# Appendix B: Literature Review of Economy-Wide Deep Decarbonization and Highly Renewable Energy Systems

## For the New York State Energy Research and Development Authority

June 24, 2020

Energy+Environmental Economics

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# 1 Background

As the global average temperature continues to climb to the highest levels in modern history, there is scientific consensus that climate change is threatening our social and economic institutions. The United Nations Intergovernmental Panel on Climate Change (IPCC), whose Fifth Assessment Report (AR5) was written by more than 830 lead authors and 2,000 expert reviewers, has found that global temperature must not increase by more than **1.5 degrees Celsius** above preindustrial levels in order to avert the increasingly damaging, irreversible effects of a changing climate. AR5 also finds that significant climate action is needed globally over the next decade to reach **net-zero greenhouse gas (GHG) emissions by mid-century**.

In response to the latest climate science, New York State passed the Climate Leadership and Community Protection Act (CLCPA) in the 2019 legislative session. Included in the CLCPA are the most aggressive climate targets signed into law in the United States: 40% GHG reductions below 1990 levels by 2030, and carbon neutrality by 2050. The midcentury goal will be accomplished by reducing GHG emissions by at least 85% below 1990 levels with in-state carbon sequestration opportunities meeting or exceeding remaining emissions, resulting in net-zero statewide GHG emissions

The CLCPA also includes specific targets to decarbonize the State's electricity sector, such as:

+ 6 gigawatts (GW) of distributed solar by 2025
+ 70% renewable electricity by 2030
+ 9 GW offshore wind (OSW) by 2035
+ 100% zero-emissions electricity by 2040

To better understand how the State might meet its ambitious targets, the New York State Energy Research and Development Authority (NYSERDA) engaged Energy and Environmental

Economics (E3) to conduct a strategic analysis of New York's decarbonization opportunities. E3 conducted this literature review for the New York State Energy Research and Development Authority (NYSERDA) of journal articles, policy reports, and policy commentary to synthesize findings on the challenges and impacts of pursuing deep decarbonization targets and high levels of renewables across an economy.

This review is divided into six sections. Section 1 is this introduction to the review. The rest of the review proceeds as follows:

+ *Section 1* provides background and objectives of this review
+ *Section 2* introduces the methods used by different analyses in the literature to explore deep decarbonization and highly renewable energy systems.
+ *Section 3* explores the findings of analyses on achieving deep greenhouse gas emission reductions across many sectors of an economy.
+ *Section 4* reviews the findings of these analyses, considering the challenges of targeting very high levels of delivered renewable electricity generation.
+ *Section 5* explores the additional challenges of achieving carbon neutrality economy-wide.
+ *Section 6* provides a summary of unanswered questions and conclusions relevant for New York State.

# 2 Methods for deep decarbonization and highly renewable systems

In this section, we review methods used by studies considering renewable electricity along with general climate mitigation strategies at the state or national level. These studies investigate three different kinds of policy goals, detailed below.

**(1) Economy-wide decarbonization**

These studies focus on achieving long-term decarbonization across the economy approximately consistent with the IPCC climate stabilization target of 80% reductions in GHGs below 1990 levels by 2050.[1] They typically model technologies that represent both the energy demand and supply systems and focus on economic trade-offs between mitigation options in different sectors. They also include interactions between mitigation strategies, such as electrification and decarbonized electricity. Decarbonized energy sources may include fossil with carbon capture and sequestration (CCS) and nuclear power as well as renewables. Non-energy GHGs are typically accounted for but with a lower degree of detail. Studies here are based on models ranging from simple models of the macroeconomy and energy system to specialized GHG mitigation

[1] The 80% target corresponds to about 2 (metric) tons $CO_2$-equivalent per year per capita by 2050. This target is estimated to provide a mean likelihood of avoiding greater than 2°C global mean temperature rise relative to pre-industrial, interpreted as the threshold for "dangerous anthropogenic interference" in the climate system (IPPC, n.d.; IPCC 2014). The 2015 Paris agreement also identified a stricter target of less than 1.5°C global mean temperature increase, which recent studies have estimated as consistent with achieving net-zero GHG emissions by 2050 if large negative emissions requirements are to be avoided after 2050 (Blok, Terlouw, and van Exter 2018; van Vuuren et al. 2018). This is the subject of the draft IPCC special report (**http://www.ipcc.ch/report/sr15/**).

optimization tools that include a thorough representation of energy demand and supply, with a detailed treatment of electricity.

**(2) Decarbonized electricity and high-renewable electricity**

These studies investigate the technical challenges associated with achieving high levels of renewables in the electricity system, including accessing sufficient energy resources, meeting operational constraints, and maintaining reliability. They sometimes focus on Renewable Portfolio Standard (RPS) policies, which target meeting certain percentages of end-use electricity with renewable energy. Studies here utilize models with a wide range in complexity, from simple tools that estimate resource costs, to full capacity expansion models with robust power systems modeling including power system dispatch and transmission constraints along with cost optimization.

**(3) Economy-wide renewable energy**

Some researchers are investigating the possibility of achieving 100% renewable energy across the economy. This goal is partially motivated by the need to eventually bring fossil energy GHG emissions to zero to achieve climate stabilization. However, this goal is stricter than those focusing only on energy GHG emissions, as it excludes non-renewable energy sources like nuclear and fossil with CCS.

Table 1 lists the studies reviewed in this analysis, which include both primary modeling studies and review articles.

**Table 1. Primary studies reviewed in this analysis**

| Study | Jurisdiction | Model (if any) | Summary of goals |
|---|---|---|---|
| *I. Economy-wide decarbonization studies* | | | |
| 1. (L. E. Clarke et al. 2014) | US | *Multiple* | 80% GHG reduction below 2005 levels by 2050 |

| | | | |
|---|---|---|---|
| 2. (Haley, Kwok, and Jones 2016) | Washington | PATHWAYS | 80% GHG reduction below 1990 levels by 2050 |
| 3. (Krey et al. 2014) | Multiple | *Multiple* | Decarbonization scenarios for 450 to 550 ppm $CO_2$ |
| 4. (Mahone et al. 2015) | California | PATHWAYS | 80% GHG reduction below 1990 levels by 2050 |
| 5. (Mahone, Subin, Kahn-Lang, et al. 2018) | California | PATHWAYS | 80% GHG reduction below 1990 levels by 2050 |
| 6. (Ribera and Sachs 2015) | International | *Multiple* | 80% GHG reduction below 1990 levels by 2050 for sixteen countries |
| 7. (The White House 2016) | US | NEMS, GCAM | 80% GHG reduction below 2005 levels by 2050 |
| 8. (Wei et al. 2014) | California | SWITCH | 80% GHG reduction below 1990 levels by 2050 |
| 9. (Williams, Haley, *et al.*, 2015) | US | PATHWAYS | 80% GHG reduction below 1990 levels by 2050 |
| 10. (Yang et al. 2016) | California | CA-TIMES | 80% GHG reduction below 1990 levels by 2050 |
| 11. (National Grid 2018) | Northeast | *Unspecified* | 80% GHG reduction below 1990 levels by 2050 |
| 12. (J.H. Williams et al. 2018) | Northeast | EnergyPATHWAYS | 80% GHG reduction below 1990 levels by 2050 |
| *II. Decarbonized electricity and high renewable electricity studies* | | | |
| 13. (Becker et al. 2014) | US | Analysis-specific modeling | Optimal mix of wind and solar for 100% renewable generation |
| 14. (Gillespie, Grieve, and Sorrell 2015) | Britain | BERIC | 50-100 kg $CO_2$ per MWh for 2030 |
| 15. (Brick and Thernstrom 2016) | California, Wisconsin, & Germany | *Unspecified* | Case studies of high wind & solar |
| 16. (Brinkman 2015) | WECC | NREL ReEds | Up to 90% renewable generation |
| 17. (Elliston, MacGill, and Diesendorf 2013) | Australia | Analysis-specific modeling | 100% renewable generation by 2030 |
| 18. (Frew et al. 2016) | US | POWER | 20 to 100% RPS |
| 19. (Jenkins and Thernstrom 2017) | N/A | *Review* | Reviews 30 high renewables studies with a focus on costs |
| 20. (Jenkins, Luke, and Thernstrom 2018) | US | *Review* | Reviews 40 electricity decarbonization studies to highlight role of firm low-carbon resources |

| | | | |
|---|---|---|---|
| 21. (MacDonald et al. 2016) | US | NEWS | 80% GHG reduction below 1990 levels for electricity |
| 22. (Mai et al. 2014) | US | NREL ReEds | 80% renewable generation |
| 23. (Mileva et al. 2016) | WECC | SWITCH | 85% GHG reduction below 1990 levels for electricity |
| 24. (Ming et al. 2019) | California | RESOLVE | Up to 100% renewable electricity |
| 25. (Olson et al. 2017) | Pacific Northwest | RESOLVE | Up to 100% renewable or decarbonized electricity |
| 26. (Orans et al. 2016) | Hawaii | RESOLVE | 100% RPS by 2045 |
| 27. (Pierpont et al. 2017) | *Multiple* | *Review* | 80-90% renewable generation case studies |
| 28. (Platt, Pritchard, and Bryant 2017) | California | DOSCOE | Idealized cost estimates for up to 100% zero-carbon electricity |
| 29. (Pleßmann and Blechinger 2017) | European Union | elesplan-m | 98.4% GHG reduction below 1990 levels for electricity |
| 30. (Sepulveda et al. 2018) | US | GenX | 100% carbon-free power with and without firm low-carbon generation |
| 31. (Clune, Noffsinger, and Tai 2019) | New York | *Unspecified* | 100% zero-emissions electricity by 2040 |
| *III. Economy-wide renewable energy studies* | | | |
| 32. (Connolly and Mathiesen 2014) | Ireland | EnergyPLAN | 100% renewable energy by 2050 |
| 33. (Jacobson *et al.*, 2015) | US | LOADMATCH | 100% wind, water, and solar (WWS) by 2050 |
| 34. (Jacobson et al. 2013) | New York | LOADMATCH | 100% wind, water, and solar (WWS) by 2030 |

Most modeling studies across the three categories include some representation of the electricity system as well as a consideration of cost impacts. In addition to the policy goal itself, important differences among the studies that may affect their conclusions include:

- **Level of detail for electricity system representation**: is there an electricity dispatch model that balances generation and storage resources with load every hour for a representative year? Are transmission constraints considered?
- **Level of renewable energy in electricity generation**: for studies assessing high renewable electricity, scenarios range from 80% to 100%.

+ **Geographic specificity**: is the analysis tailored for a specific geographic region? Are resources such as electricity imports or supply of bioenergy made available from other regions? Are local physical resource limits considered?
+ **Transmission infrastructure**: is there a large upgrade of transmission infrastructure to allow transport of intermittent renewable electricity over long distances spanning multiple states or countries?
+ **Availability of firm, zero-carbon resources**: are baseload or firm decarbonized resources available? These could include nonrenewable resources such as nuclear or fossil with CCS, or reliance on extensive hydroelectric capacity.
+ **Utilization of bioenergy**: does bioenergy make a substantial contribution to the primary energy supply, either as dispatchable zero-carbon electricity generation or as biofuels that displace fossil energy consumption in end-uses that are difficult to electrify? If so, what limits on biomass availability are assumed?
+ **Inclusion of advanced renewable integration solutions**: are advanced solutions such as extensive flexible loads and flexible electrolysis for hydrogen fuel production assumed?
+ **Philosophy towards technological innovation**: how strong is the reliance on technologies that are not widely available or commercially proven?

These questions will play a key role in the following sections.

# 3 Deep decarbonization

## 3.1 Overview

Comprehensive assessments of country-wide GHG emissions reduction date back at least a decade (L. Clarke et al. 2007), with extensive modeling undertaken prior to the landmark 2015 Paris agreement. In 2014, the Energy Modeling Forum (EMF) 24 explored the technology options and macroeconomic costs of US decarbonization pathways (L. E. Clarke et al. 2014). Despite requiring "a dramatic transformation of the energy system over the next 40 years," the EMF 24 found costs to be on the order of 1% of gross domestic product (GDP), with varying predictions associated with different models and different technology assumptions.

The EMF was followed by the Deep Decarbonization Pathways Project (DDPP) (Ribera and Sachs 2015): sixteen country teams, representing over 70% of global emissions, modeled pathways to reduce emissions to under 2 tons per capita by 2050.[2] The 2015 Paris Agreement further invited countries to develop "mid-century, long-term low greenhouse gas emission development strategies" (The White House 2016).

Following the DDPP and the 2015 Paris Agreement, "deep decarbonization" assessments have targeted approximately 80% GHG emission reductions below 1990 levels by 2050. All GHG emissions across all sectors of the economy are included: $CO_2$ emissions from the consumption of fossil fuels for buildings, transportation, industry, and electricity generation, in addition to other GHG emissions.[3]

[2] Country teams included: Australia, Brazil, Canada, China, France, Germany, India, Indonesia, Italy, Japan, Mexico, Russia, South Africa, South Korea, the United Kingdom, and the United States.

[3] $CO_2$ emissions associated with fossil fuel combustion represent the dominant anthropogenic forcing on the climate system and are the focus of this review. Other atmospheric forcings include $CO_2$ from land use change, additional well-mixed GHGs [$CH_4$, $N_2O$, and fluorinated gases such as ozone-depleting substances (ODS) and their substitutes], and shorter-lived forcing agents such as black carbon and aerosols. See IPCC (2013) for a comprehensive treatment.

Across different regions studied, common themes emerge regarding the strategies necessary to mitigate GHG emissions. The DDPP synthesis found that deep decarbonization of the energy system "rests on three pillars. All pathways incorporate, at scale, energy efficiency and conservation, decarbonization of fuels and electricity, and the switch to low-carbon energy" (Ribera and Sachs 2015). The various DDPP country strategies all assumed improved vehicle, building, and industrial efficiency. Each resulted in a very low emission intensity for electricity generation, though they varied in terms of their reliance on the three main sources of zero-carbon energy: (a) renewable electricity and bioenergy, (b) nuclear power, and (c) fossil energy with CCS. The large progress assumed in electricity decarbonization compensated for reduced decarbonization in transportation and industry, due to the difficulty of completely switching to electric or hydrogen final energy sources in these sectors. In many scenarios, biofuels helped displace remaining fossil energy in these sectors.

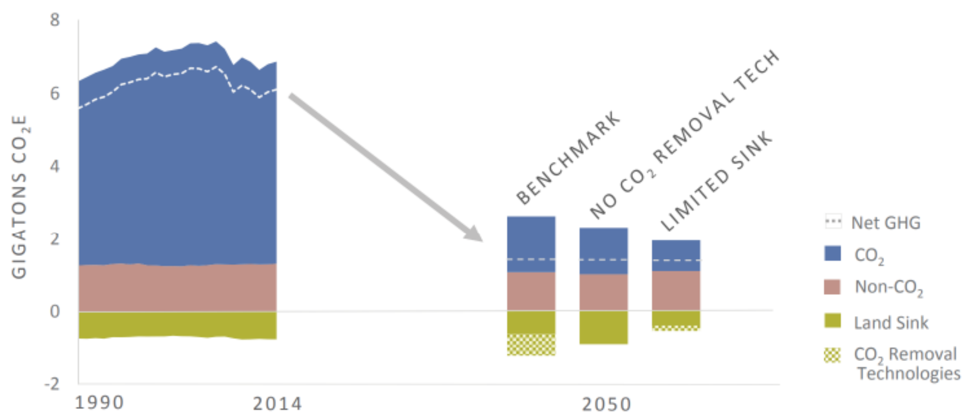
As noted in Jenkins and Thornstrom (2017), "deep decarbonization may require a significantly different mix of resources than more modest goals; long-term planning is important to avoid lock-in of suboptimal resources." For instance, reliance on fuel switching from coal or petroleum fuels to natural gas would be a very low-cost short-term mitigation strategy, but it may not help with deeper emissions reductions and could even be counter-productive if it delayed progress on more robust strategies or resulted in forced early retirements.

The United States Mid-Century Strategy (MCS) for Deep Decarbonization, filed as part of the U.S. commitment under the Paris Agreement of the UNFCCC, emphasized the same three pillars for reducing GHG emissions from the energy system (The White House 2016). In addition to energy-system GHG reductions, it also highlighted the need to reduce net non-combustion GHG emissions by enhancing $CO_2$ sequestration in soils and forests and reducing emissions of non-$CO_2$ GHGs. The MCS noted that US energy-related emissions had decreased by 9% between 2008 and 2016,[4] but were still well above 1990 levels. The MCS assumed that

[4] Attribution for this decrease is the subject of current research, with reduced economic growth following the 2008-2009 recession and market-driven substitution of natural gas for coal in electricity generation likely being the dominant factors.

both enhanced biogenic sequestration and active $CO_2$ removal would lessen the burden of emissions reductions for the energy system (Figure 1).

**Figure 1. Historical emissions and deep decarbonization scenarios considered by the US Mid-Century Strategy** (The White House 2016)**.**




*Multiple pathways to 80 percent GHG reductions by 2050 are achievable through large reductions in energy $CO_2$ emissions, smaller reductions in non-$CO_2$ emissions, and delivering negative emissions from land and $CO_2$ removal technologies. Note: "No $CO_2$ removal tech" assumes no availability of negative emissions technologies like BECCS.*

## 3.2 Costs

The DDPP and subsequent deep decarbonization studies reviewed here share a common philosophy, where the pathways explored are intended to have three features: (a) preserving existing lifestyles without large changes in behavioral conservation, (b) avoiding a large burden on the economy, and (c) emphasizing reliance upon proven technologies rather than speculative ones[5]. With these goals in mind, the DDPP concluded that, across a variety of countries, decarbonization was indeed compatible with economic growth. Most US studies have found that reaching the target of 80% below 1990 levels by 2050 would place a minimal

[5] "Deep decarbonization can be achieved in the U.S. using existing commercial and near-commercial technologies, and does not require deployment of technologies that are currently in an early stage of development including Gen IV nuclear, deep offshore wind, advanced geothermal, advanced cellulosic ethanol, advanced biodiesel, or CCS with greater than 90% capture rate. While these could help facilitate the transition, they are not necessary conditions for it." (Williams, Haley, *et al.*, 2015)

burden on the economy amounting to less than 1 percent of GDP (James H. Williams et al. 2015; Mahone et al. 2015; Haley, Kwok, and Jones 2016; Yang et al. 2016; Mahone, Subin, Kahn-Lang, et al. 2018).

Predictions of future mitigation costs are very uncertain and pose difficulties for models. The California-TIMES study, which included extensive macroeconomic modeling, also included a *Monte Carlo* uncertainty analysis (Yang et al. 2016). The base scenario following California's current policy trajectory through 2050 predicted a cumulative, undiscounted mitigation cost of $33B, or $10/ton of $CO_2$-equivalent ($CO_2e$). In an ensemble of over 1000 individual simulations with different assumptions and parameter sets, the mitigation cost clustered around the base scenario, never exceeding the equivalent of 1% of GDP. According to Yang et al. (2016), one of the biggest sources of cost uncertainty is projected fossil fuel prices, as new capital investments are partially offset by cost savings from reduced fuel use in these scenarios. This same dynamic has been widely found in other studies [e.g., Mahone et al. (2018)]. Expected costs of key mitigation technologies such as batteries represent a second major source of uncertainty (Yang et al. 2016), with scenarios assuming technology "optimism" vs. "pessimism" varying by a factor of 2 or more in net costs (L. E. Clarke et al. 2014). When considering social costs of carbon and air quality benefits in addition to the direct costs of infrastructure, operations, maintenance, and fuel, some scenarios or sensitivities have found the possibility of decarbonization strategies being lower cost than reference scenarios (Mahone, Subin, Kahn-Lang, et al. 2018; Alexander et al. 2019).

The relatively small economy-wide net mitigation costs mask large flows throughout the economy with disparate impacts on individual households and businesses. Because some households may spend a disproportionate amount of income on fuel-intensive goods and services, or may lack access to credit needed to take advantage of capital-intensive energy efficiency or fuel-switching opportunities, careful policy implementation should consider equity and avoid undue burdens on disadvantaged communities (James H. Williams, Haley, and Jones 2015). These technology-agnostic policy implications are reviewed in E3 (2017).

Consumer decision-making plays a large implicit role in these scenarios that has yet to be fully explored in the literature: consumer-facing technologies providing efficiency and fuel-switching opportunities rely on consumer adoption. This represents an implementation challenge and a source of uncertainty distinct from those associated with technology efficiency and cost attributes. For example, the California-TIMES study attempted to quantify some of the impacts of consumer preferences on technology adoption choices, which limited the uptake of all-electric cars in some scenarios (Yang et al. 2016). However, more research is needed to better understand the social factors that may drive or impede low-carbon energy system transition.

## 3.3 Challenges for decarbonizing end-uses

Given the three scenario features highlighted at the beginning of Section 3.2 (maintaining lifestyles and avoiding large economic costs or reliance on speculative technologies), the fuel-switching pillar — converting from fossil end-uses to electric or electricity-derived fuels – is typically found to be one of the most challenging. Challenges to electrifying buildings include technology barriers to heat pump adoption, market barriers as consumers and contractors are unfamiliar with heat pump technologies, potential expense of retrofitting buildings for electric appliances, and consumer preferences for other technologies such as natural gas furnaces or stoves; these challenges can be at least partly mitigated, for example by installing highly efficient cold climate heat pumps or heat pumps with fossil backup to reduce peak load impacts (Energy and Environmental Economics Inc. 2017; Mai et al., n.d.; Energy and Environmental Economics Inc. 2018).

When considering transportation and industrial end uses, particularly difficult are the conversion of internal combustion vehicles to fully electric vehicles and the displacement of fuels consumed for process heating in industry. Mobile end-uses are difficult to electrify because liquid and gaseous fuels (combined with an internal combustion engine [ICE] or jet engine) are still unsurpassed in their energy and power density, exceeding those of batteries by more than an order of magnitude.[6] Light-duty battery-electric vehicles (BEVs), electric buses, and electric short-haul freight vehicles are now becoming commercially viable, but they still have range and refueling limitations compared to conventional vehicles. Long-haul trucking, shipping, and aviation pose even more severe challenges than light-duty vehicles in terms of the energy densities required, and few zero-carbon options currently exist commercially. Industry electrification is difficult for a variety of reasons: some processes have no existing electrification technology replacement; it is expensive to replace older, functioning equipment that has already been amortized; industrial processes are highly optimized systems and while electrification might be a viable replacement for a single energy demand such as heating, it might not be a viable option for an entire industrial process where, for example, a fuel can act as both an energy source and a reagent (Deason et al. 2018; De Pee et al. 2018).

To meet the challenges of decarbonizing transportation and industry, different scenarios and studies use varying combinations of these three strategies: (a) the use of bioenergy, (b) the use of decarbonized energy carriers derived from electricity such as hydrogen, and (c) reservation of the remaining fossil emissions budget for these sectors. Bioenergy offers the advantage of providing drop-in fuels that require little changes to fueling infrastructure, vehicles, or consumer behavior. However, suitable feedstocks are limited and generally far costlier than fossil fuels: this is explored further in Section 3.4. Mahone et al. (2015) compare a scenario using bioenergy for liquid transportation fuels with one focusing on biomethane for buildings and industry.

Hydrogen is a promising alternative energy carrier to convey renewable primary energy to end uses, but it would require widespread infrastructure replacement before it is commercially feasible, and it would still be expensive without additional innovation. Most

[6] Commercial Li-ion battery energy densities are in the range of 150 to 250 Wh/kg (Amine, Kanno, and Tzeng 2014), compared with 13,000 Wh/kg for gasoline. Power densities vary depending on the battery application and engine type, but jet engines provide more than 10 times that of a 2-hr Li-ion battery. Gasoline ICEs have much less power density than jet engines but still more than the best available batteries.

commercially available hydrogen today is produced from steam reformation of natural gas, which entails fossil $CO_2$ emissions. The US DDPP “High Nuclear” scenario relies heavily on hydrogen produced by electrolysis from clean electricity (James H. Williams et al. 2015). Synthetic climate-neutral fuels are another possibility still in their technological infancy: to be truly climate-neutral, $CO_2$ from air or seawater would need to be captured for reduction by electricity-derived hydrogen to liquid or gaseous fuels. This possibility was explored in PATHWAYS scenarios (Mahone et al. 2015; Mahone, Subin, Kahn-Lang, et al. 2018) and in several of the US DDPP scenarios (James H. Williams et al. 2015). Owing to physical limitations, this is likely to be expensive and use a large amount of primary energy even after additional innovation.

Finally, as none of the deep decarbonization studies achieved 100% decarbonization of the energy system, some fossil energy budget remains in 2050 in the scenarios to allow residual consumption of petroleum fuels in transportation and natural gas in industry: in Williams et al. (2015) these end-uses represent most of the 2050 energy-related GHG emissions.[7]

## 3.4 Low-carbon energy supply

Most scenarios in other studies considering deep decarbonization have considered renewable electricity, biofuels, and other low-carbon resources such as CCS and nuclear energy in decarbonizing the energy supply. The US DDPP had several sensitivity scenarios, including one that excluded CCS and limited nuclear (10% of generation in 2050) in favor of high renewables, but this scenario was predicted to be more than $200B more expensive than the base case “mixed” scenario in 2050 (James H. Williams et al. 2015). In some studies, bioenergy is combined with CCS to yield a theoretically negative-emissions electricity generation technology (Bioenergy with Carbon Capture and Sequestration, BECCS), which can offset fossil fuel emissions in other sectors [e.g., The White House (2016)]. In Krey et al. (2014), the

[7] Within a decade or two after 2050, fossil energy emissions will have to come to near zero to be consistent with the IPCC 2°C climate stabilization target (IPCC 2014).

availability of bioenergy and CCS were the largest factors affecting total scenario cost in scenarios achieving stabilization of atmospheric $CO_2$ concentrations at 450 to 550 ppm [450 ppm is roughly consistent with the 2°C target (IPCC 2014)].

Studies which analyzed highly renewable electricity systems without relying on significant CCS or nuclear generation have recognized specific challenges: (a) limited supply of sustainable biomass available for biofuel, and (b) difficulties integrating high levels of variable renewables into the electricity grid without zero-carbon firm generation; the second challenge will be discussed further in Section 4. While many of the deep decarbonization studies rely substantially upon bioenergy, only a few include or reference a detailed estimate of sustainable biomass potential. The US DDPP (James H. Williams et al. 2015) utilizes the US Department of Energy (DOE) Billion Ton Study (BTS) (Perlack et al. 2011). This study estimated sustainable biomass potential for the US at 1.1 billion bone dry tons (BDT) annually by 2040, or about 18.5 EJ of primary energy per year (James H. Williams et al. 2015).[8] This amounts to about 46 GJ per person per year. For comparison, New York primary energy consumption was about 159 GJ per person in 2015.[9] This illustrates that even with dramatic progress in energy efficiency, biofuel can play only a limited role in decarbonizing the energy system. If used primarily to satisfy non-electric final energy demands, a limited amount will be available to provide firm zero-carbon electricity generation.

While the BTS attempted to include only sustainable biomass, excluding from consideration biofuels that would directly compete with food crops, concerns remain that such large quantities of US biomass would inevitably result in indirect land-use impacts and other negative impacts on the climate system (Plevin, Delucchi, and O'Hare 2017; Melillo et al. 2009; Searchinger et al. 2008; Plevin et al. 2010). For instance, even the consumption of agricultural

[8] The BTS has recently been updated with additional analysis of feedstock sustainability as well as the inclusion of additional biomass feedstocks such as algae. The base case reaches a total of 1.2 billion BDT, with up to 0.1 billion BDT additional high-yield algal feedstock (Langholtz, Stokes, and Eaton 2016).

[9] Based on previous E3 analysis for NYSERDA, 159 GJ per person per year includes all final fuel consumption in addition to fuel combustion, nuclear energy, and renewable generation required for in-state electricity generation. Note that 46 GJ of biomass is a high estimate as it assumes direct combustion, e.g. in a steam turbine electric generator, while most of the 159 GJ consists of final refined fuels.

or forest residues could result in the net emission of carbon that would have been sequestered in soils, forest biomass, or wood products, on timescales of decades to a century (Birdsey et al. 2018), and a uniform framework for accounting for these emissions is yet to be developed (U.S. Environmental Protection Agency 2014). Considering these concerns, the sustainable bioenergy potential in the US may be more limited than 46 GJ per capita, making it difficult for bioenergy to fully displace fossil fuels from non-electric end uses *and* to generate zero-carbon firm electricity. A constrained biofuel supply may favor deep decarbonization pathways that rely more heavily on renewable electricity and electrification (Mahone, Subin, Kahn-Lang, et al. 2018).

One jurisdiction relying heavily on variable renewable energy is California, where recent scenarios have typically phased out nuclear and excluded CCS to be consistent with state policy goals (Mahone et al. 2015; Yang et al. 2016; Mahone, Subin, Kahn-Lang, et al. 2018). These scenarios still include substantial amounts of fossil energy and bioenergy outside the electricity sector: the base PATHWAYS scenario reaches only 52% of economy-wide primary energy from non-biomass renewable electricity in 2050 (mostly composed of wind and solar with some hydroelectric and geothermal; biomass generation and imported electricity provide another 3%) (Mahone et al. 2015).

## 3.5 Timing of energy transitions

Although not closely tied with the deep decarbonization literature reviewed in the rest of this section, recent literature has considered the timescale of energy transitions in the context of deep decarbonization needs (Sovacool 2016). Sovacool (2016) reviews the conventional view of historical energy transitions as idiosyncratic evolutions of fuels and technologies spread over time and space that take up the better part of a century. He contrasts this conventional view with a comparison of ten transitions in either supply or demand technologies that have occurred much faster, such as the shift to nuclear electricity in France. Most of these examples involve small national populations, highly centralized governance, or large and tangible consumer benefits associated with transition. Even so, a main conclusion of Sovacool (2016) is that relatively rapid transitions typically require about a decade for new technologies to reach 25% of market share.

To avoid severe climate change, the transitions associated with achieving the pillars of energy decarbonization need to be rapid by comparison with historical transitions. Whether this is feasible is an open question in the literature. Sovacool (2016) suggests that we might be able to move faster today because we have learned from the past, and because the urgency of the climate challenge will inspire coordinated action. This question is debated in a special issue of *Energy Research and Social Science* (Sovacool and Geels 2016; Smil 2016; Bromley 2016; Grubler, Wilson, and Nemet 2016; Kern and Rogge 2016; Fouquet 2016): some authors contextualize Sovacool (2016) with features that can hasten or slow energy transitions, while others argue for or against the hypothesis that a rapid transition to a decarbonized energy system is possible.

## 3.6 Conclusion

The deep decarbonization studies tend to find that electricity decarbonization is one of the cheapest and most technologically feasible ways to reduce emissions, and that it must proceed beyond the 80% economy-wide goal to compensate for more limited options in other sectors. Most economywide decarbonization analyses indicate electrification of end uses is a key mitigation strategy, as the combination of electrified demand technologies and deeply decarbonized electricity supply can be a relatively low cost, technically feasible way to reduce emissions as part of an economywide deep decarbonization effort (Energy and Environmental Economics Inc. 2018; Haley, Kwok, and Jones 2016; Ribera and Sachs 2015; J.H. Williams et al. 2018).

However, only one of the reviewed studies (Yang et al. 2016) modeled near-complete decarbonization of electricity, and the electricity system modeling for this study appears limited; other analyses chose to stop at ~80-95% carbon-free. Scenarios constructed for Germany and California had some of the highest levels of renewable electricity. The DDPP country scenario for Germany included nuclear phase-out and no CCS, considering scenarios with over 70% wind and solar photovoltaic (PV), but left open the question of which solutions would be used to feasibly integrate this level of intermittent renewables (Waisman et al. 2015). The California PATHWAYS base scenario utilized 84% renewable electricity in 2050, including large hydro-electric generation (Mahone et al. 2015), making use of a variety of integration solutions as well as balancing with 12% in-state thermal generation and additional firm imports. Studies considering higher levels of renewables have primarily been focused specifically on the electricity system and are reviewed in the next section. Finally, we note that most of the studies reviewed in this section preceded the rapid cost declines in wind, solar photovoltaic (PV), and battery costs observed over the last several years that could make higher levels of wind and solar more cost-effective.

# 4 Zero emissions and renewable electricity

This section reviews the literature on opportunities and challenges for achieving zero emissions electricity with a focus on attaining very high renewable shares of electricity generation. In Section 4.1, we introduce key renewable energy technologies and their resource constraints. In Section 4.2, we describe flexible electric grid management and energy storage technologies. In Section 4.3, we outline the main challenges associated with high levels of renewable integration, with additional discussion of renewable integration solutions in Section 4.4 including the role of firm, low-carbon renewable resources. In Section 4.5 we provide a brief summary of how integration challenges are handled in previous studies reaching greater than 95% renewables. In Section 4.6 we discuss an alternative approach to decarbonized electricity that includes non-renewable but firm, low-carbon resources. Finally, Section 4.7 compares the costs and challenges of low-carbon, zero-carbon, and 100% renewable electricity systems.

## 4.1 Environmental and resource constraints for renewables

Before tackling challenges associated with integrating high levels of renewable into the grid, it is important to briefly discuss challenges associated with obtaining the large quantities of renewable energy generation capacity that would be needed to meet most electricity needs. The potential development of renewables is limited by a hierarchy of considerations, ranging from the broadest resource limits based on energy flows, to local market and political conditions as well as competing environmental requirements: while renewables reduce or eliminate the $CO_2$ emissions associated with fossil electricity generation, they still compete with other land uses such as conservation for biodiversity.

The technical potential describes the limits placed on an energy resource by physical constraints such as land use, topography, and generator system characteristics (Lopez et al. 2012). Importantly, the technical potential varies geographically, and the available resources in a region shape the integration challenges associated with high renewable levels.

In the rest of this section, we briefly review the technical potential of major renewable resources along with environmental and land-use considerations. This is intended as a general discussion, not a specific assessment of New York's resources. We include only commercially demonstrated resources: solar, wind, hydroelectric, geothermal, and biomass. Note that all resources are limited economically by access to transmission and other considerations.

#### 4.1.1 Solar

Solar energy is by far the most abundant energy source, with the global resource potential exceeding global energy demands by more than four orders of magnitude. The National Renewable Energy Laboratory (NREL) estimates 154,000 GW of solar potential in the US (Lopez et al. 2012), as compared with less than 1,000 GW of peak load. Electricity can be generated with solar thermal or photovoltaic (PV) technologies. Solar thermal ("concentrating solar thermal" or CST) can provide integrated energy storage with the capability of being dispatchable on an intra-day time frame; this capability may be important at high levels of renewables, but PV has been commercialized much more quickly and has the potential for continued reductions in installed costs.

Solar PV absorbs the solar energy striking the panels, shading plants or buildings beneath. Consequently, it is appropriate for urban uses (i.e. rooftops or parking lots) or for dedicated utility-scale installations that displace other land uses. Siting thus favors sunny areas served by the existing transmission infrastructure but without sensitive habitats or competing needs for sunlight such as agriculture.

### 4.1.2 Wind

Wind is the second most abundant renewable resource, with 15,000 GW of potential in the US including offshore wind (Lopez et al. 2012). Excluding hydroelectric, it also represents the majority of installed renewable capacity, reaching 73 GW in the US in 2015. Wind has lower terrestrial power densities than solar, but it does not completely consume the utilized land. It can be co-located with cropland, pasture, or conserved land, with a relatively small impact on biodiversity and competing land uses. Onshore wind is cheaper to install but regionally limited and more intermittent, as compared with offshore wind.

Despite being relatively low impact, local environmental and aesthetic considerations limit its installation in some areas. Avian mortality has been a major perceived concern. While this problem can be largely mitigated by appropriate siting and the use of newer, larger turbines whose slower-moving blades make them more easily avoided by birds, continuing concerns about avian mortality, along with perceived negative impacts on views and generation of noise, have slowed wind development both in California and in the Northeast.

### 4.1.3 Hydroelectric

Hydroelectric generation is one of the oldest forms of electricity generation and the major renewable form to be widely utilized before modern innovations in wind and solar generation technology. NREL estimated US potential at 60 GW (Lopez et al. 2012). It has the advantage of being dispatchable on a timescale of minutes to months: with pumped storage, it can absorb excess generation of other renewables at high efficiency and make the energy available for later use.

Although it does not emit $CO_2$, hydroelectric power can cause large impacts on the associated watershed, and it can even lead to large emissions of methane in submerged land that can offset a significant portion of the $CO_2$ savings in some circumstances, although this is poorly quantified globally (Barros et al. 2011; Li and Lu 2012; Bastviken et al. 2011). Moreover, most of the appropriate sites have already been developed. Because of these concerns, renewable policies in the US and Europe have largely avoided incentivizing the construction of new dams for large hydroelectric plants, although smaller "run-of-the-river" plants may be incentivized. Nevertheless, existing capacity provides a useful dispatchable renewable generation source that can assist with renewable integration in some areas.

### 4.1.4 Geothermal

Geothermal electricity based on heat flow from the earth's interior is a source of firm renewable power. While theoretically one of the most abundant renewable energy resources, commercial-scale development has been limited to concentrated areas where there are shallow thermal reservoirs ("conventional geothermal" or "hydrothermal"). Obtaining thermal energy from deeper in the crust using a technology similar to hydraulic fracturing would allow access to more energy ("enhanced geothermal"). NREL estimated the US potential of conventional geothermal at 38 GW and enhanced geothermal at 4,000 GW (Lopez et al. 2012).

### 4.1.5 Biomass

Biomass energy can take a variety of forms. Raw biomass (such as wood) can be combusted directly in a steam turbine for firm generation, or it can be processed into biofuel (e.g., biodiesel or biomethane[10]) for use in a more efficient and flexible generator. Biogas from feedstocks such as manure, municipal solid waste (MSW), or landfill gas can generate electricity along with the co-benefit of avoided methane emissions. NREL estimated the technical potential of biomass electricity at approximately 62 GW in the US, assuming all available biomass residues are used for electricity generation, not including purpose-grown crops or plantations (Lopez et al. 2012).

[10] Here, we distinguish between biogas, which is an unprocessed result of anaerobic digestion and is suitable for combustion in a steam turbine or reciprocating engine, and biomethane, which has been upgraded to pipeline quality and can be used in a gas turbine.

While biomass could be a high-value source of dispatchable generation, the sustainable biomass feedstock is limited, and biomass electricity competes with other uses of biomass: food, fuel, and fiber. Using significant amounts of bioenergy in electricity could preclude its use in transportation or industry to displace fossil fuels in end-uses that are difficult to electrify. These issues are discussed more in Section 3.4. Nevertheless, targeted use of biomass as a backstop renewable integration solution could facilitate very high levels of renewable energy in electricity systems, discussed further below in this section.

## 4.2 Technologies for flexibility and storage

In a very high renewable future, technologies for flexibly managing the grid will be critical. These are reviewed in the context of renewable integration challenges in the next section but are introduced here.

### 4.2.1 Flexible loads

Since highly renewable energy systems tend to derive a large amount of their energy from an inflexible, intermittent *supply* (e.g. wind and solar), one solution would be to make *demand* more flexible instead. In this work we refer to this solution as "flexible loads". The general principle of managing loads to meet system needs is usually referred to as "Demand Side Management (DSM)".

Flexible loads could help balance the grid in three ways (Alstone et al. 2016):

1. **Shed**: Loads can be occasionally curtailed to provide peak capacity and support the system in emergency or contingency events lasting up to several hours. This is what is currently known as *shed* demand response and is already widely used. Examples are interruptible processes, advanced lighting controls, and air-conditioner cycling.

2. **Shift**: Loads can *shift* their energy consumption from times of high demand (and/or low supply) to times of low demand (and/or high supply). For example, electric vehicles could charge during the middle of the day when there is excess solar generation, rather than in the evening, when demand peaks and solar generation is declining. Other examples are air-conditioner pre-cooling and flexible fuel production (hydrogen or synthetic methane).

3. **Shimmy**: Loads can dynamically adjust their energy consumption to alleviate short-run ramps and disturbances at timescales ranging from seconds up to an hour. For example, electric vehicles could adjust the rate at which they charge dynamically, based on short-duration system needs.

The two keys to enabling flexible loads are a mechanism to aggregate and/or control loads and aligning incentives for consumer. Real-time pricing would be one way to provide incentives for consumers to shift and/or curtail demand. Allowing loads to participate in wholesale markets, including ancillary services, is another way to provide incentives.

As decarbonization of the non-power sectors results in a variety of new loads, such as heat pumps, electric vehicle charging, electrified industry loads, and fuel production, ensuring that those loads are flexible could provide value in the power sector. Electric vehicle charging could readily provide *shift* on a daily basis, while fuel production would be invaluable for *shift* on seasonal basis. The latter is especially important, since there are not many proven, scalable alternatives for seasonal storage (see next sections).

### 4.2.2 CONVENTIONAL ENERGY STORAGE

The following forms of conventional storage can be distinguished:

+ **Pumped Hydro Storage (PHS)**: Electricity is stored by pumping water from a low reservoir to a reservoir uphill, storing the electricity as potential energy in the water. PHS is the most mature of all storage technologies and is responsible for the vast majority of electricity storage currently in operation. The advantage of PHS is that it is relatively cheap to store large amounts of energy. The disadvantages are that it is relatively costly per unit of peak capacity and it is very site-specific, eliminating this option for many areas in the world.

+ **Battery Storage**: Electricity is stored in rechargeable batteries. Li-ion is currently the most mature battery chemistry in the power sector, but there are other possible contenders including flow batteries. The advantages are that batteries are modular, can be deployed anywhere, and are relatively cheap per unit of peak capacity, with costs on a downward trajectory at present. The disadvantages are that they tend to have a short lifetime and costs per unit of stored energy are high, making them a poor option for long duration (seasonal) storage.
+ **Compressed Air Energy Storage (CAES):** Electricity is stored by compressing air and storing it, usually in an underground cavern. To re-capture the stored energy, the compressed air is used to power a combustion turbine which generates electricity. Since the expansion process cools the air, it is reheated with a natural gas fired burner. Research is underway to store the compression heat and use it to re-heat the air upon expansion (adiabatic storage), thus eliminating the need to burn natural gas. However, the only commercial plants currently in operation still require re-heating with natural gas. The advantage of CAES is low cost per unit of energy stored, while the disadvantages are that it is very site-specific (requires specific geology for underground cavern), has a low round-trip efficiency, and still emits $CO_2$ during the discharge phase.

The limitations of these technologies with respect to the challenges imposed by highly renewable systems will be discussed in Section 4.3.

### 4.2.3 ADVANCED LONG-DURATION ENERGY STORAGE

In this section we will discuss several storage technologies that could potentially store energy very cheaply per unit of energy stored, making them suitable to store energy over the course of many days or even months. Currently, none of these technologies are widely deployed, but they could be a key pillar of a future decarbonized electricity system. A recent review summarizes options for long-duration storage (Blanco and Faaij 2018).

**Power-to-Gas (P2G):** P2G is the conversion of electricity to a gaseous chemical fuel, either hydrogen ($H_2$) or methane ($CH_4$; synthetic natural gas). This fuel can then be used in the buildings, industrial, transportation, or electricity sectors. The key to P2G is that it enables a flexible link between the electricity sector and the transportation and industrial sectors, while also providing long-term energy storage that is vital at high levels of renewables (Götz et al. 2016; Lehner et al. 2014).

Regardless of the end-product (hydrogen or methane), electric power is first used in an electrolysis plant to produce hydrogen and oxygen from water. Hydrogen can then either be used as a fuel directly, or it can be converted to methane by combining it with carbon dioxide ($CO_2$). The advantages of using hydrogen directly are it is more efficient and cheaper than methane; it does not require a source of pure carbon dioxide; and it has a much lower global warming potential associated with leakage than methane. The main disadvantage of hydrogen is that it is somewhat harder to store and transport than methane and can only be blended in small proportions in the existing natural gas infrastructure. Combining the hydrogen with renewable $CO_2$ via methanation to produce to methane can allow using existing gas transmission and distribution infrastructure. However, the requirement of a renewable $CO_2$ source is challenging, as bio-derived sources are limited, so direct air capture or similar climate-neutral source would be required if performed on a large scale.

It is important to distinguish between the use of P2G to produce fuel for transportation and industry, and the use of P2G as a long-duration electricity storage solution. In the former case, P2G would add additional flexible load to the system, whereas in the latter case, P2G is used as a (relatively inefficient) means of electricity storage. Potentially, a combination of both could be used, leveraging the infrastructure as much as possible.

**Thermal Energy Storage (TES):** TES is a technology to store thermal energy by heating or cooling a storage medium so that the stored energy can be used at a later time for heating and cooling applications and/or power generation (Rosen and Kumar 2012).

The main kind of TES is sensible heat storage, which heats or cools a liquid or solid storage medium such as water, sand, molten salts, rocks, etc. The other two kinds of TES are phase change materials (PCM), and thermo-chemical storage (TCS), but they are not widely deployed due to their higher cost and complexity. The main advantage of sensible heat storage is the very low cost per unit of energy stored whereas its main disadvantages are the low energy density and round-trip efficiency, thus requiring large volumes of the storage medium. PCM and TCS could provide higher energy densities, but at a higher cost. Round trip efficiencies range from 50-90% for sensible heat storage, depending on the specific heat of the storage medium and thermal insulation technology. PCM and TCS systems could potentially improve this range to be from 75% to nearly 100% efficiency.

Currently, the two most widely used thermal energy storage technologies are hot water tanks, which are essentially large insulated tanks of water with heat exchangers, and underground thermal energy storage (UTES), which makes use of the subsurface as a storage medium for both heat and cold storage.

Thermal energy storage is particularly interesting when it is centralized, such as in district heating or cooling systems, large industrial plants, combined heat and power plants, and concentrated solar plants. In these centralized use cases, economies of scale and load diversity can be maximally utilized.

## 4.3 Renewable integration challenges: technical requirements for maintaining reliability

The conventional electricity grid was built and operated around the assumption that demand for electricity is exogenous and generation capacity is simply dispatched (and new capacity constructed) to meet demand, usually from flexible thermal generation. Switching to a grid dominated by variable renewable generation, chiefly wind and solar, requires a fundamental paradigm shift to maintain a reliable grid at reasonable cost.

The Climate Policy Initiative (CPI) recently published an extensive review of the challenges associated with maintaining a reliable grid with high levels of renewable generation (Pierpont et al. 2017). CPI identifies six categories of reliability primarily depending on timescale, along with a discussion of which integration solutions can best serve each of these categories, including: (a) demand-side regulation and flexible loads; (b) conventional generation; and (c) storage. Some solutions are inherently supply-limited, including both flexible loads and dispatchable renewables such as hydroelectric, while others may be more expensive but are technically unlimited, such as gas turbine generators or battery storage. Solutions are required not only across timescales but also across space: sufficient transmission must be available so that additional energy can be transported to where it is needed [“locational reliability” (Pierpont et al. 2017)].

We adapt and combine some of CPI’s categories below along with examples from the literature of relevant modeling studies. CPI also includes a discussion of the policy and market-design implications of an effective paradigm for the grid at high renewables, but we will primarily focus on technical and high-level economic considerations in this section.

### 4.3.1 REGULATION, SHORT-TERM RESERVES, AND RAMPING

On a timescale of seconds to minutes, supply and demand must be kept within careful balance with very narrow tolerance for discrepancy. This creates a need for short-term regulation, including “spinning reserves” and load-following, requiring responsive generators or other nodes in the system to compensate for fluctuations. On a timescale of minutes to hours, short-term reserves are also maintained to respond to net load forecast uncertainty and unexpected outages. Variable renewables increase the forecast uncertainty somewhat by making the supply variable as well as the demand.

A related requirement is the need for "ramping," or the rapid change in generation output. Sharp but predictable changes in supply or demand may require cycling a generator between low output and full output in a matter of minutes. A prime instance of renewables increasing the need for ramping services is the rapid decrease in solar power output around sunset, at a time when demand may be near peak.

Conventionally, regulation and short-term reserves are provided by flexible thermal generators, and to a lesser extent by hydroelectric and nuclear: mechanical generators have large inertial masses that inherently stabilize frequency and they can be configured to quickly respond to power fluctuations. The modern power electronics associated with renewable generation are also capable of providing regulation and short-term reserves, if a small portion of the renewable capacity – or storage capacity – is reserved for this use: typically 5% of peak load would be needed for these two services (Pierpont et al. 2017). This requirement could cause a slight decrease in renewable generation and thus an increase in costs per energy delivered, but it appears there are no technical obstacles to renewables, storage and power electronics providing these services (Ramasubramanian, Vittal, and Undrill 2016; Pierpont et al. 2017). Indeed, the capacity needed for these services would be dwarfed by that needed for longer-timescale integration services, discussed below.

Ramping services are cheaply provided by flexible gas generators using gas turbines, including both simple combustion turbines (CTs) and combined cycle gas turbines (CCGTs), which are superior to steam turbines for this application. These already provide the primary ramping service in California as the now-considerable solar PV capacity turns off at sunset. While much larger capacities are needed than for regulation and short-term reserves, storage can also provide this service.

### 4.3.2 Intra-day energy balancing

Imbalances between demand and supply on an hourly timescale inherently result from the use of variable renewable generation, especially solar PV but also wind. In short, electricity demands continue when solar output is zero at night or when winds are weak. Intraday balancing services are a good match for all three categories of renewable integration solutions described above: flexible loads, conventional dispatchable generation, and/or storage (Pierpont et al. 2017). Flexible loads are ideal for this challenge and are theoretically the cheapest option: for instance, electric vehicles (EVs) can be charged overnight when demand is low, or at mid-day when solar output is high. However, this option is inherently supply-limited. Power-to-gas is an example of an advanced flexible load with less stringent supply limits that will be discussed further below.

Prime options for intraday balancing include conventional generation (either fossil, resulting in less than 100% renewables, or renewable thermal generation) and storage, such as pumped hydro or batteries. Here, Li-ion battery storage is only slightly more expensive than a new CCGT at present and may be cheaper by 2030 (Pierpont et al. 2017). This is an ideal application for storage because the energy-to-capacity ratio needed is low and the storage cycles daily, meaning it will be utilized at a relatively high capacity factor, spreading the fixed costs over large numbers of hours. For this reason, Mileva et al. (2016) rely heavily on battery storage for intraday balancing in a scenario achieving high decarbonization of the US western grid (WECC). While the costs for using storage in this way are considerable and likely larger than other solutions like regional integration (Section 4.4.1), they are not so large as to preclude consideration of relying heavily on this approach. For instance, with extensive use of battery storage, Mileva et al. (2016) achieve a reduction in emissions of 85% below 1990 levels for electricity at a per-energy cost less than double that of present-day, using higher battery costs in their base scenario than recent projections suggest (Schmidt et al. 2017).

### 4.3.3 SEASONAL ENERGY BALANCING AND PROLONGED ENERGY SUPPLY SHORTFALLS: *DUNKELFLAUTE*

While they are sometimes combined in the literature, we here distinguish between two related challenges: (1) predictable variation in the seasonal balance between supply and demand; and (2) occasional events of limited predictability associated with prolonged energy deficits. The former is primarily an issue of economics, while the latter is also an issue of reliability. The latter challenge has become known in the German renewable integration literature as *dunkelflaute*, roughly translated as dark doldrums.

Predictable supply and demand imbalances over the course of the year vary regionally. Brick and Thernstrom (2016) compare idealized case studies of California, Wisconsin, and Germany. For instance, California benefits from a coincidence of peak solar PV supply and electricity demand in the summer (without considering future electrification of heating), while Germany is a winter-peaking system that would rely on wind in a high renewables scenario. In contrast, in Hawaii, little seasonal variation in both supply and demand limits the need for seasonal balancing (Orans et al. 2016).

While seasonal imbalances can be partially addressed with a very large overbuild and associated curtailment [e.g., 48% in Frew et al. (2016) at 100% renewables], occasional prolonged energy deficits of days to weeks are an even harder challenge, and are critically important from a reliability standpoint. For instance, modeling of a 100% renewable electricity system for Great Britain highlighted challenges associated with occasional persistent power supply deficits lasting 2-3 weeks (Gillespie, Grieve, and Sorrell 2015). These supply deficits can result from sustained weather events that cause large reductions in wind and solar output: in Boston and Thomas (2015), these occurred twice in a simulated year and each had a net energy shortfall of 6 to 8 TWh. Sizing the variable renewable capacity to be sufficient for these occasional events would be extremely inefficient and uneconomic, increasing the annual fixed costs several-fold or more.

Brick and Thernstrom (2016) conclude that the need for seasonal storage would overwhelm any conventional energy storage strategy, such as relying on pumped hydro or batteries, because of the large magnitude of energy storage needed. Pierpont (2017) agrees, noting that storage capacity that is only cycled once or twice a year would have such a low capacity factor as to be prohibitively expensive, and instead recommends conventional CCGT generation as a backup option: Pierpont (2017) estimates the cost of storage with Li-ion batteries would be $10,000 to $20,000 per MWh in 2030, about two orders of magnitude higher on a per-energy basis than using a CCGT for this application. This is because the magnitude of storage required is estimated to be as high as 10% to 30% of annual electricity demand (Becker et al. 2014; Pierpont et al. 2017), although a highly flexible and integrated energy system could reduce this magnitude (Blanco and Faaij 2018). In contrast, the "ten largest pumped hydro storage facilities in the U.S. are collectively capable of storing a total of just 43 minutes worth of U.S. energy consumption" (Brick and Thernstrom 2016). Recent studies tracing out the marginal cost curve towards 100% renewable and decarbonized electricity agree, finding that without additional options, the costs of overbuilding variable renewables and storage approaching 100% levels of renewable generation are prohibitively large (Section 4.7).

Rather than pumped hydro or battery storage, conceivable solutions to these challenges are either (a) backup firm generation, or (b) advanced energy storage, supplemented by regional integration (Section 4.4.1). For goals short of 100% renewables, conventional fossil-fueled thermal generation can serve as an occasional backup. Firm renewable options include hydroelectric or biomass power, which are inherently supply-limited. Because of the large power capacity needed, biomass would be the likely candidate in most locations. Alternatively, advanced energy storage options that are not yet commercialized could be used: "underground thermal energy storage, electrolytic hydrogen production, and/or production of synthetic natural gas" (Jenkins and Thernstrom 2017). A key feature of these advanced storage options is that their costs scale only weakly with the total energy stored (or may be low per unit energy, in the case of underground thermal energy storage), in contrast to Li-ion batteries, whose costs are nearly proportional to the total energy capacity.

## 4.4 Approaches to mitigate storage requirements for high renewables

### 4.4.1 Regional integration and renewable diversity

Expansion of the transmission system to allow deeper connectivity at larger scales enhances geographic diversity in both demand and supply resources, mitigating local imbalances. This is for two reasons: (a) averaging across larger scales tends to reduce the net magnitude of variation, which underlies conventional grid expansion; and (b) renewable resource diversity is especially important for cost-effective integration. We note that even with a single renewable resource, averaging over large geographic areas reduces variability due to local weather conditions (although it does not come close to *eliminating* this variability unless the grid extends over continental scales).

Many of the studies reviewed here suggest a large role for expansion of transmission infrastructure and find it to be one of the cheapest renewable integration solutions (Mai et al. 2014; Becker et al. 2014; Pierpont et al. 2017; Pleßmann and Blechinger 2017; Frew et al. 2016). Several studies emphasize the need for a national high-voltage direct current (HVDC) system in the US. Pleßmann and Blechinger (2017) design their study around a fully integrated transmission grid for the European Union (EU). However, such a large buildout of infrastructure would require a high degree of political cooperation across different jurisdictions. Brick and Thernstrom (2016) emphasize that political and institutional feasibility are important considerations for planning an optimal future system. Enhanced regional integration may be more practical as a first step.

Renewable resource diversity decreases integration costs by allowing resources with different temporal characteristics to complement each other (Pierpont et al. 2017). In the US Western grid, solar PV in California and the Southwest complements northwestern hydroelectric and wind in the mountain West (Mileva et al. 2016). The optimal mix of wind and solar varies geographically and has been explored by several studies (Pierpont et al. 2017; Becker et al. 2014). Pleßmann and Blechinger (2017) note that an optimal portfolio for an EU grid would be wind-dominated, while the inclusion of North Africa in the transmission system would allow more solar.

Finally, where available, the inclusion of firm renewables such as geothermal and hydroelectric can complement intermittent resources. In Australia, extensive hydroelectric as well as semi-dispatchable solar thermal resources were assumed in a study of 100%

renewables (Elliston, MacGill, and Diesendorf 2013). While geothermal and hydroelectric can complement intermittent resources, not all regions have significant quantities of these resources; other firm low-carbon resources are discussed in Section 4.4.2 and in Section 4.6.

### 4.4.2 FIRM LOW-CARBON RESOURCES

In very high renewable electricity systems (i.e., >80% to 95%), firm low-carbon resources can provide occasional high-value energy to the grid, typically at high power capacity, when it is most needed (Sepulveda et al. 2018; Jenkins, Luke, and Thernstrom 2018). "Firm low-carbon resources" are defined in Sepulveda et al. (2018):

> [Firm low-carbon resources] are technologies that can be counted onto meet demand when needed in all seasons and over long durations (e.g., weeks or longer) and include nuclear power plants capable of flexible operations, hydro plants with high-capacity reservoirs, coal and natural gas plants with CCS and capable of flexible operations, geothermal power, and biomass- and biogas-fueled power plants.

Here, we distinguish between firm renewable resources which have low capital cost and high variable cost, such as thermal plants using bioenergy (or renewable hydrogen, which can be considered a form of long-duration storage), with geothermal and hydroelectricity, which are geographically limited and have high capital costs with low variable costs. Non-renewable firm low-carbon resources are discussed in ?.

A small quantity of bioenergy can be used to displace the last ~2% to 10% of fossil generation, in the form of solid, liquid, or gaseous biomass or biofuel combusted in conventional thermal generators (Orans et al. 2016; Elliston, MacGill, and Diesendorf 2013; Olson et al. 2017; Ming et al. 2019). Biomass generation is complementary to storage: the former has low capital cost per power capacity but high variable cost per energy supplied, while the latter has high capital cost per power and energy capacity but very low variable cost per energy supplied. Consequently, biomass generation can relatively cheaply provide backstop thermal generation to address the challenges of seasonal energy storage and occasional prolonged supply deficits.

The biomass requirement for displacing the last remaining fossil generation is small but not insignificant in the context of economy-wide decarbonization, with different end uses competing for this scarce resource. None of the studies reviewed here comprehensively analyzed biomass quantities needed for this application in the context of sustainable biomass supplies and demands in a region. We illustrate the moderate scale of the challenge using the US DDPP analysis (James H. Williams et al. 2015). In the base "mixed" scenario (reaching about 95% zero-carbon generation, including CCS), about 30 EJ of electricity is consumed in 2050). Displacing 10% of this with biomass generation would mean supplying 3 EJ of biomass generation, or at least 6 EJ of biomass primary energy. This is about one third of the sustainable US biomass supply assumed in Williams et al. (2015). Consequently, we conclude that this approach is feasible, but it could substantially reduce the biomass available for decarbonizing other end uses.[11] Making use of storage and other solutions to reduce renewable balancing requirements to 5% of annual generation or less would mitigate this impact. Determining whether this is the optimal use of scarce biomass depends on the relative value in electricity vs. use in decarbonizing hard-to-electrify end uses: this depends on the availability of alternatives in each sector, the availability of biomass, and the stringency of the economywide emissions target.

## 4.5 Previous studies considering near-100% renewables

We reviewed four sets of studies comprehensively modeling the attainment of greater than 95% renewables in a geographic area. All of them include one or more of the following: (a) very large expansion and transformation of transmission and storage infrastructure; and/or

[11] From a societal perspective, it makes no difference whether the scarce biomass is used to displace fossil fuel in electricity or in other sectors, assuming similar conversion and utilization efficiencies. It only affects emissions and cost allocation. This is nevertheless relevant when considering sector-specific policies such as 100% renewable electricity.

(b) reliance on a limited quantity of firm generation (< 10% of annual demand) derived from biomass or power-to-gas. Note that while the quantity of energy needed from firm resources is limited, the capacity required may still exceed peak demand (Jenkins and Thernstrom 2017). These studies are identified below.

- For Hawaii, which benefits from fairly constant seasonal supply and demand in addition to relatively abundant wind and solar, Orans et al. (2016) nevertheless utilized biodiesel backup generation to cost-effectively address occasional energy shortfalls.[12] This represented < 5% of annual generation.
- Several US studies (Becker et al. 2014; Jacobson, Delucchi, Cameron, et al. 2015; Frew et al. 2016) utilize a national HVDC system as well as ample advanced energy storage and a high degree of flexible load; Jacobson et al. (2015) will be discussed further in Section 7. In addition, Sepulveda et al. (2018) models the costs of US electricity system decarbonization with and without the availability of firm low-carbon generation; this study will be discussed in the next Section.
- In Europe, power-to-gas is used as a long-term advanced energy storage option to absorb excess generation and address energy shortfalls (Pleßmann and Blechinger 2017). The power-to-gas is assumed to be based on synthetic methane, though the study provides little detail on what cost-effective climate-neutral carbon source would be available for the methane. The synthetic methane would be used in conventional gas turbine generators. A fully integrated EU grid is also assumed.
- In Australia, in addition to the inclusion of some hydroelectric generation and concentrating solar thermal with storage, biomethane used in conventional gas turbine generators is utilized for load balancing, amounting to about 6% of annual generation (Elliston, MacGill, and Diesendorf 2013).

[12] The precise generation mix differed by island, but the total supply was dominated by wind and solar PV, including rooftop PV.

## 4.6 Alternative approaches to achieve zero emissions electricity: higher shares of non-renewable, firm low-carbon resources

The focus in this chapter has been considering the options for achieving zero emissions electricity systems with an emphasis on high renewable shares of electricity generation. These typically rely on variable renewable generation coupled with short-duration and intra-day balancing resources such as flexible loads and Li-ion batteries. An additional renewable integration option is likely necessary to achieve zero emissions electricity: occasional utilization of thermal generators using bioenergy or renewable power-to-gas; advanced long-duration storage approaches like underground thermal energy storage; or vast expansion of transmission infrastructure across large spatial scales.[13]

Many of the studies in Section 3 assumed additional firm decarbonized energy sources would be available to aid economywide decarbonization: nuclear energy and fossil energy with carbon capture and storage (CCS). These energy sources can provide electricity generation that is both firm and low- or zero-carbon, and in some cases may provide a more cost-effective approach to complete electricity decarbonization than the additional renewable integration options listed above. Of interest are emerging technologies that may offer advantages in terms of cost, modularity, flexibility, or emissions as compared with currently commercialized nuclear and CCS approaches. These include small modular nuclear reactors, molten salt nuclear reactors, and Allam cycle natural gas with CCS (Allam et al. 2013; Scaccabarozzi, Gatti, and Martelli 2017; Sadekin et al. 2019; Hong 2018).

The studies of highly renewable electricity systems all include another renewable integration solution: auxiliary resources that run at low capacity factor to address occasional energy

[13] Ample availability of regional hydroelectric or geothermal resources could also satisfy this requirement. It is key to note that both a large energy and power capacity would be required for this application, even if the average energy requirement is low. Very large thermal or hydro reservoirs would be needed to provide multi-day energy storage at a peak power output of a sizeable fraction of the electricity demand.

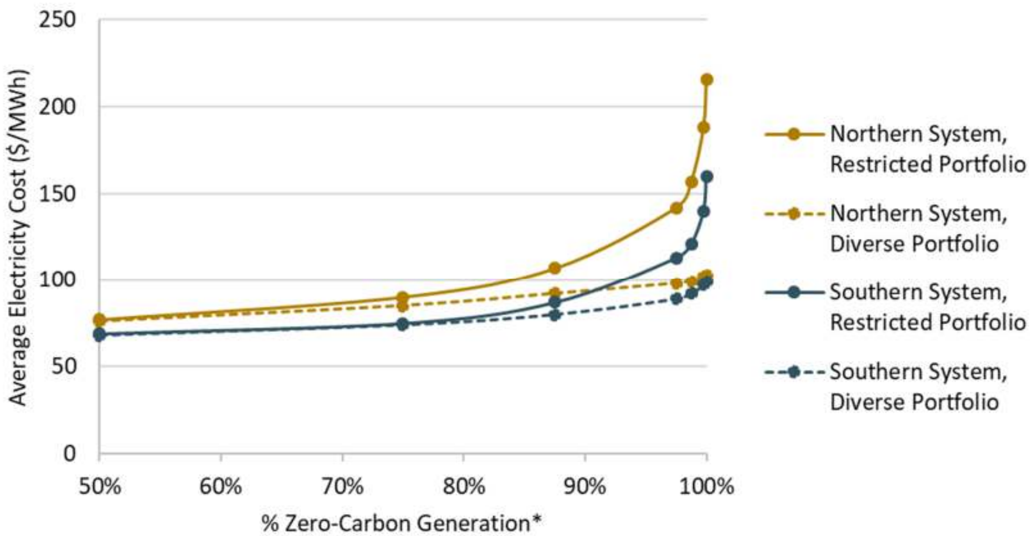
shortfalls, either in the form of overbuilding variable renewables and storage or maintaining backup thermal generators using renewable fuels. Additional decarbonized electricity technologies may be especially valuable in 100% decarbonized electricity systems because they could satisfy the need for firm resources that provide reliability and address the problem of *dunkelflaute* events (Section 4.3) without the need for these additional resources. However, in addition to ongoing questions about the technological, environmental, or economic risks of these technologies, their main disadvantage relevant here is their much higher capacity cost on a $/kW basis, compensated for by relatively low variable costs.

## 4.7 Distinct costs and challenges for low-emissions, zero-emissions, and 100% renewable electricity systems

Different challenges are associated with renewable integration at modest levels of renewable generation as opposed to very high levels. Several studies predict escalating costs of progressive decarbonization associated with the challenges described in Section 4.3. The studies suggest different mechanisms for mitigating these costs, as described in Sections 4.3 and 4.4. Furthermore, the availability of firm low-carbon generation has been shown to dramatically reduce system costs.

Broadly, we can distinguish three regimes along the supply curve from zero to 100% renewables in systems dominated by wind and solar PV with limited integration solutions, with the precise ranges dependent on region and technology assumptions (Platt, Pritchard, and Bryant 2017). These regimes appear in Sepulveda et al. (2018), reviewed below, echoed in other recent studies tracing out the trajectory towards 100% renewable generation (Ming et al. 2019; Olson et al. 2017).

**Figure 2. Average electricity cost as a function of the share of zero-carbon generation***




**Notes:** Northern and Southern Systems represent dissimilar US regions corresponding approximately to New England and the Electricity Reliability Corporation of Texas, respectively. The restricted portfolio includes only wind, solar, and battery storage, while the diverse portfolio also includes dispatchable bioenergy, CCS, and nuclear power. *Percent zero-carbon generation was converted from carbon intensity by assuming the remaining generation share is combined cycle gas natural gas. Adapted from Sepulveda et al. (2018)**.**

The three regimes are as follows:

1. For the introduction of variable renewables (0% to ~50%) to a conventional system, the average electricity cost is comparable to conventional generation, with small incremental costs varying by location and market conditions.

2. As more variable renewables are added (~50% to ~80% or ~95%), substantial intraday balancing is required, which can be addressed by a combination of flexible loads and battery storage. The average cost may increase modestly as compared with conventional generation.

3. To displace the final ~5% to ~20% of thermal or other firm generation from the system with variable renewables, cost increases rapidly and the average cost may exceed conventional generation by a factor of two or more without additional solutions. This is due to the related challenges of seasonal energy balancing and *dunkelflaute*, occasional shortfalls in wind and solar generation for periods of one day to several weeks. Mitigating these costs will be key to any low-carbon electricity system.

The literature shows a consensus around this basic understanding but with studies differing on the implied conclusions and in the level of confidence that advanced technologies can cost-effectively displace the last few percent of fossil generation. Some studies consider a maximum of 80% to 90% renewable generation (MacDonald et al. 2016; Mileva et al. 2016; Gillespie, Grieve, and Sorrell 2015; Mai et al. 2014; Brinkman 2015). In a second set of studies, biomass or power-to-gas in thermal generators is used to reach near-100% with incremental changes to existing infrastructure, as discussed in Section 4.4.2. Finally, some studies exclude biomass and instead model very large additions to transmission and storage infrastructure, with large renewable overbuild. For instance, Frew et al. (2016) show 100% renewables to be twice as expensive as 80% with three times the curtailment, even after assuming a fully integrated national transmission system. Jacobson et al. (2015) include a national HVDC transmission system as well as very large quantities of energy storage from underground thermal and power-to-gas, equivalent to 2.5 times the current US power capacity and a storage energy capacity exceeding 12 weeks of current electricity consumption.

Sepulveda et al. (2018) describes the importance of firm low-carbon generation in reducing the costs of US electricity system decarbonization. The study models decreasing $CO_2$ limits in systems with two different sets of low-carbon technologies: one resource set only allows solar, wind, and batteries, while the other resource set also includes firm low-carbon resources (Sections 4.4.2 and 4.6) such as flexible nuclear power, high-capacity hydro, thermal plants with CCS, geothermal power, and biomass. The model is run with numerous distinct assumptions for technology costs and, at electricity sector emissions rates below 50 $gCO_2$/kWh (approximately 1/10 of the US emissions rate in 2017), firm low-carbon resources are found to lower costs in the vast majority of cases. This effect is amplified as emissions rates approach zero, with firm low-carbon resources decreasing system costs by 2 or 3-fold.

Sepulveda et al. (2018) explain this result: "VRE [variable renewable energy] and batteries are only weak capacity substitutes for firm low-carbon resources, and significantly more than one megawatt of combined VRE and storage capacity is required to replace one megawatt of firm low-carbon capacity in equally reliable systems achieving the same $CO_2$ emission reductions." The corresponding renewable overbuild is significant without these firm resources: "For zero emissions cases without firm resources, the total required installed generation and storage power capacity in each system would be five to eight times the peak system demand, compared with 1.3–2.6 times peak demand when firm resources are available."

Sepulveda et al. (2018) additionally models the mitigating effects of new transmission infrastructure. The study finds that transmission interconnection is effective in reducing costs of decarbonized electricity systems, especially in the absence of firm low-carbon resources. However, even with this enhanced transmission capacity, system costs are dramatically reduced by the availability of firm resources.

Unlike "100% zero-carbon electricity," a stricter definition of "100% renewable electricity" would exclude nuclear power and CCS that could provide a firm resource to the system. The studies described in this section suggest that the availability of firm renewable resources would dramatically reduce electricity costs under a 100% renewable requirement. If nuclear power and CCS are off the table, other renewable options, such as geothermal power, sustainable bioenergy, and/or hydropower would be needed to bring down costs associated with meeting seasonal storage needs but may have limited resource potential; alternatively, hydrogen or power-to-gas can be used as a form of long duration energy storage. Furthermore, while none of these studies closely investigated the political or temporal feasibility of these scenarios, we conclude that a strict 100% renewable electricity scenario without firm low-carbon resources would require a much longer time and/or greater level of political coordination to achieve the required levels of storage and transmission infrastructure. In contrast, a scenario that makes use of firm zero-carbon or fossil generation to generate a small fraction of annual electricity would require less time, less political coordination, and likely run at lower cost.

# 5 Achieving carbon neutrality across the economy

Recent policymaking and research, accelerated by the 2018 IPCC Special Report on Global Warming of 1.5°C, has focused on moving beyond 80% reductions by mid-century to deeper emissions targets (IPCC 2018). For example, the UK government recently commissioned a report on transitioning the entire British economy to net zero emissions by 2050 that built on a series of earlier sector-specific decarbonization studies (Committee on Climate Change 2019). Here we briefly review some recent studies which have investigated the actions needed to achieve carbon neutrality economy-wide. This section is not meant to be an exhaustive literature review of the carbon neutrality literature. The studies reviewed in this section include the aforementioned United Kingdom Committee on Climate Change net zero report and associated Royal Society analysis of NETs; the United States National Academy of Sciences report on negative emissions technologies; and a report written by Evolved Energy Research on decarbonizing the United States economy on a pathway consistent with returning the world's global atmospheric concentration of carbon dioxide to 350 ppm by 2100 (Committee on Climate Change 2019; Royal Society and Royal Academy of Engineering 2018; National Academies of Sciences Engineering and Medicine 2019; Haley et al. 2019). The actions needed to achieve carbon neutrality economy-wide generally fall into one of three categories:

+ Acceleration of mitigation measures that have already been initiated or are included in 80% by 2050 scenarios
+ Adoption of new mitigation measures that are often excluded from less aggressive decarbonization scenarios due to cost, technological readiness, or political feasibility
+ Adoption of measures which have a net reduction in $CO_2$ from the atmosphere, such as bioenergy with carbon capture and sequestration; increased carbon uptake into

natural and working lands; and measures to remove CO2 from the atmosphere for geologic storage or other long-term sequestration.

The acceleration of mitigation measures necessary to reach 80% by 2050 targets, some of which have already begun being implemented in New York, is necessary when trying to achieve lower emissions over the same time span. This could mean earlier sales saturation for zero-emissions vehicles or appliances or even the early retirement of fossil fuel consuming equipment.

Beyond the acceleration of existing mitigation measures, new measures will be needed to achieve net-zero emissions. These could be supply-side measures directly affecting the carbon intensity of fuels or products consumed throughout the economy or demand-side measures aimed at reducing energy consumption. Supply-side measures could include using advanced renewable liquid and gaseous fuels (synthetic and/or biogenic) to displace conventional fossil fuels or greater use of CCUS (carbon capture, utilization, and storage) to reduce the carbon-intensity of fuels used for electricity generation or industry..

The final category of measures contains a range of technological options, including both negative emissions technologies (NETs) and natural carbon dioxide removal (CDR) solutions like increased carbon storage in terrestrial ecosystems. Negative emissions may be needed particularly for ongoing emissions from more challenging sectors mentioned in Section 3, such as non-road and heavy duty transportation, high-temperature industrial heating, and non-combustion emissions sources. They will also likely be needed to draw down excess $CO_2$ emissions to compensate for “overshoot” of global temperature targets, as considered in most global scenarios that reach a 1.5°C or 2°C stabilization goal.

# 6 Conclusions and remaining challenges

In this report, we reviewed more than 30 previous studies (including both original modeling studies and review articles). We discuss broad conclusions and implications for New York below, along with suggestions for additional research.

In Section 3, we reviewed economy-wide deep decarbonization studies. These conclude that it is possible to reduce GHG emissions by 80% while maintaining existing lifestyles, using only incremental improvements on existing technology, and limiting economic costs to 1% of GDP or less. However, this would require large changes to the energy system including investments in new infrastructure, a large tradeoff of upfront capital costs for fuel savings, and work to ameliorate disparate impacts on some segments of the economy. Literature on social factors, transition timing, and policy implications of deep decarbonization is more limited than that on the technical requirements.

In Section 4, we reviewed studies considering scenarios of high renewable electricity. These studies, while varying in goals and methods, agree that achieving 100% renewable electricity with mostly variable renewables such as wind and solar, poses different challenges than 100% zero-carbon generation or than achieving more modest levels of renewable electricity, even up to 80% or 90% renewable. Getting to 100% zero carbon will require either zero carbon firm generation or transformational advances in expanding transmission infrastructure and developing advanced energy storage. Firm zero carbon energy generation could either consist of occasional use of decarbonized renewable fuels like biomethane and hydrogen or include firm non-renewable options like advanced nuclear generation and natural gas with CCS. This presents policymakers with important choices on how best to develop "least regrets" long-term strategies based on today's information.

New York can learn from previous studies considering high renewable electricity. New York's renewable resource mix and electricity demand characteristics would be similar to those considered in studies focusing on Germany, the United Kingdom, or the EU as a whole, so these studies can serve as a starting point for an analysis tailored to the state.

In Section 5 we briefly introduce the emerging concept of economywide carbon neutrality and outline considerations for a more in-depth review.

Several areas for future research remain, including the following:

+ What quantity of sustainable, climate neutral bioenergy is available and within what framework should remaining uncertainty the environmental impacts of bioenergy resources be assessed?
+ What social dimensions drive or impede the transition to a low-carbon energy system? What factors lead to changes consumer decision-making in favor of low-carbon alternatives to fossil-fueled appliances and vehicles?
+ Will the costs of electrolyzers, fuel cells, and direct air capture modules become affordable with continued innovation? How quickly could such technologies become widespread in the economy?
+ What is the potential for extended demand response to allow large reductions in load during periods of low renewable availability lasting longer than 8 to 12 hours?
+ How does policy appropriately set ambitious long-term goals while avoiding overdependence on unproven technologies (for example, synthetic climate-neutral fuels)?
+ How can large-scale infrastructure associated with district heating and transmission expansion be made politically and institutionally viable?
+ Should investment in broad decarbonized electricity generation options, including nuclear and fossil with CCS, be undertaken now in order that they may be scaled up to serve as a primary component of a decarbonized electricity portfolio? Or is it better to continue to scale up renewables to the point where they can be cost-effectively

integrated using current approaches and wait to see if new renewable integration solutions are commercialized?

Finally, this report has focused primarily on the technical challenges associated with deep decarbonization and high renewable energy systems, but additional analysis of the policy mechanisms capable of achieving these goals is needed. There are different philosophies about how to best achieve the transition. Some studies focusing on 100% renewable energy systems propose transformative rather than incremental progress toward a known end goal as the best way forward. In contrast, the US Mid-Century Strategy (The White House 2016) recommends flexible long-term targets to allow for lower cost technologies to emerge in the long-run.

# 7 Appendix: Achieving 100% renewable energy throughout the economy

This section discusses the goal of achieving economy-wide 100% renewable energy. In addition to generating 100% of electricity from renewable sources, a 100% economy-wide renewable energy target would also require 100% displacement of fossil fuels in the rest of the economy. As it is stricter than the goals considered in Sections 3 and 4, this goal faces distinct challenges. At the same time, the broader scope of this goal presents the opportunity to reconsider how the energy system might look if it were fundamentally designed around the characteristics of renewable energy, rather than incrementally incorporating new resources into existing energy systems. Below, we review the distinct challenges associated with a 100% renewable energy goal and the innovative approaches proposed to deal with these challenges in two studies. We note that this is a nascent body of literature with limited studies available at the time this review was drafted, and we expect that understanding will improve as more researchers begin to examine these questions.

## 7.1 Introduction to 100% renewable energy scenarios

We reviewed two studies examining scenarios for 100% renewable energy throughout the economy, briefly summarized below.

Jacobson et al. (2015) propose 100% elimination of fossil energy throughout the US economy via the substitution of “wind, water, and sunlight” (WWS) renewable energy for fossil fuels, excluding bioenergy, nuclear, and CCS. Targeting 2050 to 2055 for achieving this target, they model a wholesale restructuring of the energy supply and demand infrastructure by transitioning all final demands to electricity and hydrogen. Primary energy is provided mostly by utility-scale PV and wind, with a small amount of hydroelectric, concentrating solar thermal (CST), geothermal, tidal, and wave energy. Energy storage is provided by pumped hydro, CST, hydrogen power-to-gas, and underground thermal energy storage (UTES), with the bulk of storage power capacity coming from CST but the bulk of storage energy capacity coming from hydrogen and UTES. Their analysis is based on the combination of a weather model to simulate hourly renewable energy generation for 6 years of simulated weather with an electricity dispatch model intended to ensure load can be reliably met during the time frame simulated. They model the availability of renewable generation from the entire US (all 50 states), along with assuming a significant expansion in grid infrastructure to allow nationwide hourly balancing. Serving all energy needs reliably with WWS energy also requires a several-fold expansion in electricity generation capacity and a large expansion of energy storage infrastructure. Demand technology assumptions, including energy efficiency, vehicle, building, and industrial electrification, and hydrogen, are found in Jacobson, Delucchi, Bazouin, et al. (2015). A critical assessment of this study questioned some of the assumptions and the modeling approach (Clack et al. 2017), and this was followed by a rebuttal from the authors (Jacobson et al. 2017).

Connolly and Mathiesen (2014) propose a framework for 100% renewable energy using Ireland as a case study. Their framework suggests 7 stages, beginning with the current system, for transitioning to a 100% renewable energy system. Each stage is intended to be viable on its own, although in practice the timing could overlap. Steps in the demand-side transformation include the adoption of district heating, heat pumps, flexible loads, and electric vehicles. Moving to renewable electricity with pumped hydro storage and producing synthetic fuels represent the supply-side transformations. Primary energy includes wind, solar PV, hydroelectric, and biomass; the biomass represents about a third of primary energy and is used for heating as well as a carbon source to produce synthetic fuels. Modeling uses an energy system analysis tool that includes the capability of simulating advanced renewable integration technologies. It simulates the energy system hourly to ensure that supply and demand is balanced. District heating is used in densely populated areas, with electric heat pumps used elsewhere. Biomass is used as a carbon feedstock to develop electricity-derived synthetic fuels including methanol, dimethyl ether (DME), and methane; these synthetic fuels help decarbonize non-electric end uses in transportation and industry while also serving as a flexible load and a form of energy storage.

## 7.2 Distinct features of 100% renewable energy scenarios

The 100% renewable energy scenarios build on the approaches discussed in previous sections: electrification and integration of high levels of variable renewable electricity generation. These scenarios extend these approaches to displace remaining fossil fuel use in difficult-to-electrify end uses like non-road transportation and industry, as well as displacing remaining fossil fuel electricity generation that serves as a relatively inexpensive form of renewable integration in scenarios targeting ~80% GHG reductions. To accomplish this, the scenarios pursue tighter linkages between previously distinct sectors of heating, transportation, and electricity generation. This entails a paradigm shift from dispatchable supply and forecast load to *forecast* supply and *dispatchable* load (Connolly and Mathiesen 2014). Both scenarios assume large expansions in transmission and storage infrastructure and include advanced, long-duration storage technologies such as underground thermal energy storage (UTES) and power-to-gas. These components are discussed in more detail below.

### 7.2.1 Flexible electric loads and demand response

High levels of end-use electric flexibility facilitate integration of variable renewable resources. In Jacobson et al. (2015), most electric end uses are assumed to be able to shift or be deferred for 8 hours. Connolly and Mathiesen (2014) assume that electric vehicles can be charged flexibly or provide energy back to the grid, and some other electric end uses are flexible.

Most of the literature on flexible loads and demand response (Section 4.2.1) has so far focused on the challenges associated with occasional demand response to avoid peak hours, or for daily shift for intraday balancing, such as moving daily loads to be coincident with mid-day solar. This application should be distinguished from extended demand response, in which industrial and other nonessential loads could be deferred during periods of low renewables lasting from 8 hours to several days or more. A more comprehensive assessment of the value and supply potential of this form of demand response is needed in the literature.

### 7.2.2 Hydrogen and electricity-derived synthetic fuels

Electricity-derived liquid and gaseous fuels add several forms of value to a 100% renewable energy scenario: displacement of fossil end uses without the use of biofuels [or reduced use of biofuels as in Connolly and Mathiesen (2014)]; addition of a large flexible load; and addition of a much larger amount of chemical energy storage than feasible with batteries. This is also known as "power-to-gas," (Götz et al. 2016; Blanco and Faaij 2018; Lehner et al. 2014) discussed in Section 4.2.3.

In Jacobson et al. (2015), hydrogen produced from renewable electrolysis is used to power trucks, planes, and other end uses that are not easily electrified. Many of the studies reviewed in Section 3 found this to be an expensive but technically feasible option, while the supporting study (Jacobson, Delucchi, Bazouin, et al. 2015) assumes that innovation allows the incremental capital cost of hydrogen vehicles to fall to zero. Connolly and Mathiesen (2014) utilize electrolytically-derived hydrogen along with carbon from biomass to produce synthetic liquid and gaseous fuels. This avoids the cost of hydrogen distribution infrastructure and fuel cells while increasing reliance upon limited biomass. Another option not explored in these two scenarios is a climate-neutral inorganic $CO_2$ source, such as from direct air capture (DAC).

To the extent that hydrogen can be stored in the existing natural gas pipeline system, or some portion of the pipeline could be upgraded to accept hydrogen, several weeks to months of energy storage are afforded to the electricity system. In Jacobson et al. (2015), this represents 432 TWh of storage nationwide. Hydrogen can be consumed directly in combustion turbines, with the potential of using existing gas turbine power plants with some refurbishment. This would be less energy efficient than using fuel cells to generate electricity as in Jacobson et al. (2015), but it would minimize the need for new infrastructure while addressing the *dunkelflaute* problem (Section 4.3.3). Other studies reviewed in Section 4 as well as Connolly and Mathiesen (2014) assume that synthetic methane with a climate-neutral $CO_2$ source can play this role without modification of the gas distribution system or gas generation fleet.

The primary uncertainty associated with this approach is in the future costs of electrolysis, hydrogen fuel cells, and DAC equipment, which are the subjects of ongoing research.

### 7.2.3 District heating and underground thermal energy storage

Underground thermal energy storage (UTES) offers a potentially abundant and relatively inexpensive form of long-duration energy storage. This resource provides the majority of the energy storage capacity utilized in Jacobson et al. (2015), representing 515 TWh nationwide. (It provides a smaller proportion of the storage power capacity, which also comes from CST, hydrogen fuel cells, and pumped hydro.) As noted in Section 4.2.3, coupling UTES with district heating can jointly address the challenges of renewable integration and efficient renewable building heating (Levihn 2017). This approach also mitigates the potential for increased peak electricity demand associated with cold weather conditions.

Although relatively abundant and inexpensive, thermal energy storage has lower round-trip efficiency than batteries and likely power-to-gas, meaning that a large quantity of renewable overbuild would be needed for it to serve the needs of seasonal energy storage. If coupled with district heating, it would require a large development of new infrastructure in existing communities, which may face deployment challenges.

### 7.2.4 Expansion of transmission infrastructure

Geographical diversity in both renewable resources and electricity demands is one of the main approaches to renewable integration discussed in Section 4 Over large areas, variable renewable availability becomes less correlated than at small scales due to different weather conditions. Also, different geographical areas can have complementary renewable resource technical potential. Jacobson et al. (2015), as in several studies reviewed in Sections 4.4.1 and 4.5, includes a continental-scale grid with HVDC lines used for long distances. Perhaps even more than the development of district heating or upgrades to the gas pipeline network to accommodate hydrogen, such a large expansion of transmission infrastructure would require a large degree of political coordination across length scales as well as an appetite for major infrastructure investment. If this were feasible, the future cost savings could be considerable, as transmission is often shown to be one of the least expensive forms of renewable integration (Section 4.4.1).

### 7.2.5 Other considerations

#### *7.2.5.1 Role of bioenergy*

A key question for 100% renewable energy scenarios is whether bioenergy should be available. Jacobson et al. (2015) limited primary energy to wind, water, and solar (WWS) resources with a very small amount of geothermal, thus assuming 100% displacement of fossil fuels and biofuels by electricity and electricity-derived fuels in the rest of the economy, as well as the use of advanced long-duration storage to maintain grid reliability. Other studies examining 100% renewable energy, such as Connolly and Mathiesen (2014), include some bioenergy.

All of the deep decarbonization studies reviewed in Section 3 used substantial quantities of bioenergy to displace fossil fuels in end uses that are difficult to electrify. Some also used bioenergy for electricity generation, in some cases combining it with CCS to yield negative-emissions energy with BECCS. In addition, several of the studies investigating very high renewables in Section 4 utilized dispatchable biomass electricity to balance variable renewables. The challenges associated with having limited sustainable biomass supply were discussed in these sections and deserve more attention for future research. A key research question is whether enough sustainable, climate-neutral biomass is available to allow a 100%

renewable energy goal to be achieved with similar approaches, or incrementally more challenging approaches, than those used in the existing deep decarbonization studies. In other words, how much more difficult is it to achieve 100% reduction of energy GHGs than to achieve 80% reductions below 1990 levels, given that nuclear and CCS are excluded? Connolly and Mathiesen (2014) propose to stretch the energy value of limited biomass by using it as a carbon source combined with electrolytically-derived hydrogen to create synthetic fuels.

#### *7.2.5.2 Approach to costs and innovation*

The deep decarbonization studies reviewed in Section 3 tend to rely as much as possible on proven technologies, without a high degree of innovation or dramatic cost reductions in technologies not yet commercialized. Consequently, they typically find upward-sloping marginal costs of abatement: Yang et al. (2016) show marginal abatement costs exceeding $1,000 per ton of $CO_2e$ in 2050 for an 80% reduction below 1990 levels in California, with the highest costs associated with off-road transportation mitigation measures. Based on these studies, eliminating all fossil energy emissions would be likely to result in substantially higher total costs than merely an 80% reduction.

The studies reviewed in this section take a broader approach to costs and assume high levels of innovation are possible along with a willingness to heavily invest in new infrastructure that will pay back over a long period. While costs in Section 3 are typically developed in a cost-effectiveness framework, estimating the direct economic costs of meeting a GHG policy goal, the studies here use a social cost-benefit framework that includes other external benefits from a renewable energy-based system such as avoided air pollution impacts on human health. These benefits could be large but are more difficult to quantify than direct energy-system expenditures. Nevertheless, a recent study has found that the benefits of reduced fossil fuel combustion could be of the same order of magnitude as the energy system costs associated with climate mitigation (Zapata et al. 2018). Connolly and Mathiesen (2014) as well as Zapata et al. (2018) also show large economic benefits to Ireland and California based on shifting from fossil fuel to renewable energy expenditures, estimating that the latter generates more jobs and transfers less wealth outside the jurisdiction.

With the included public health benefits, local economic benefits, and high level of innovation, both studies reviewed in this section conclude that a 100% renewable energy system would have net benefits relative to the current energy system, even without accounting for avoided climate damages. However, these benefits would accrue over time after large upfront investments. In Jacobson et al. (2015), the overnight capital cost of new generation and storage infrastructure would total $14.6 trillion nationwide, representing an average annual investment of about $420B (undiscounted) over the 35-year time period from 2015 to 2050.

## 7.3 Summary

This section highlights the additional challenges of a 100% economy-wide renewable energy goal, explored by two studies. These studies relied upon wholesale energy infrastructure replacement across geographic scales with advanced technologies, rather than incremental addition of commercially proven options. One study provided a phased sequence of infrastructure replacement, however, arguing that each step in the sequence could be viable and produce net benefits on its own.

The two studies reviewed in this section represent a growing body of literature contending that 100% renewable energy is achievable and relatively low cost given several prerequisites, including: (a) high levels of innovation and infrastructure investment, (b) incorporation of high levels of flexible loads and advanced long-duration storage, (c) the use of hydrogen or synthetic fuels, and (d) the expansion of infrastructure across geographic scales to allow for the use of district heating and long-distance transmission. These studies are motivated in part by the eventual need to reduce net GHG emissions all the way to zero to achieve climate stabilization.

However, there is a continued debate about whether the 2050 timing and the exclusion of nuclear and CCS in these studies are realistic goals, and the extent to which these goals overlap with the broader goal of reducing GHG emissions as quickly as possible while protecting the economy (Brown et al. 2018; Heard et al. 2017).

# 8 Appendix: New York State and Northeast regional decarbonization studies

As part of the literature review, we evaluated four recent studies investigating deep decarbonization and/or highly renewable systems specifically for New York State or the Northeast Region.

## 8.1 New York State studies

Clune et al. (2019) analyzes what changes in investment and system operation would be required to meet the electric sector emissions targets from the 2019 Climate and Community Protection Act. These include the requirements of 70% renewable electricity production by 2030 and 100% zero-emissions electricity by 2040. The authors also assume that these targets must be met while demand for electricity is increasing, with statewide load growing by a third between 2020 and 2040. The study finds that renewables will account for more than 60% of New York State's electricity by 2040, but that a range of supply-side and demand-side resources (zero-carbon firm capacity, battery storage, demand-side management, etc.) will be necessary for such a highly renewable system to reliably function. The study also finds that typical north-to-south transmissions flows in New York will eventually reverse direction due to the deployment of off-shore wind, that pumped hydro storage will be utilized at a much higher rate, and that market mechanisms for compensation will need to change to ensure that conventional resources like combined-cycle natural gas plants remain available to serve as backup despite having low capacity factors.

Jacobson et al. (2013) examines the technical and economic feasibility of a 100% renewable energy economy powered by electricity from wind, water, and sunlight (WWS) and electrolytic hydrogen in New York State by 2030. This study follows the same methodology as other world and U.S.-wide WWS studies conducted by the author (Jacobson, Delucchi, Bazouin, et al. 2015) and is the first WWS plan developed for an individual state. The plan requires 254 GW (nameplate capacity) of renewables by 2030 to meet an annual statewide demand of 60 GW, in addition to replacing all fossil-fuel consuming end-use devices and processes in buildings, transportation, and the industrial sector with either electricity, hydrogen fuel cells, or hydrogen combustion. In addition to wind, solar PV, and hydroelectric resources, the plan requires the large-scale deployment of concentrated solar (38.7 GW), wave (1.4 GW), and tidal (2.6 GW) power. The study finds that the WWS plan is cost-effective compared to a business-as-usual case when including environmental externalities for air pollution and climate impacts.

## 8.2 Northeast regional studies

National Grid, one of the largest energy companies in the Northeast United States and an electric and gas provider in New York, published a white paper in 2018 presenting a pathway for the Northeast to reduce greenhouse gas emissions 80% by 2050 and 40% by 2030 (relative to 1990 levels) (National Grid 2018). The white paper describes the three overarching principles of the pathway: "target the highest emitting fuels and sectors first; optimize the utilization of existing networks; and avoid price shocks through strategic use of electricity and natural gas use." While the resulting pathway achieves the 2030 target through a combination of measures across the electricity generation, transportation, and building heating sectors, the transportation sector appears to shoulder a greater share of emissions reductions. The pathway requires 100% EV sales for light and medium-duty vehicles by 2030, with half of the on-road light duty vehicle fleet being EVs by that year as well. In comparison, the share of zero-carbon electricity increases from 50% to 67% over the same period, while in building heating, the share of heating demand increases from 2% to 28% for electricity and from 55% to 60% for natural gas. The white paper does not present pathway results post-2030, and the measures needed to reach the 2050 targets are only discussed qualitatively.

Williams et al. (2018) examines the changes in energy system infrastructure and technology needed for the Northeast to reach an 80% greenhouse gas emission reduction by 2050 and the potential impact of expanded coordination between the Northeast and Hydro Quebec. The study compares four increased coordination scenarios to a deep decarbonization base case. The increased coordination scenarios include expanded transmission capacity between the Northeast and Hydro Quebec, new Canadian hydro resources, new Canadian wind resources, and the inclusion of PJM as a participant in the expanded coordination. The study finds that all four increased coordination scenarios provide net benefits relative to the deep decarbonization base case. While expanding transmission capacity only increased annual net benefits by ~$130 million in 2050, the other three scenarios all provided annual net benefits of over $4 billion (including cost savings to PJM). The study authors find that the scale of potential benefits warrants further investigation into increased coordination between the Northeast and Quebec as the regions pursue deep decarbonization.

# 9 Appendix: Glossary

## Acronyms of technical concepts

| Acronym | Definition |
|---|---|
| BDT | Bone dry tons |
| BECCS | Bioenergy with carbon capture and sequestration |
| BEV | Battery-electric vehicle |
| CCGT | Combined cycle gas turbine |
| CCS | Carbon capture and sequestration |
| CHP | Combined heat and power |
| CST | Concentrating solar thermal |
| CT | Combustion turbine |
| DAC | Direct air capture |
| DSM | Demand-side management |
| EV | Electric vehicle |
| GDP | Gross domestic product |
| GHGs | Greenhouse gas emissions |
| HVDC | High-voltage direct current [transmission] |
| LCOE | Levelized cost of energy |
| MSW | Municipal solid waste |
| P2G | Power to gas |
| PCM | Phase change material |
| PHS | Pumped hydro storage |
| PV | Photovoltaic [solar] |
| RPS | Renewable portfolio standard |
| TES | Thermal energy storage |
| TCS | Thermochemical storage |
| UTES | Underground thermal energy storage |
| WWS | Wind, water, and sunlight |

## Acronyms of models and institutions

| Acronym | Definition |
|---|---|
| BTS | Billion Ton Study |
| CPI | Climate Policy Initiative |
| DOE | [US] Department of Energy |
| DOSCOE | Dispatch-optimized system cost of electricity |
| EU | European Union |
| IPCC | Intergovernmental Panel on Climate Change |
| NEMS | National Energy Modeling System |
| NEWS | National Electricity with Weather System |
| NREL | National Renewable Energy Laboratory |
| POWER | Power system Optimization With diverse Energy |
| ReEds | Regional Energy Development System |
| RESOLVE | Renewable Energy Solutions Model |
| SWITCH | Solar and Wind energy Integrated with Transmission and Conventional sources |
| WECC | Western Electricity Coordinating Council |

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