point of view.

The point at which costs increase in a sharp, non-linear fashion (as the percentage of renewables grows) will dependent on specific characteristics of the electricity grid and how integration requirements are met. If modelers make certain assumptions on integration methods and costs, they can envision power grids with very high percentages of variable renewables. Various credible modeling studies of a generation mix of 80% to 90% wind and solar suggest that these *could* be technically feasible, and that the cost of electricity *could* remain reasonable.

As noted earlier, a small group of modelers argue that entire grids, or even entire economies, could be supplied with 100% renewable energy. These modelers assume that various technologies and systems will emerge at reasonable cost in coming years, so that a 100% renewable system will be able produce electricity at all times of day, every day of the year, and under extreme weather conditions. However, in this modeling of power systems with very high renewable shares, many assumptions need to "turn out right" in order to maintain

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[16] Dispatchable power plants with 100% carbon capture or that use a zero-carbon fuel made from electricity (e.g., hydrogen, ammonia, or synthetic methane) could also play this role. Again, significant technical and economic hurdles remain on the path to major production of such zero-carbon fuels.

[17] See: NREL 2018.

a reliable grid and keep electricity costs affordable.[18] Key assumptions relate to the three integration methods noted above. If those assumptions "turn out wrong" then the cost of electricity could soar and reliability problems could emerge.

Transmission. There are no technical or feasibility issues with expanding the transmission system, and it is typically a relatively low-cost integration strategy. The obstacle is balkanized decision-making and political opposition to new transmission lines. An expanded, truly national transmission system faces these significant obstacles, but should be pursued. Without it, the U.S. cannot fully tap into the low-cost wind resources of the Great Plains states or the low-cost solar resources of the Southwest and transmit that renewable power to major load centers.

Load Shifting or Demand Response. Utilities and regional grid operators have applied a variety of programs and pricing structures that have succeeded in shifting modest amounts of load, typically from on-peak to off-peak hours. Jacobson (2015) assumes that flexible load could constitute 75% of total load. However, there is simply no track record in any country of shifting loads of such magnitudes, nor is there a reliable basis to gauge costs or customer acceptance.

Storage. Storage can take many forms and provide many functions. Batteries can provide short power bursts (to maintain frequency response) and hours of electricity to balance the variable output of renewable energy. Pumped hydro and ice chillers can provide "night-to-day" shifting, to decrease peak power needs. Some modelers envision very low-cost batteries or thermal storage that could provide hours, days, or even weeks of storage to address the different time scales of variation in renewable energy. Scenarios of 100% renewables in the U.S. would require weeks of storage of U.S. electricity demand (Shaner et al. 2018).[19] This *might* become feasible, but storage technologies have multiple technical and economic hurdles.

In sum, there are big unknowns related to each of the three types of integration methods, and they include technical, economic, political, and behavioral unknowns. If the assumptions that various modelers make on integration methods "turn out right," grids may be able to have very high percentages of renewables and keep electricity reliable and affordable. If some assumptions "turn out wrong," models predict that reliability challenges and large cost increases could occur well below 100% renewables.

WHY ELECTRICITY COSTS WOULD GO NON-LINEAR AT HIGH PENETRATION OF RENEWABLES

There are two main factors that would push costs to extreme levels:

Diminishing Returns on Storage Investment. Assuming that a grid has maximized its integration options through transmission and load shifting, grid operators would turn increasingly to storage. Initial investments in storage would account for the daily, predictable variations in solar output. These investments would bring value 365 days per year in their daily cycles of charging and discharging. To add more renewables to displace more and more nonrenewable sources, grid operators would have to use storage to back up renewables for more infrequent events and less predictable events (in contrast to the daily cycle of solar input). Investments in storage would have to cover seasonal variation in output of wind and solar, and inter-annual variations in the same. Finally, investments in storage would have to cover infrequent, random weather events that cause solar and wind output to plummet for days or weeks.

Storage costs consist of nearly all fixed capital costs and few operating costs. As the percentage of renewables on the system increases, storage would be called on to cover less and less frequent events, and the capital costs of storage would be delivering fewer MWh of electricity. Thus investments in storage face sharply diminishing returns.

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[18] In economists' terminology, variable renewable electricity is an input to the output of a 24/7 reliability electrical grid. The cost curve of that grid is likely to become sharply convex as renewables approach 100% of the generating mix. Under some specific optimistic assumptions, this might be avoided, but again the key question turns on a broad versus narrow portfolio of climate solutions, all of which carry some uncertainty.

[19] Shaner et al. (2018) estimate the capital cost of 3 weeks of battery storage at $26 trillion. The Jenkins and Thernstrom (2017) literature review suggests 8 to 16 weeks would be needed.

The traditional solution to this problem, of course, is a relatively low-capital-cost dispatchable plant with relatively high operating costs (i.e. fuel). If zero-carbon fuels (e.g., hydrogen) can be developed at reasonable cost, then zero-carbon dispatchable plants can provide the solution.[20] A similar solution could come in the form of gas with CCS technology that allows 100% capture of CO_2.[21]

Overgeneration. As more and more variable wind and solar are added to a grid, more of that electricity would simply be wasted. This is typically labeled "overgeneration" or "curtailment." This is electricity that is not coincident with any remaining demand and can't be stored. When this happens, some of the capital costs of the renewables would add to overall system costs but would not produce electricity that is consumed, and thus the overall cost of electricity would increase.

To keep a grid reliable, when it is heavily dependent on variable wind and solar and little or no dispatchable electricity, a grid operator would have to choose some combination of massive investments in storage (where every incremental investment provides less and less value) and massive overbuilding of wind and solar capacity (that partially makes up for the periods of low output while overgenerating and wasting electricity at periods of high output).[22]

None of the arguments above are intended to diminish the challenges that the alternatives to renewable electricity face. Nuclear (existing and new) and CCS face their own sets of technical, economic, and political challenges and unknowns. The argument here is that it is prudent to invest in, create, and maintain a diversified portfolio of low- and zero-carbon options, and *not* place all our "betting chips" on renewables.

NON-LINEAR COSTS: AN ILLUSTRATION

A good illustration of overgeneration and non-linear costs is provided by Frew et al. (2016). This study models least-cost generation mixes and examines the impact of increasing penetration of renewables for the U.S. electricity grid, corresponding to national Renewable Portfolio Standards (RPS) of 20, 40, 60, 80, and 100 percent. The study models six scenarios for each RPS, with variations related to transmission expansion, growth in plug-in electric vehicles (PEVs), and a with path-dependent feature (Figure 6).

The results for the six scenarios cluster into two groups. One group of two scenarios (labeled "Indep." and "Indep. PEV" in Figure 6) assumes the U.S. transmission system will be as it is now, with limited inter-regional connection. The other group (consisting of the other four scenarios) assumes a significantly expanded transmission system with inter-regional connections that allow regions rich in wind and solar to export to other regions. This system also promotes integration of variable renewables in general by effectively pooling renewable production from large geographic areas, hence reducing variability in output. The summary below describes the results for both groups of scenarios.

The key results of the modeling are presented on the two vertical axes of Figure 6. The left axis shows the total annual system cost (in billions of dollars, indicated by stacked bar graphs with bar segments indicating cost of generation sources, transmission, storage). The right axis shows the amount of total annual overgeneration (in billions of TWh, indicated by black diamonds). The dotted blue lines in Figure 6 are added here to highlight battery storage costs, and are not in the original.

In the first group of scenarios (assuming the existing transmission system), costs are fairly constant for a 20% and 40% RPS, but begin to escalate at 60%. Total annual costs go from $250 to $300 billion per year (2006$) to over $400 billion at 60%. Overgeneration goes from near zero to roughly 200 TWh/year at 60%. Costs increase nonlinearly at 80% and 100% RPS, increasing to roughly $700 billion per year (80% RPS) and then to $1.2 trillion per year (100% RPS).

Overgeneration follows a similar pattern, increasing to over 400 TWH per year (80% RPS) and then to over

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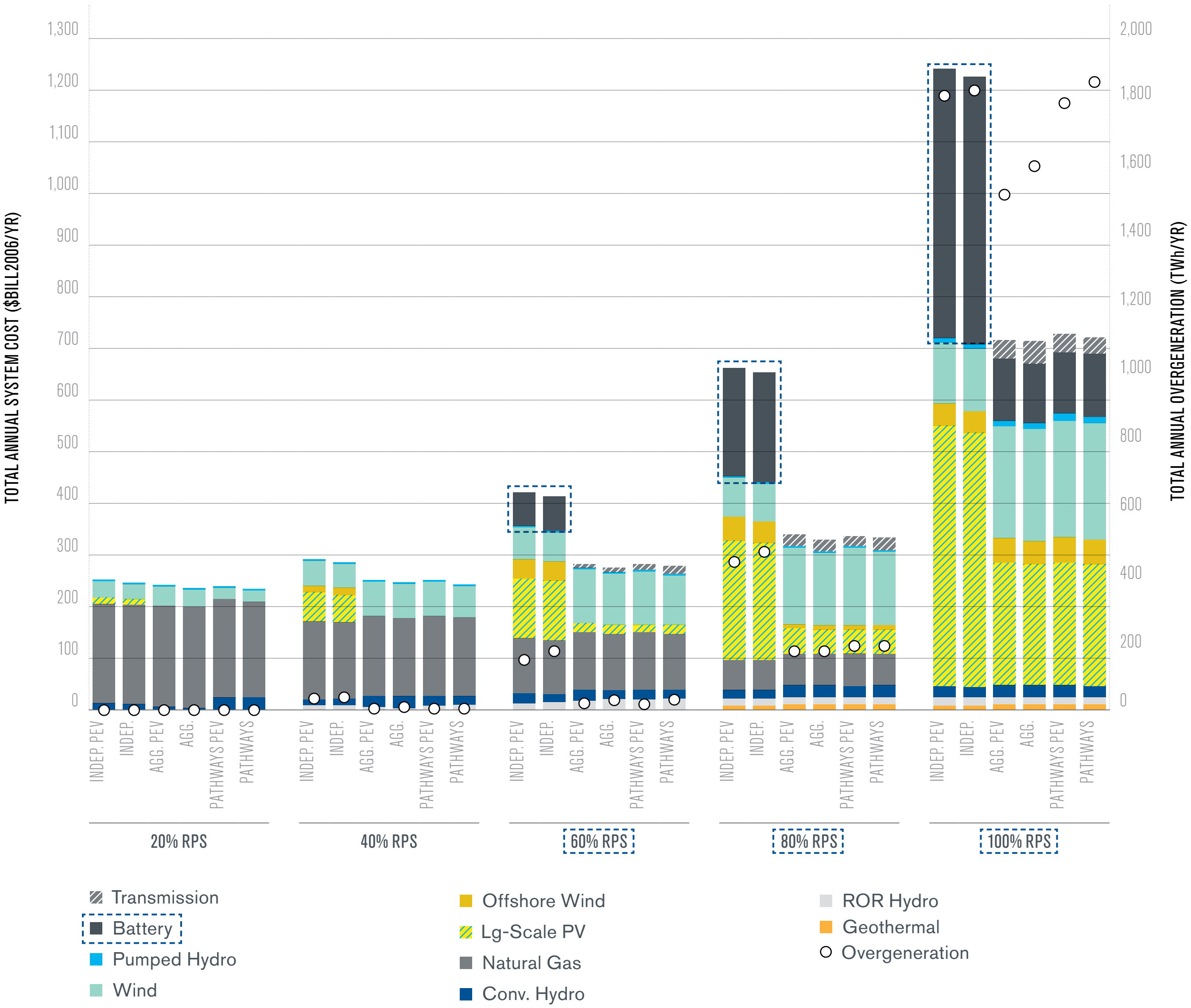
[20] See Teske 2019 for a recent 100% renewable modeling effort that assumes a large role for hydrogen.

[21] See: NetPower n.d. and Roberts 2018.

[22] For an example of trading off storage and overbuilding, see: Weaver 2018.

FIGURE 6: IMPACTS OF 20% TO 100% RPS ON U.S. SYSTEM COSTS AS MODELED IN FREW ET AL. 2016 *(DOTTED BLUE LINES NOT IN ORIGINAL)*



Additional supply options appeared in the original legend, but the modeled scenarios included no or negligible role for them, hence they are not represented in the bar graphs. These options were: concentrated solar power, residential PV, coal, and nuclear.

1,800 TWh per year (100% RPS). Battery storage is a key driver of cost increases, as highlighted in the dotted blue lines. At 100% RPS, battery storage grows to nearly half of total annual cost. The message here is that, without effective use of transmission as an integration strategy and with strong dependence on storage for integration, electricity costs could begin sharp escalation with as low as 60% renewable penetration.[23]

In the second group of scenarios (assuming expansion of the U.S. transmission system), costs are remarkably constant up to an 80% RPS. Total annual costs remain in the $250 to $300 billion per year range, escalating slightly at 80%. Overgeneration stays near zero for 20%, 40%, and 60% RPS, and then increases to roughly 200 TWh/year at 80%. However, in the jump from 80% to 100%, costs more than double to over $700 billion per

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[23] The POWER model used in Frew et al. (2016) is a linear programming model that minimizes annual system cost subject to the constraints assumed. As such, the model uses a least-cost set of generation and storage options. It's worth noting that there are large differences in the cost of storage if considered stand alone or in combination with PV at utility scale, and there are significant economies of scale. See: Lazard 2018.

year. Overgeneration increases dramatically to a range of 1,500 to 1,900 TWH per year at 100% RPS. Battery storage is again a key driver of cost increases. The corollary here is that with effective use of transmission as an integration strategy, electricity costs could remain fairly stable up to 80% renewable penetration.

The nonlinear increase in system costs indicated in Frew et al. (2016) is consistent with the findings of similar modeling studies that deliberately explore different shares of variable renewables, and the impacts on integration costs and total system costs. See for example Shaner et al. (2017), Platt et al. (2017), and Sepulveda et al. (2018). The nonlinearity in costs can be dampened, as noted above, by transmission expansion, successful large-scale load shifting, and by substantial decreases in storage. However, the challenges posed by the underlying variable nature of wind and solar power never disappear.

> Without effective use of transmission as an integration strategy and with strong dependence on storage for integration, electricity costs could begin sharp escalation with as low as 60 percent renewable penetration.[23]

POLICY POSITIONING ON DECARBONIZING THE ELECTRICITY SECTOR

Policymakers are staking out various positions on strategies for decarbonizing the electricity sector with regard to supporting 100% renewables versus all zero- and low-carbon options. Some actors in this arena appear to avoid clear positions as a deliberate tactic for coalition-building.[24] Effective coalitions are clearly needed to move forward in the face of powerful forces that continue to oppose serious action on the issue.

SUPPORTERS OF 100% RENEWABLES

At the federal level in 2016, Senator Markey and several co-sponsors tried to advance Senate Resolution 632 calling for a 2050 national goal of transitioning to 100% renewable electricity. In 2017, Rep. Gabbard introduced legislation that would require 100% renewable electricity nationwide by 2035 and aggressively electrify transport. The bill gathered 45 co-sponsors. Both the resolution and the legislation employed the phrase “clean energy” but also clearly limited its meaning to renewable. The outcome of the November 2018 election clearly bolstered the numbers and influence of the progressive wing of the Democratic party. Early versions of a “Green New Deal” floated in the fall of 2018 would have required 100% renewable electricity within a 10-year timeframe, along with other objectives.[25] However, the final text of the Green New Deal resolution introduced by Rep. Ocasio-Cortez and Sen. Markey called for 100% “clean, renewable, and zero-emission energy sources” thus leaving the door open, in theory, to a role for nuclear and/or CCS.[26]

At the state level, Hawaii passed a law requiring 100% renewable electricity by 2045. The Massachusetts Senate passed a bill by a 35 to 0 vote that sets a goal of 100% renewable electricity by 2035 (and a 100% renewable energy economy-wide goal by 2050).[27] A similar 2035 mandate has been introduced in the Colorado General Assembly and the state’s new governor campaigned on a platform of 100% renewable electricity.[28]

California, long a leader in renewable energy, enacted in 2018 a 60% renewables mandate for 2030, combined with a 100% clean electricity mandate for 2045. The final law allows the state’s substantial large hydro resources to count toward the mandate, and leaves the door open to all zero-carbon sources. Accounts of the bill took an interesting turn, as various advocacy groups claimed the law called for 100% renewable electricity by 2045.[29] Perhaps most revealing is the text on the webpage of the California State Democratic Caucus that touts the new law:

> 100% Clean Energy—Senator de León announces SB100 that puts California on the path to 100% fossil-fuel free electricity by the year 2045. 100% renewable energy means a cleaner and better future for our children.[30]

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[24] This section draws heavily on the author’s decades of first-hand experience in government, NGOs, and consulting in observing and participating in these debates.

[25] See: Final Select Committee for a Green New Deal n.d.

[26] United States Congress 2019.

[27] See: General Court of the Commonwealth of Massachusetts 2018.

[28] See: Colorado General Assembly 2018.

[29] See for example: Sierra Club 2018 and Tseng 2018.

[30] See: California State Senate 2019.

This language neatly blurs any distinction between three types of energy ("clean," "fossil-free," and "renewable") that conceivably could have three separate definitions. Many accounts of the legislation point to some ambiguity and flexibility in what is going to happen by 2045 as a successful tactic in building and maintaining the coalition that carried the law forward.[31]

Often elevating climate to their number one issue, some climate activists support a strategy of 100% renewables coupled with opposition to nuclear power and fossil fuels in general, especially coal and "fracking." They are active in policy processes, lobbying, marches, protests, etc. Responding to consumer sentiment and/or reflecting company values, more and more firms are committing to purchasing 100% renewable electricity, as are cities, universities, and other nonprofit entities. Though some organizations advertise their "carbon neutral" status, a "100% renewable" target and label seems more appealing and is more widely highlighted.

SUPPORTERS OF ZERO-CARBON ELECTRICITY

In addition to the interesting path (and ambiguity) of California's embrace of 100% zero-carbon electricity, a growing number of states are deviating from a focus on simple ratcheting upward of a Renewable Portfolio Standard. Pennsylvania blazed a trail way back in 2004 with its Alternative Energy Credit Program. The AECP has two tiers with 8% and 10% targets respectively. Tier 1 is defined as mostly conventional renewable sources, but Tier 2 defined to include new and existing waste coal, distributed generation, demand-side management, large-scale hydro, municipal solid waste, wood pulping and manufacturing byproducts, and integrated gasification combined cycle coal facilities.[32]

The idea of a broad definition of "clean" that goes beyond renewables is was embodied in national legislation sponsored by then-Sen. Bingaman in 2012. His Clean Energy Standard Act would allow all sources (solar, wind, nuclear, fossil plants with carbon capture and storage, etc.) to be used to meet a flexible standard, and would create a market mechanism to guide the mix of technologies and fuels ultimately used.[33] Some states are contemplating an evolution of an RPS in this direction.

Several states are concerned that nuclear reactors, their largest source of zero-carbon electricity, are being driven to retirement by low natural gas prices and/or market designs that result in chronically low prices and do not account for environmental attributes. New York,[34] New Jersey,[35] and Illinois[36] have created Zero Energy Credits to provide support for existing nuclear plants in their jurisdictions.

Recognizing the important role existing reactors play, the Union of Concerned Scientists (UCS, 2018) issued a report in November 2018 that concluded that more than one-third of existing nuclear plants are uneconomic or slated to close over the next decade. Without new policies, UCS projected that if these and other marginally economic nuclear plants were to close before their licenses expired, natural gas generation would replace most of their output, boosting U.S. CO_2 emissions from the power sector by up to 6% above baseline. UCS concluded that a carbon price or a low-carbon electricity standard (LCES) would be the best option for providing a level playing field for all low-carbon technologies.

On the corporate purchasing side, there are also signs that some leading firms are realizing the limited value of purchasing 100% renewables. In 2016, Google, the largest corporate buyer of renewable electricity, posted a thought-provoking white paper that reviewed its history of purchasing and the new direction the corporation should head to continue the process of decarbonizing the grid (Google 2016). The new direction and underlying rationale are notable:

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[31] See for example: Roberts September 2018.

[32] See: Pennsylvania Public Utility Commission 2018.

[33] See: U.S. Senate Committee on Energy and Natural Resources 2012.

[34] See: New York State n.d.

[35] See: State of New Jersey Board of Public Utilities 2018.

[36] See: Illinois Power Agency 2018.

> [T]here is an upper limit to the portion of intermittent renewable energy that can be effectively integrated on a grid. Over the long term, clean and reliable baseload energy will be a critical component of achieving a truly carbon-neutral electricity grid. Reaching 100% renewable energy purchasing for our operations is an important milestone, and we remain committed to this achievement even as our energy use grows. But to ultimately tackle the emissions associated with our electricity consumption, we need to move beyond our global, annual matching method to ensure that hour by hour our operations are powered by clean energy. A key hurdle here remains the variability of renewable energy technologies like wind and solar. For Google, reaching our 100% goal on a global and annual basis is just the beginning. In addition to continuing to aggressively move forward with renewables like wind and solar, we will work to achieve the greater, longer-term challenge of powering our operations on a region-specific, 24–7 basis with clean, zero-carbon energy. This more ambitious approach is an important next step toward achieving a truly zero-carbon electricity grid. . .
>
> To this end, in complement to our wind and solar purchasing, in the future we may pursue dispatchable, zero-carbon generation energy options for our portfolio. These options could include purchasing energy from technologies like renewables paired with utility-scale energy storage, advanced nuclear power, geothermal energy, low-impact hydro, demand response and energy efficiency resources, or others.

The white paper also included CCS on its list of options for future portfolios. Google expanded on its plans in a second white paper in 2018 (Google).

In a similar signal on emerging corporate buying strategy, WRI's Clean Power Council[37] issued a short paper entitled “Beyond Renewable Energy: New Strategies for Low-Carbon Impact.” The paper shared themes similar to the Google paper:

> [O]ptions that address greenhouse gas (GHG) emissions in the wider energy system represent the next frontier as large buyers pursue substantial commitments to consuming renewable energy. The goal is to measure low-carbon impacts while also promoting renewable energy generation. Recognizing this reality, large buyers and their utility providers are collaborating on new approaches that can guarantee GHG emission reductions. In some cases, the most economical solution with the lowest carbon impact is not a new wind or solar plant for an individual company, but rather a systemwide approach to providing clean energy for multiple customers.
>
> While continued deployment of wind and solar is a cornerstone, other relevant technologies and portfolio approaches need to be on the table. For example, electric vehicles, large batteries, hydroelectric systems, nuclear energy, demand response strategies, etc., all have the potential for providing a high-value contribution to achieving stretch goals for GHG reductions.

If corporate buyers (and/or other buyers) begin to actually follow this type of portfolio strategy, they could have a substantial impact on how the generation mix evolves.

THE CHALLENGE OF BUILDING AND MAINTAINING POLITICAL SUPPORT

With the Democratic party leading on advocating climate mitigation, it faces the task of building and maintaining political support and coalitions to advance policies at the federal, state, and local levels. An important element of that support is the community of climate activists that tends to support a strategy of 100% renewables, often coupled with opposition to nuclear power and fossil fuels. The political strategy that appears to have emerged (and was strengthened by the November 2018 election outcomes) was described well in reporting by *Politico* titled “Democrats embrace ambitious 100 percent clean energy goal”:[38]

> At least six of this year's candidates for governor and a handful of the party's possible presidential contenders are backing proposals to transition the U.S. economy off of coal and oil in the coming decades. While the plans leave plenty of details to be filled in, climate change activists are encouraged to see the idea gaining steam in races across the country. . . Environmentalists say part of the appeal is the goal's aspirational nature. . . There are important differences in the details of the pledges that have been put forward so far, including how quickly to move and what to define as a clean source of energy. In some proposals, existing nuclear power plants and future natural gas plants that capture and bury their carbon emissions count toward clean energy goals. In other places, Democrats say that only truly renewable sources like wind, solar and geothermal should count.

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[37] The World Resources Institute has convened a collaboration among leading U.S. electric utilities and major commercial customers—jointly committed to the rapid deployment of low-carbon energy supply through innovative and mutually beneficial utility sector solutions. See: World Resources Institute n.d.

[38] See: Adragna 2018.

One environmentalist stated to *Politico*: “I think the 100 percent metric is a good target setting and then you can figure out how you get there—each part of the country would probably have to get there a little different way. That type of vision is one that can have pretty broad support from sea to shining sea and all the places in the middle.” Some environmentalists embrace this as a “creative ambiguity” that can hold together supporters of 100% renewables (anti-nuclear, anti-fossil fuels) and supporters of all low-carbon electricity sources.

That type of ambiguity surfaced earlier than 2018, to be sure. In 2017, Sen. Merkley introduced the “100 by ‘50 Act,” a bill to transition the U.S. away from fossil fuel sources of energy to “100 percent clean and renewable energy by 2050.”[39] However, the bill does not explicitly define “clean and renewable energy.” It does explicitly and gradually phase out by 2050 any use of fossil fuel to generate electricity, and that would seem to exclude fossil plants with CCS. The bill text does not contain the word “nuclear” but does not explicitly rule it out.

This somewhat ambiguous bill succeeded in winning the support of environmental, social justice, and labor leaders.[40] Perhaps in a similar spirit, Governor Murphy of New Jersey issued an executive order tasking state agencies to create a new Energy Master Plan providing a “comprehensive blueprint for the total conversion of the State’s energy production profile to 100% clean energy sources.”[41] The order does not define “clean energy,” but it does call for inclusion of wind, solar, and storage. The governor signed the New Jersey ZECs law noted above, so one might infer that nuclear is “clean.” The potential role of CCS in the Energy Master Plan is unknown.

CONCLUDING THOUGHTS

It will take considerable skill to build and maintain the political coalitions needed in the years ahead to strengthen climate mitigation policies at the federal, state, and local levels. Regardless of the tactics used, the policies should be grounded ultimately in the mainstream analysis and modeling summarized here.

Solar and wind are likely to grow and become a major portion of the generation mix in the decades ahead, but power systems dependent 100% on renewables are likely to face reliability and affordability challenges. The level of renewable penetration at which those challenges become significant is impossible to predict now. It will depend on many highly variable factors: the particular power system; the level of transmission interconnection achieved; the role demand response can play; and the role that storage can play.

Our strategies for holding global warming to 1.5 or 2°C should be resilient in the face of the many ways that various integration strategies and zero-carbon technologies could develop, and the multitude of ways that:

- Technical and economic feasibility could change over time (e.g., with R&D and scale-up in production)
- Various political and institutional factors could change over time (e.g., the political acceptability of large-scale renewables deployment, nuclear, CCS, large-scale transmission expansion)

In other words, it’s risky to “bet the climate” on any single set of technologies. The United States should strive to make a broad portfolio of zero-carbon electricity options commercial and available, given the many uncertainties related to the evolution of any single technology. Above all, “clean energy” should be defined as zero-carbon, and not be limited to renewables.

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[39] See: United States Congress April 2017 and companion House bill: United States Congress July 2017.

[40] See: KTVZ 2017.

[41] See: Murphy 2018.

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