POWER INFRASTRUCTURE NEEDS FOR ECONOMYWIDE DECARBONIZATION

C2ES CLIMATE INNOVATION 2050

by

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April 2021

Achieving net-zero emissions will require large scale change across all sectors of the economy, and efforts to drive this transition are intensifying. Over the past several years, through the Climate Innovation 2050 initiative, the Center for Climate and Energy Solutions (C2ES) has engaged closely with leading companies across diverse sectors to examine challenges and solutions to decarbonizing the U.S. economy by 2050. As we laid out in *Getting to Zero: A U.S. Climate Agenda*, reaching net-zero will require this large-scale change, but it will also require us to address a number of discrete and urgent challenges. To inform policymakers considering these near- and long-term questions, C2ES launched a series of "Closer Look" briefs to investigate important facets of the decarbonization challenge, focusing on key technologies, critical policy instruments, and cross-sectoral challenges. These briefs will explore policy implications and outline key steps needed to reach net-zero by mid-century.

EXECUTIVE SUMMARY

The power sector must play a central role in the decarbonization of the U.S. economy. Other sectors such as buildings, industry, and transportation will be electrifying to reduce their emissions, which means the power sector over the next few decades not only has to be 100 percent non-emitting, but also much larger. It will need to accommodate massive deployments of variable renewable energy resources such as solar and wind, as well as burgeoning numbers of electric vehicles, distributed energy resources, and energy storage technologies. This will require a significant buildout of power system infrastructure, including additional generation, distribution, and transmission capacity. The mix of centralized and distributed resources and the two-way power flows introduced by resources such as rooftop solar and vehicle-to-grid technologies will also necessitate infrastructure upgrades to enhance deployment of intelligent systems.

Getting that new and upgraded infrastructure built can be very challenging, however, particularly for interregional transmission. Transmission projects can face significant planning and permitting hurdles and therefore, if they manage to clear the hurdles at all, can take more than a decade to deploy. There are potential pathways, though, to smooth and speed deployment. Approaches such as competitive renewable energy zones and undergrounding and co-locating transmission

in existing rights-of-way could be models for making progress in deploying interregional transmission. Siting new non-emitting centralized generation plants near or at the same location as existing or retiring plants can minimize the need for new transmission infrastructure, as can deploying smaller, more distributed power generation resources that are sited closer to demand and within local lower-voltage distribution networks. Energy storage is also emerging as a non-wires alternative to upgrading substations and building new transmission lines, though long-duration storage technologies need to be further developed. Policies and reforms must reduce the need for transmission, help get transmission built, and strengthen transmission connections between regional grids.

To lessen the amount of transmission needed, policymakers should adopt policies that:

- maintain existing firm non-emitting generation for as long as possible
- advance the production and supply of low-carbon fuels to replace emitting fuels in existing firm generation
- invest in innovation to help develop and deploy low-cost, flexible, firm low-carbon generation technologies that are currently at a more nascent stage
- incentivize energy efficiency across sectors
- deploy incentives and implement programs to minimize increased peak demand due to electric vehicle charging
- increase support for public transportation systems and other measures to reduce the need for vehicle use
- increase support for and adoption of low-carbon alternative transportation fuels, particularly for medium- and heavy-duty vehicles
- advance deployment of distributed energy generation resources
- Require utilities to evaluate non-wires alternatives such as energy storage in addition to new transmission line proposals
- invest in energy storage research, development, demonstration, and deployment, including on long-term storage options.

To overcome past transmission deployment challenges and get more transmission built, policymakers should adopt updated strategies and policies that:

- utilize ‘Smart from the Start’ siting policies and criteria
- co-locate transmission infrastructure in existing transportation corridors.
- direct the Federal Energy Regulatory Commission to develop a comprehensive, long-range national infrastructure strategy
- facilitate the siting of “climate-critical” infrastructure.

In addition, strengthening the connections and increasing the transfer capacity between the three major regional interconnections in the United States, as well as across the seams between neighboring regional transmission organizations within an interconnection, should be encouraged and incentivized to enable greater resource sharing and enhanced resilience.

These measures will help ensure that the infrastructure needed for a clean, resilient, and affordable power system will actually be deployed, providing the foundation for economy-wide decarbonization.

INTRODUCTION

In order to have a reasonable chance of keeping global average temperatures from warming 2 degrees Celsius (3.8 degrees Fahrenheit) above pre-industrial conditions, as agreed to by the international community in hopes of avoiding the worst effects of climate change, global net greenhouse gas emissions must be approaching zero in the second half of this century.[1] The timeline and pace of reductions must be even quicker if the aim is to limit warming to 1.5 degrees Celsius, which will require global anthropogenic carbon dioxide (CO_2) emissions to reach net-zero around 2050.[2]

As described in **Figure 1**, pathways to deep decarbonization generally focus on three important strategies for the energy system: (1) increasing energy efficiency; (2) decarbonizing the energy supply; and (3) fuel switching.[3] Fuel switching strategies include electrification of end-uses (e.g., from gasoline- and diesel-powered cars to electric vehicles, from natural-gas-fired furnaces and

FIGURE 1: Decarbonization Strategies

ENERGY EFFICIENCY	ENERGY SUPPLY DECARBONIZATION	FUEL SWITCHING
Making final energy consumption more efficient in buildings, industry, and transport.	Shifting electricity generation mixes to low-carbon resources, including renewables, nuclear, and fossil with CCUS.	Electrifying end-uses and using more low-CO_2 alternatives such as hydrogen where possible.

Source: U.S. Deep Decarbonization Pathways, E3, LBNL, PNNL, 2015.

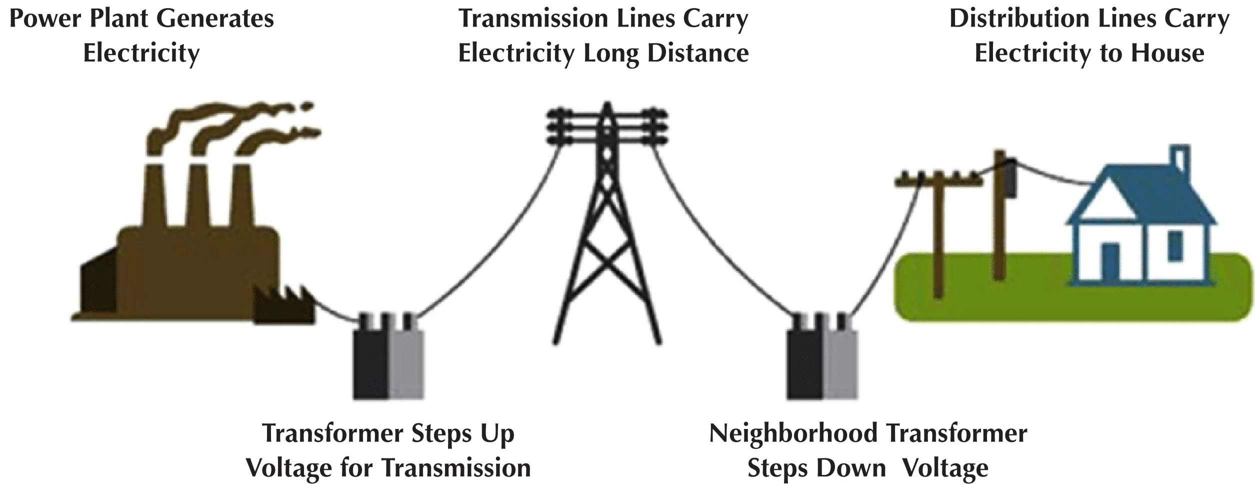
water heaters to electric versions), as well as greater use of lower-CO_2 alternatives such as biofuels and hydrogen.

Increasing electrification in other sectors—such as transportation, buildings, and industry—will require much greater quantities of electricity than the power sector delivers today. Modeling suggests that U.S. electricity production will have to grow substantially, perhaps by 75 percent or more by mid-century, though that growth could be somewhat mitigated by improved energy efficiency.[4]

In addition to being much larger, the future U.S. power system must also effectively be 100 percent non-emitting. While there are many possible technological combinations and approaches that could achieve decarbonization of the power sector, most studies suggest that the least costly and least technically challenging path to achieve the mid-century goal involves a diverse mix of resources, including not just renewables such as wind and solar, but also firm, low-carbon generation that can be dispatched on demand and for long periods of time.[5] Firm, low-carbon generation includes hydropower with large reservoirs, nuclear power, geothermal, and fossil fuel plants that have either switched to decarbonized fuels (e.g., biomass, renewable natural gas, hydrogen) or deployed carbon capture, utilization, and storage (CCUS).[6] Even though additional transmission capacity can lower the overall cost of entirely renewable electricity systems, these systems are still significantly more costly than those that include firm generation sources.[7] Having a broader portfolio of clean electricity can also help minimize delivery disruptions, whether caused by physical, technical, weather, cyber, or other threats.

Delivering greater quantities of 100 percent clean electricity—with the expectation that it will be as reliable,

FIGURE 2: Traditional Electricity Grid—One-Way Power Flow



Centralized power plants generate electricity, which is transmitted long distances on high-voltage power lines, i.e., high-voltage bulk-transmission system. Neighborhood transformers or substations step down the high-voltage power, and lower-voltage distribution lines deliver power to homes and businesses.

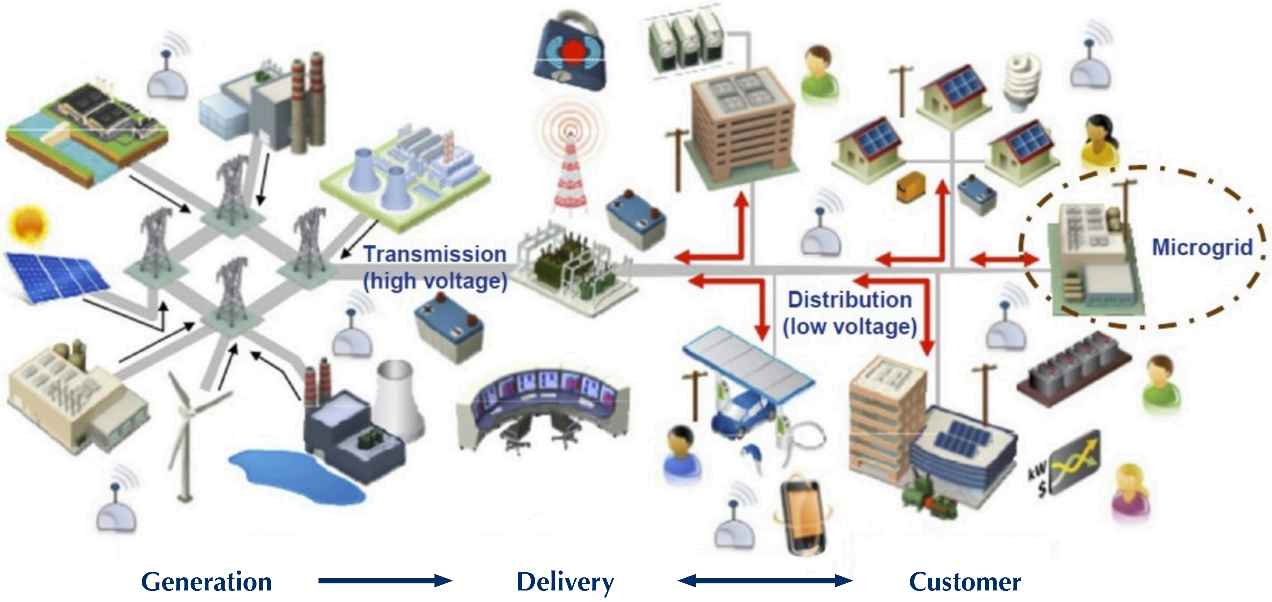
Source: U.S. Energy Information Administration, "How Electricity is Delivered to Consumers", October 22, 2020, https://www.eia.gov/energyexplained/electricity/delivery-to-consumers.php.

affordable, and resilient as electricity today—will require a fundamental revamp of the electric power system and a significant amount of new infrastructure. Traditionally, the electric power system has been designed for one-way power flow (see **Figure 2**), with centralized power plants generating electricity that is transmitted long distances on high-voltage power lines—also known as the high-voltage bulk transmission system, local transformers or substations decreasing or "stepping down" the voltage, and lower-voltage distribution lines delivering power to homes and businesses.

Increasingly, however, the electric power system is changing in ways that necessitate infrastructure deployment (see **Figure 3**). At the distribution level, solar rooftops, electric vehicle (EV) charging, and microgrids are introducing two-way power flows, requiring infrastructure upgrades and battery storage to support more active electricity "prosumers" (i.e., who both produce and consume electricity). On the generation side, sources such as wind and solar are introducing more variability, increasing the need to deploy greater capacity, energy storage, and other backup and supporting infrastructure. In addition, there is an increased need to make grids more resilient to both physical threats (e.g., storms, electromagnetic pulses) and cyber threats. As the U.S. electricity system has gotten cleaner, more variable, more distributed, and more challenged by threats—all trends that will continue—the need for new power system infrastructure has become ever clearer.

This brief takes a closer look at U.S. power sector infrastructure needs. It begins by reviewing what recent power sector modeling illuminates with regard to new infrastructure needs and then highlights some of the challenges and opportunities involved in actually getting that infrastructure built. The brief then discusses three current and emerging trends—electric vehicle growth, distributed generation deployment, and energy storage deployment—and assesses the impacts they could have on infrastructure development. Finally, the brief discusses policies and reforms that will help ensure that the necessary infrastructure will be in place for the clean power system of the future.

FIGURE 3: An Interconnected Power System Balancing Forecast Resources with Dispatchable Loads



The electricity grid of the future will feature more clean variable generation, battery storage, smart systems with active consumers, vehicle-to-grid integration, and two-way power flows among other things.

Source: Richard Stuebi, "Electricity Industry Transformation: Pathway to the Grid-of-Grids," Boston University, March 7, 2019, https://www.bu.edu/ise/2019/03/07/electric-industry-transformation-pathway-to-the-grid-of-grids/.

DECARBONIZATION MODELING

Power sector decarbonization modeling to date has generally taken two distinct approaches. Some studies look at a mid-century power sector that is comprised nearly entirely of variable renewable generation (i.e., wind and solar power) and is bolstered by energy storage, demand response, and a significant expansion of transmission.[8] Other studies rely on significant expansions of wind and solar generation but also include firm, dispatchable low-carbon electricity sources such as nuclear power, fossil fuels with CCUS, geothermal energy, and biofuels.[9] Regardless of the approach pursued, the modeling scenarios make clear that a lot of additional infrastructure is needed to make the power system function reliably, though some scenarios require more infrastructure than others.

Models that involve high levels of variable renewable energy (VRE), in particular, depend on a highly integrated national high-voltage transmission network; the lower capacity factors for wind and solar compared to dispatchable power plants mean more VRE generation capacity needs to be built and connected.[10] In any power sector future, significant expansion of VRE is likely and necessary, and substantial new transmission will be needed to get that power to consumers. For example, in the U.S. Energy Information Administration's (EIA) *Annual Energy Outlook 2020*, an additional 25 gigawatts (GW) of interregional transmission capacity is added in the 'Carbon Fee $35' case (i.e., the case that sees the greatest deployment of renewable capacity—an additional 370 GW—above the Reference case).[11] The National Renewable Energy Laboratory (NREL) suggests that a 56 to 105 percent increase in long-distance transmission capacity is needed for a grid with 80 percent renewable electricity.[12] Preliminary data from Evolved Energy Research indicates an 80 percent expansion of interregional transmission, primarily from the wind belt (i.e., Central United States) toward the south and east, is necessary in its lowest-cost case in order to achieve economy-wide decarbonization by 2050.[13]

While modeling is helpful in revealing the scale of the needed infrastructure, the models do not say much about how the infrastructure will actually get built; they just presume it will be there. Infrastructure is largely a second-order modeling consideration that follows from scenario constraints (e.g., "high renewables", "high nuclear", "high CCUS", "high efficiency"). Infrastructure such as new transmission is acknowledged as a cost in the modeling (e.g., reflected in the electricity rates that consumers pay), with models 'constructing' transmission lines as needed at an assumed price to ensure reliable power flow.[14] However, as described below, much more is at play in making needed power sector infrastructure into a reality.

TRANSMISSION CHALLENGES AND OPPORTUNITIES

Policy dimensions, social factors (e.g., public support, consumer preference, equity), land use constraints, and costs will all be key considerations in developing the infrastructure needed to transition to 100 percent clean power.[15] Construction of power system infrastructure has therefore run into numerous challenges, though there are potential models that could provide a measure of optimism going forward.

TRANSMISSION INTERRUPTED

Siting any lengthy, high-voltage power line across multiple states and jurisdictions has proven to be exceptionally challenging in recent years. (Many other types of energy infrastructure—from fuel pipelines to wind farms—have also faced significant opposition.) Interregional transmission can face planning and permitting hurdles—including contested permits and litigation—from multiple states, regional authorities, federal agencies, and local interests.[16] Individual lines can therefore take more than a decade before they are fully deployed, assuming they successfully make it through the gauntlet of obstacles at all.

Table 1 highlights three high-voltage transmission projects that have suffered repeated setbacks (some fatal) over the past decade. The Sand Hills Transmission Project in Nebraska, proposed in 2012 to enhance system reliability and enable output from future wind farms, has faced numerous legal challenges from historic preservationists, environmental activists, and anti-wind-farm groups.[17] After seemingly having the go-ahead last year,

TABLE 1: Challenges for New Transmission

PROJECT NAME	LOCATION	YEAR PROPOSED	RECENT ACTION
Sand Hills 345 kV transmission project	Nebraska	2012	Federal judge revokes permit, delays project: June 2020
Northern Pass HVDC transmission project	New Hampshire	2011	Eversource cancels the project: July 2019
Grain Belt Express	Kansas, Missouri, Illinois, and Indiana	2011	Updated plan would deliver more renewable energy to Missouri: August 2020 Missouri House legislation requiring approval from each county commission: February 2021

a federal judge revoked the project's permit. Similarly, Eversource's Northern Pass project in New Hampshire, which sought to bring hydropower from Quebec into the New England power market, was cancelled after eight years of opposition from a deeply divided public and the state Supreme Court's upholding of the rejection of its permit.[18] This power line's dedicated opponents felt the project would harm New Hampshire forests and property values.[19] The Grain Belt Express transmission line, originally proposed to convey 4,000 MW of Kansas wind power to Indiana, faced opposition from the states it would cross through and so has been reimagined to deliver power to those states as well—and the line continues to face significant opposition.[20] Notably, Clean Line Energy, the original (non-utility) owner of the Grain Belt Express and four other long-distance high-voltage transmission projects, has sold its assets and exited the business.[21]

If power system infrastructure projects are always this hard to build, it will be impossible to get in place the infrastructure needed to achieve full power sector decarbonization.

SOME OPTIMISM

There have been power infrastructure success stories as well.[22] Texas, for example, successfully spurred infrastructure development by establishing competitive renewable energy zones (CREZ or REZ).[23] More than 3,500 miles of transmission lines capable of carrying more than 18,500 MW of electricity were constructed in the state between 2005 and 2013, and wind curtailments dropped significantly.[24] While the Texas power system certainly has other challenges, as made starkly apparent in February 2021, the Texas approach to proactive transmission development, which included strong stakeholder collaboration and coordination of regulatory authorities at all levels, should be a model for future development.[25]

Another promising approach that could ease transmission siting difficulties involves undergrounding and co-location in existing rights-of-way. While burying or undergrounding can cost ten times the amount of overhead transmission, it can increase system resilience and mitigate public opposition by eliminating visible infrastructure.[26] Undergrounding still requires transmission projects to get all of the necessary permits and can require the use of eminent domain to access the land on the planned route (which can spur lots of public opposition), but co-location can eliminate some of those hurdles. For example, the Direct Connect Development Company is advancing the SOO Green HVDC Link to bring 2,100 MW of clean electricity from western Iowa to the Chicago suburbs, via underground high-voltage transmission sited along existing railroad (and other transportation) rights-of-way to minimize environmental and visual impacts and avoid eminent domain issues.[27] With future additional HVDC links, Direct Connect seeks to repeat for clean electricity transmission the successful model previously used to build out the nation's fiber optic network.[28]

OTHER TRENDS IMPACTING POWER INFRASTRUCTURE

Developments regarding end-use electrification, distributed energy resources, and energy storage will influence the total amount, type, and location of power infrastructure that needs to be in place by mid-century. As noted earlier, electrification of end uses—switching from fossil fuels to clean electricity in transportation, buildings, and industry—will involve substantial expansion of overall power demand, not to mention significant demand increases in particular locations, which will in turn have a large impact on power system infrastructure. Policies mandating zero-emission vehicle sales and city bans on new natural gas hookups will accelerate these electrification trends. Similarly, deployment of distributed energy resources has been growing, and as that trend continues, more electric generation will be sited near points of consumption, which will impact the type of electric infrastructure required—though centralized generation and its associated infrastructure will continue to be necessary. Deployments of energy storage (which can be a type of distributed energy resource) have likewise been booming and are projected to continue to do so, which will have a range of implications for power sector infrastructure, such as helping to defer or eliminate investments in transmission lines. The implications of these trends are reviewed in more detail below.

EVs AND HIGHWAY TRANSPORTATION

Electrification in the transportation, industrial, and buildings sectors will significantly increase annual electricity demand in the United States. Though electrification will occur in all sectors, the shift in at least some parts of the transportation sector from oil-based fuels to electricity could arguably have the most dramatic impact on power sector infrastructure. Utilities, grid operators, and government leaders should start planning now for the challenges and opportunities provided by transportation electrification.

Electrification of the nation's 250 million light-duty vehicles is already underway, with more than 20 automakers offering electric vehicles (EVs) and annual sales of EVs at around 2 percent of total vehicle sales.[29] Forecasts estimate that the number of EVs in the United States could swell from 1.5 million to 10 to 35 million by 2030.[30] If the actual number falls somewhere in the middle of that range, around 20 million EVs by 2030, that would create an additional 60—95 TWh of annual demand and potentially 10—20 GW of peak load (see **Text Box**).[31] For reference, the United States produced 4,118 TWh of electricity in 2019, excluding distributed solar generation.[32]

BOX 1: Peak Load

Any power system must be built to support the anticipated peak load—the period of maximum demand. Electricity peaks occur daily, weekly, and monthly. But a system's most critical peak loads are typically driven by extreme weather days (e.g., heat waves, cold snaps), when exceptionally high demand for heating or cooling coincides with typical industrial and commercial demand. On these days, there needs to be sufficient available power plant generation to call on. For system reliability purposes, there is therefore a buffer of additional plant capacity that must be maintained and ready to be called upon, whether due to peak demand or the unavailability of a regular generation source. The North American Electric Reliability Corporation (NERC) performs seasonal and long-term reliability assessments for power systems (e.g., balancing authorities, regional transmission operators) across the country.

Finding ways to avoid growing the peak such as: load shifting, e.g., charging storage assets, which could include EVs, during non-peak periods for usage during peak periods, implementing demand response programs during periods of high usage and other adopting other policies (e.g., time-of-use pricing) to encourage power savings during periods of high demand could help minimize the need for infrastructure upgrades and new power plant construction, which are costs that are typically borne by ratepayers or consumers.

To meet customer needs, the United States will need to make significant investments in infrastructure to support charging in residential, workplace, and public settings. In the not-too-distant future, some consumers will need to charge multiple vehicles at home, significantly increasing residential load. Since many people do not own single-family detached homes, consideration must be given to accommodate the needs of renters and those who live in multi-unit dwellings. Additionally, some large retailers want to provide charging for customers (as well as their delivery vehicles), and other businesses want to provide on-site charging capability for their employees. To enable interstate travel and commerce, a nationwide charging network will be needed as well, with deployment of new chargers along highways and charging services offered at traditional fuel (i.e., gas) stations across the country. This will all require careful planning and investment at the distribution level.

A key dimension to consider is the type of charging required (i.e., Level 1, Level 2, or DC fast). The faster the charging time, the greater the instantaneous power requirement per vehicle; in other words, a faster recharge time means a charger has to be able to draw more power (i.e., watts) at any given moment (see **Table 2**).[33] When added up across numerous chargers on the grid, greater instantaneous power requirements for EV charging mean greater potential to increase peak load, which could require additional generation and transmission capacity to ensure reliability and minimize congestion. Whether it is Level 1 or Level 2 charging in homes or fast charging along highways and at businesses, new charging infrastructure will precipitate major upgrades to local distribution networks and the high-voltage bulk transmission system. These upgrades can be minimized to some extent through intentional approaches to reduce the impact of EV charging during times of high demand, including: setting vehicle charging prices higher during typical seasonal and daily peak periods to encourage charging during non-peak times; incentivizing charging opportunities during periods of high renewable production (i.e., solar midday and wind overnight) non-coincident with peak periods; and adopting "managed" or "smart" charging technologies and programs that give electricity suppliers remote control over EV charging times and levels. Note that the Pacific Northwest National Lab found that the existing grid can likely accommodate up to 30 million EVs with unmanaged charging, but with thoughtful management that number doubles.[34]

Although tariffs will play a vital role in ensuring that vehicles charge off-peak, they could nevertheless result in consumers all starting to charge at the beginning of the off-peak period (e.g., 11:01 PM), resulting in a "mini-peak." For this reason, active load management/smart charging will likely become increasingly beneficial to the electric grid as more EVs are deployed. In order to enable active load management/smart charging programs, utilities, ISOs, and other stakeholders will need to work together to develop incentives which provide reasonable compensation for the development and operation of these programs, including customer recruitment and retainment.

The impacts of transportation electrification for the U.S. power system extend well beyond light-duty vehicles. Today, there are nearly 9 million motorcycles, nearly 1 million buses, and more than 13 million medium- and heavy-duty trucks on the road.[35] To enable electric medium- and heavy-duty trucks to recharge in a reasonable amount of time, instantaneous power loads in the hundreds of kW to one MW range are being studied.[36] Under such loads, 100 heavy-duty trucks recharging simultaneously could require their own 100 MW power plant, which would be costly and entail a significant amount of infrastructure buildout (e.g., new power

TABLE 2: Comparison of Instantaneous Power Requirements for Light-Duty Vehicle Charging

TYPE	INSTANTANEOUS POWER PER VEHICLE (KW*)	TIME TO CHARGE	WHERE IT IS USED
Level 1	1	~20 hours (100%)	Standard wall outlet
Level 2	6–20, typically 6–7	~5 hours (100%)	Most public charging
DC Fast Charger	25–50	30 minutes (80%)	Highways

*1 kW is equal to 1,000 watts of power. A typical LED lightbulb uses about 10 watts of power.

Source: ChargePoint

plants, transmission and distribution lines, substations).[37] This is one reason why alternatives, such as hydrogen, are being considered for decarbonizing at least some medium- and heavy-duty transport; while these alternatives are costly as well, they could scale better than electricity with less infrastructure buildout and speedier refueling.

Power demand and infrastructure needs will expand significantly due to transportation electrification, but EVs could also *be* power system infrastructure through vehicle-grid integration programs and technologies. EVs have the potential to serve as smart, flexible load and charging can be managed to match grid needs through smart charging programs that can leverage technologies such as automaker telematics to actively manage charging. Going a step further, by leveraging the stored energy in a multitude of car and truck batteries, vehicles could help balance intermittency issues and mitigate future peak load challenges. Vehicle-to-grid (V2G) technology allows two-way flow between vehicle batteries and the grid. However, vehicles and potentially their chargers have to be designed and enabled for this technology.

Currently, very few light-duty and medium-duty vehicles can use V2G charging, though there are pilot programs in various states exploring the V2G potential of electric school buses.[38] Conflicting technical standards regarding inverter operation will need to be resolved before V2G equipped vehicles or charging stations are allowed to connect to the grid in any widescale fashion. The Combined Charging System—a widespread EV charging standard—is currently establishing a range of V2G standards, which could help enable much greater participation; more complete standards are expected by 2025, and products could follow soon afterward.

Another key variable is uptake by consumers; how much can they be counted on to participate in V2G to reliably manage intermittency and peak loads in the future? Currently, there is no compensation mechanism for exporting power back to the grid under V2G for retail customers; the situation is more complex for commercial and industrial customers. Without a clear and easily accessible economic incentive for customers, V2G's use will remain limited.

CENTRALIZED AND DISTRIBUTED GENERATION

Where new generation is deployed will have an impact on the quantity and type of power sector infrastructure required. In the simplest terms, the two options for siting new generation are either large, centralized power stations or smaller, distributed power resources.

Historically, the power system has been based on large centralized power stations that are connected to the high-voltage or bulk transmission system in order to send power long distances to faraway consumers (see **Figure 2**, earlier). In general, new centrally located generation will likewise require new high-voltage, long-distance transmission, which, as described earlier, is challenging to deploy. Much of the appeal of large, centrally located generation is that it is generally more efficient and cost-effective than building many smaller plants, even considering line losses in delivering the power to consumers.[39]

Smaller, more distributed power generation resources (e.g., solar rooftops, microgrids) are sited closer to demand, near and within local lower-voltage distribution networks. They are therefore easier to site and build (though they certainly face opposition too). Indeed, some have argued that it would be better to focus efforts on deploying distributed clean electricity infrastructure rather than centralized. However, it is unlikely that the nation could deploy enough clean, affordable electricity locally to meet its mid-century decarbonization goals. The more the country is able to deploy clean electricity locally, the lower the burden will be on building out the more challenging bulk transmission system, but the nation's vast utility-scale renewable resources, which are inherently centrally located projects, will need to be tapped. Recognizing the scale of clean electricity deployment needed and the significant regional differences in the availability, affordability, and productivity of clean resources, the United States will have to focus on both centrally located and distributed projects.

CENTRALIZED

Over the next 30 years, a great deal of new clean power supply needs to be installed, not only to support significant electrification, but also to replace existing emitting generation. Siting new centralized non-emitting generation plants near or at the same location as existing or retiring plants (potentially after remediation) is the least-cost, lowest-impact approach in terms of the need for new power infrastructure. A new utility-scale solar or wind farm, advanced nuclear project, or fossil fuel plant (running on low-carbon fuels and/or with CCUS) can be built—dependent on land use constraints, available renewable resource, and public consent—and make use of existing power infrastructure, including rights-of-way, switchyards, substations, and transmission lines.

There are considerable utility-scale wind and solar resources, however, that are economically attractive, highly productive, and located far from existing infrastructure and electricity demand. Many gigawatts of these projects are already in the queue awaiting interconnection approval from regional transmission organizations (RTOs), independent system operators (ISOs), and other balancing authorities across the country.[40] In the decades ahead, there will be many, many more. For example, in the International Energy Agency's *World Energy Outlook 2020*, the Sustainable Development Scenario (a scenario that achieves net-zero emissions by 2070) projects U.S. solar PV capacity to increase by a factor of 10 from 76 GW in 2019 to 751 GW in 2040, while wind capacity more than triples from the current level of 104 GW to 353 GW in 2040.[41] Much of this new capacity will likely be centrally located. Importantly, the best locations in terms of high renewable resource availability, low transmission costs, and few connection challenges are being proposed earliest, so getting these projects built will only grow harder (and more costly) over time.

Other types of new centralized power projects may be similarly unlikely to be able to seize the cost advantages of using sites with pre-existing infrastructure. For example, conventional geothermal, hydropower, and pumped-storage hydropower projects can only be built where there are available resources and the necessary topography, which may not align with where existing infrastructure is. Even centrally located dispatchable plants that can more easily be located near existing power infrastructure (e.g., new nuclear, cleaner fossil plants) may be constrained, to some extent, by proximity to other needed infrastructure, such as transport links (e.g., pipelines, rail) or waste (e.g., CO_2) storage.

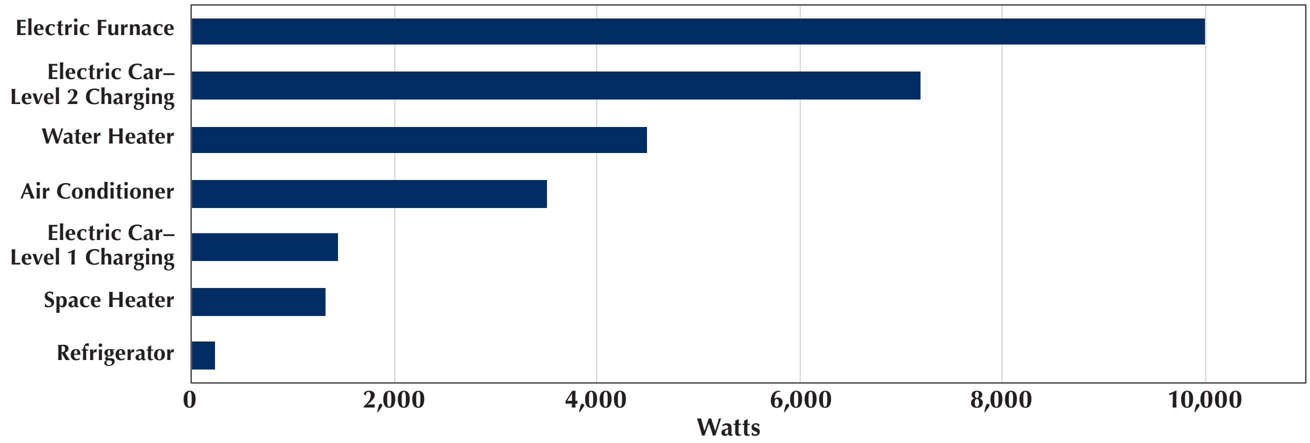
DISTRIBUTED

Generating clean power closer to where it will be consumed can reduce power infrastructure needs, particularly by reducing the need for more high-voltage transmission lines. Moreover, generating more clean power locally (coupled with greater energy efficiency) can help reduce demands on the grid and bring about earlier retirements of polluting central power stations, freeing up the associated infrastructure for use by new non-emitting generators (as described above). In contrast to long-distance high-voltage lines, local infrastructure to support distributed generators tends to be easier to build. New, smaller, distributed plants can be sited near and within local distribution networks, and, in general, lower voltage, local distribution lines are less costly to construct and can be undergrounded more easily, helping to mitigate public opposition. Local projects also involve fewer jurisdictions and stakeholders than multi-state projects.

The technical potential for local, distributed variable generation across the United States is quite large. For example, a 2016 NREL assessment found that the total estimated technical potential (all buildings) for annual generation from rooftop PV in the United States is 1,432 TWh (from an estimated installed capacity of 1,118 GW), which is a little more than one-third of total U.S. utility-scale electricity generation in 2019 (**Table 5**).[42] Technical potential will not necessarily translate into developed projects, but there is clearly substantial room for growth, given that the United States produced a total of 35 TWh of distributed solar generation in 2019.[43] The appeal for self-generation is strong, with more than 11 GW_{DC} of residential rooftop PV added over the past 5 years, and steady growth is expected to continue through mid-century.[44] Beyond roofs, there is also additional potential for solar gardens or other local smaller-scale community solar projects.

Still, local projects face cost, land use, efficiency, and other challenges that have implications for infrastructure needs. For example, community solar and rooftop residential PV are two and five times more expensive, respectively, than large utility-scale projects, which means dollars that go toward them might theoretically be more cost-effectively directed toward less costly clean generation and infrastructure options.[45] Densely populated areas may also find it challenging to identify enough space to deploy modest community solar projects, and land-use conversion (e.g., from farms or forests to solar) may both stir public opposition and lead to a counter-productive increase in net greenhouse gas emissions. Additionally, most rooftop PV is fixed, limited by roof pitch and direction, and can be obstructed by trees and chimneys, which limits its overall efficiency; likewise, the higher the latitude of the solar deployment, the less efficient the installation will be. (In the United States, December efficiency is on average 60 percent lower than the highest efficiency June days.[46]) With the limits on efficiency and roof area, a typical rooftop solar PV system only provides around 6 kW of power,[47] which is

FIGURE 4: Power Draw for a Typical Appliance



Note that in colder climates an electric furnace may draw 20,000 watts (or 20 kW).

Source: Department of Energy, September 2017

not enough to accommodate a typical household's future electricity loads (see **Figure 4**).[48] That means that self-generation often will have to be combined with excess local distribution network generation (including battery storage) and centrally generated electric power.

Not only do those resources have to be combined, but rooftop solar, EV V2G, and other distributed resources also introduce two-way power flows into local distribution networks. To achieve the necessary level of coordination and maintain safe and reliable power flows, infrastructure upgrades are needed. In addition to upgrades or replacement of equipment such as transformers, there is also a need for greater deployment of intelligent systems—including software, smart meters, and other smart technologies (e.g., synchrophasors)—to more closely monitor, manage, and control power flows.[49] Furthermore, system hardening will be necessary to address cyber vulnerabilities created by the proliferation of smart, connected devices (as well as to increase resiliency to climate impacts). Table 3 identifies, in much greater detail, the necessary characteristics for a modern, decarbonized transmission and distribution network; it also identifies, research, development, demonstration, and deployment (RDD&D) needs for the entire electric power system.

ENERGY STORAGE

Energy storage deployment in the United States has been growing rapidly as costs continue to decline –trends that are expected to continue. The U.S. battery storage market is projected to grow sixfold from 1.2 GW in 2020 to almost 7.5 GW in 2025.[50] Energy storage deployments are occurring both behind the meter (residential and non-residential) and in front of the meter, in order to smooth output from VRE, replace polluting "peaker" power plants, provide critical ancillary grid services that help prevent damage to electric equipment and infrastructure (e.g., frequency keeping), and serve many other purposes. Indeed, energy storage has been compared to a swiss army knife for all of the functions that it can perform across different parts of the power system. All of these functions have important implications for power system infrastructure.

Most important in terms of power sector infrastructure, energy storage is emerging as a non-wires alternative to upgrading substations and building new transmission lines. For example, in New York, electric utility Con Edison's Brooklyn-Queens Demand Management Program is utilizing customer-sited battery storage as part of a portfolio of distributed assets to defer a $1.2 billion substation upgrade.[51] In Arizona, electric utility Arizona Public Service (APS) deployed a 2 MW, 4-hour duration battery storage system for less than the cost of upgrading 20 miles of transmission and distribution lines to serve the rural town of Punkin Center.[52] In California, Pacific Gas & Electric is planning to deploy 10 MW of energy storage as part of a portfolio of transmission solutions during its regional transmission planning process; this will be the first storage project in the United States to provide congestion relief.[53] Energy storage

TABLE 3: Moving from Traditional to Modern Electric Power Systems: RDD&D Needs

ELECTRIC SYSTEMS	CHARACTERISTICS		RDD&D NEEDS
	TRADITIONAL	**MODERN**	
Generation	Centralized Dispatchable Large thermal plants Mechanically coupled	Centralized and distributed More stochastic Efficient and flexible units Electronically coupled	Planning tools Energy storage Control coordination Flexible thermal generators
Transmission	SCADA for status visibility (sampling, not high definition) Operator-based controls (primarily load following and balancing) Destabilizing effects Congestion, despite underutilized capacity (limited flow control) Threats/vulnerabilities not well defined	High-fidelity, time-synchronized measurements Breadth and depth in visibility Automatic control Switchable network relieves capacity constraints Threats are considered and risks are appropriately managed	Multi-terminal, high-voltage direct current Low-cost power flow controller technologies Next-generation energy management systems (EMS) Integrated planning tools Security Low-cost bulk storage
Distribution	Limited visibility Limited controllability Radial design (one-way flow) Floating on transmission Increasing fault currents and voltage issues stressing system Aging assets (unknown effects)	Enhanced observability Local, autonomous coordination Network design and two-way flow Backbone of delivery system Self-healing Active monitoring of asset conditions	Security Microgrids Advanced distribution management systems Distribution and asset sensors Solid-state transformer Smart voltage regulation equipment Community storage
Customers	Uniformly high reliability, but insensitive to upstream issues Energy consumers (kilowatt hour) Predictable behavior based on historical needs and weather Interconnection without integration Growing intolerance to sustained outages	Customer-determined reliability/power quality Prosumers (integrated) Variable behavior and technology adoption patterns Plug/play functionality Kept informed during outages (and before) Hybrid alternating current/direct current distribution Data access (outage/usage)	Single-customer microgrids Building EMS Distributed energy resource integration Security Transactive controls Behind-the-meter storage Low-cost sensors

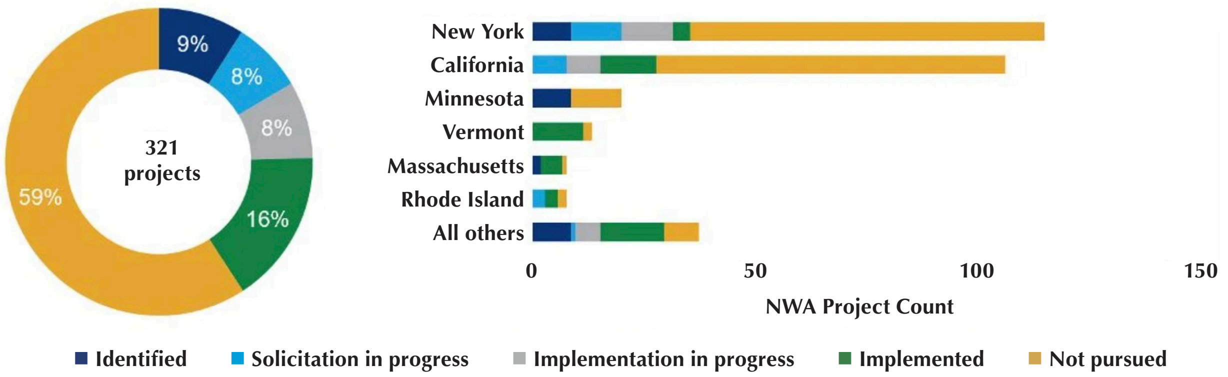
Source: Quadrennial Technology Review, Department of Energy, September 2015 projects such as these can help minimize the quantity of challenging power sector transmission projects needed to decarbonize the economy.

The hurdles to greater use of energy storage as a non-wires alternative, however, should not be understated. Although energy storage can be deployed more quickly, can perform more functions, offers more optionality with regard to siting, and has a smaller footprint than traditional transmission projects, the technology is seen as being relatively new, leading to concerns that these projects will be more costly and less reliable than conventional solutions.[54] Therefore, only around 40 percent of non-wires alternative proposals have progressed to the project development stage (see **Figure 5**).[55] In addition, traditional cost-of-service regulation models reward utilities for putting more steel in the ground, not for minimizing capital expenditures; these regulatory models can hinder energy storage deployment in many states.[56] Furthermore, public utility commissions (PUCs) may prefer or have a bias toward more established solutions (i.e., wires). As **Figure 5** shows, deployments of non-wires alternatives have been greatest in states such as California and New York that have adopted specific programs to incentivize them.

There are also important power system infrastructure implications from the fact that energy storage needs go beyond what can be provided by lithium-ion batteries. Battery storage will continue to be an increasingly valuable grid asset as VRE generation shares increase. However, with high levels of VRE and high levels of short-term (i.e., four-hour) battery deployments, the economic value of storage will reach a point of diminishing returns.[57]

An electric power system that relies on high shares of VRE must be capable of dealing with persistent lulls (e.g., days or weeks) in wind and solar output (particularly in winter months) that cannot be overcome with short-term (i.e., four-hour) batteries and flexible demand. In addition to firm generation options, long-duration storage technologies are also needed.[58] Forms of electric energy storage such as pumped hydro or traditional hydropower with large reservoirs behave more like firm, dispatchable generation and provide valuable diversity to the power system, but those types of projects can require substantial infrastructure.[59] Clean electricity sources can also be used to produce hydrogen, ammonia, or other energy carriers, which can be stored for long periods (i.e., days, weeks, or months), transported in pipelines, and used on demand as an alternative to new transmission. In addition, new battery chemistries show promise for longer duration storage; for example, Form Energy's sulfur battery concept is expected to deliver 1 MW of power for 150 hours from its one-acre Cambridge, Minnesota pilot project.[60] These technologies are nascent, however, and further research, development, and demonstration of alternative battery chemistries and other long-duration energy storage options will be critical to achieving a fully decarbonized power system without needing as much of an infrastructure buildout.

FIGURE 5: Non-Wires Alternative Project Count by Status and State



Source: Wood-Mackenzie Grid Edge Service

RECOMMENDED POLICIES AND REFORMS

In whatever manner electrification evolves in other sectors, new and upgraded infrastructure—including transmission, substations, energy storage, smart meters, and other hardware and software—will be needed to support a larger, cleaner power sector by mid-century. All the pieces are necessary, though as noted throughout this brief, transmission is among the most challenging pieces of infrastructure to deploy. Policies that help minimize the amount of transmission necessary and that help to get crucial transmission built in a timely fashion are therefore particularly essential.

REDUCING THE NEED FOR TRANSMISSION

As decarbonization modeling makes clear, very high VRE penetrations require substantial deployment of transmission infrastructure; while virtually all scenarios involve significant expansions of VRE, increasing the share of flexible, firm, non-emitting generation in the electricity mix can significantly lessen the need for transmission. Accordingly, policymakers should consider and adopt policies that:

- maintain existing firm non-emitting generation (e.g., hydro, nuclear) for as long as possible;
- advance the production and supply of low-carbon fuels (e.g., hydrogen, renewable natural gas, biofuels) to replace emitting fuels in existing firm generation; and
- invest in innovation to help develop and deploy low-cost, flexible, firm low-carbon generation technologies that are at a more nascent stage, such as advanced nuclear, advanced geothermal, and fossil fuels with CCUS.

It is also clear that energy efficiency measures across all sectors will reduce the magnitude of the mid-century power sector, and thus its associated infrastructure. Therefore, policies should be adopted to incentivize energy efficiency, such as building, appliance, and equipment standards.[61]

In addition, given the infrastructure implications of the trends reviewed earlier regarding EVs, distributed generation, and energy storage, policymakers should also consider and adopt policies that:

- help minimize increased peak demand due to EV charging, such as incentives for off-peak charging (e.g., through time-of-use pricing) and implementation of managed charging programs;
- increase support for city and regional public transportation systems and other measures (e.g., bike lanes, walkable cities) that can limit total vehicle miles traveled (i.e., reduce the need for vehicle use);
- increase support for and adoption of hydrogen and other low-carbon alternative transportation fuels, particularly for medium- and heavy-duty vehicles, which can be stored more easily than electricity, avoid huge increases in power demand, and offer other benefits (e.g., more rapid refueling times);
- advance, to the extent feasible and with consideration of affordability and other issues (e.g., public support), local construction of clean energy sources (i.e., close to demand), which helps avoid the need for additional high-voltage transmission;
- require utilities to provide non-wires alternatives such as energy storage in addition to new transmission line proposals so that they can be evaluated on cost, reliability, visual impacts, congestion relief, and so forth; and
- invest in energy storage research, development, demonstration, and deployment, on at least three fronts: (1) improving battery chemistries and designs to make them cheaper and safer; (2) developing long-term storage options that behave more like firm, dispatchable power; and (3) evaluating and advancing the production of non-emitting energy carriers (e.g., hydrogen, ammonia) using carbon-free electricity sources.

GETTING TRANSMISSION BUILT

Even if all of the above measures are implemented, there will still be a need for new transmission. There is broad consensus that generation levels from VRE in the mid-century power system will likely exceed 50 percent of the electricity mix, with much of that from utility-scale renewables. Capitalizing on the excellent utility-scale solar resources across the Southern United States, onshore wind resources in the Great Plains, and offshore wind resources will require significant new transmission infrastructure. Additionally, the addition of new electrified loads in other sectors and the retirement of large emitting power plants will force system operators to implement line upgrades, build new transmission, and adopt other transmission solutions to maintain system reliability. Updated strategies and polices to overcome past deployment challenges are therefore urgently needed.

BEST PRACTICES

Entities proposing new projects and policymakers responsible for approving them (including public utility commissioners) would be well served by studying successful transmission deployments, including the CREZ program in Texas. NREL has produced a *Renewable Energy Zone (REZ) Guidebook* on this topic, and useful planning documents have also been compiled by the Federal Energy Regulatory Commission (FERC) (i.e., *Report on Barriers and Opportunities for High Voltage Transmission*), and America's Power Plan (i.e., *Finding a Home for Renewable Energy and Transmission*).[62]

Historic transmission challenges can be overcome when 'Smart from the Start' siting policies and criteria are utilized (see **Table 4**), including early, robust stakeholder engagement.[63] Further, siting approaches that utilize existing transportation corridors, such as the Direct Connect Development Company's SOO Green HVDC Link, could help avoid many of the traditional development obstacles and provide the needed pathways for delivering remote renewable electricity.

FEDERAL POLICY

Creating a 21st-century grid to facilitate the decarbonization of the economy requires strong leadership from the federal government. In 2005, Congress granted FERC new authorities under the Federal Power Act to expand, modernize, and improve the reliability of the nation's transmission grid. This included the authority to designate national interest energy transmission corridors, where FERC could override state authorities when necessary, on siting decisions. Court challenges, however, have stymied FERC's use of these authorities.

While most utilities produce periodic long-range plans that include transmission and other infrastructure upgrades, there is a need for greater national, regional, and cross-utility coordination (e.g., between electricity and natural gas utilities). Congress should direct FERC to develop a comprehensive, long-range national infrastructure strategy and should more clearly establish its authority on siting decisions. FERC's infrastructure strategy should:

- be informed by a multi-stakeholder process;
- establish clear priorities (e.g., REZ) for staged expansion and enhancement of the grid, including the designation of high-priority high-voltage transmission routes (co-located, where feasible, with existing rights-of-way);
- identify what needs to be built and where, at a level of granularity necessary to manage progress and ensure that the desired system is deployed before mid-century;
- assess the value of national or regional interconnection of existing networks; and
- prioritize the development of complementary networks for distributing hydrogen, renewable natural gas, ammonia, and other fuels for seasonal

TABLE 4: Smart from the Start Siting Policies and Criteria

• Consult stakeholders early and involve them in planning, zoning, and siting.	• Establish, when possible, pre-screened resource zones for development.
• Collect and use geospatial information to categorize the risk of resource conflicts.	• Incentivize resource zone development with priority approvals and access to transmission.
• Avoid land and wildlife conservation conflicts (including national parks and other protected areas) and prioritize development in previously disturbed areas.	• Consider renewable energy zones or development sites that optimize the use of the grid.
• Avoid cultural resource conflicts (historic sites, tribal resources, etc.).	• Maximize the use of existing infrastructure, including transmission and roads.
• Identify excellent renewable energy resource values.	• "Mitigation that matters" (durable and planned conservation improvements at larger scales).
	• Where zoning is not feasible (as in much of the Eastern Interconnection), use siting criteria based on the above principles.

Source: America's Power Plan (2013)

energy storage and cross-sectoral purposes (e.g., fuels for transport and industry), as well as networks for captured CO_2.

Informed by FERC's national infrastructure strategy, Congress or the White House should facilitate the siting of "climate-critical" infrastructure, including grid upgrades, grid hardening to better protect customers from weather-related outages, and other key resources such as storage batteries and energy pipelines.

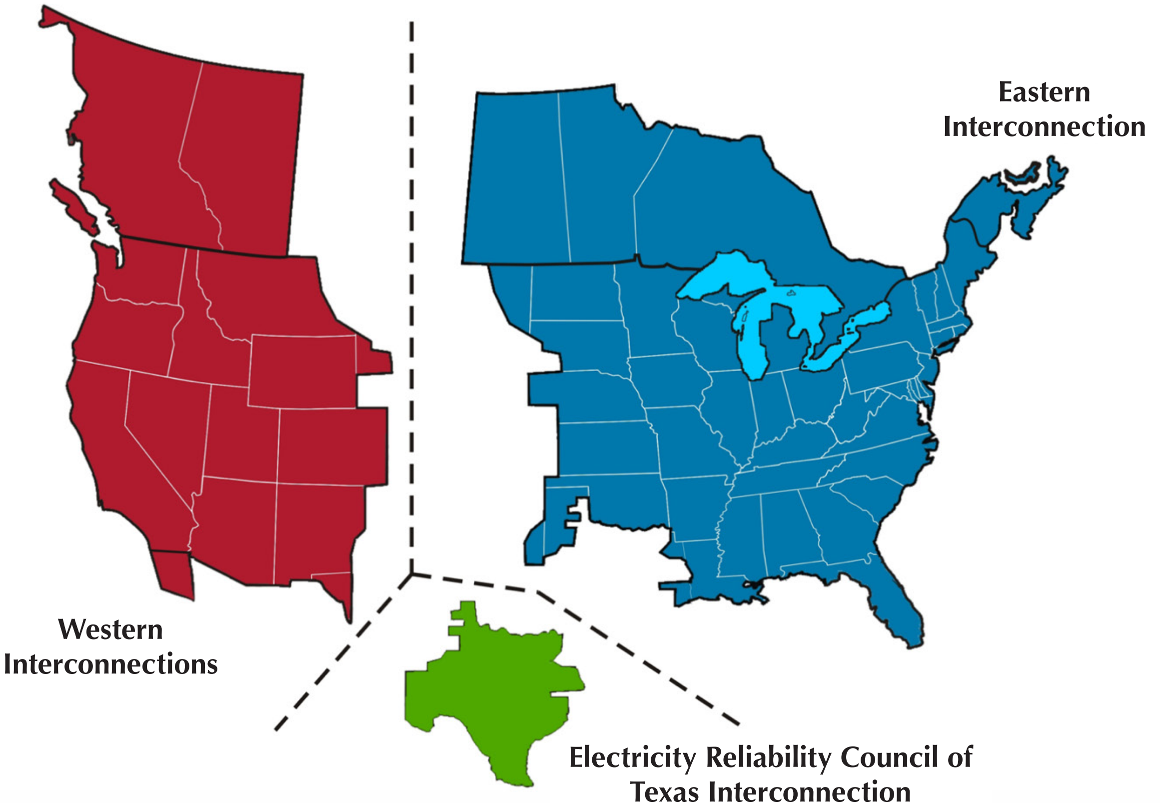
REGIONAL EFFORTS

The U.S. power system is currently split into three major areas—the Eastern Interconnection, the Western Interconnection, and the ERCOT Interconnection (see **Figure 6**)—and very little power is currently exchanged between them.[64] Strengthening the connections or increasing the transfer capacity across these seams could provide significant benefits. For example, a more integrated (national) grid could provide greater resource sharing, meaning fewer total resources would be required; and, additional connections could increase resilience to extreme events. Studies by NREL and RTOs should be continued and should help inform a FERC-led strategy. Additionally, recommendations from previous studies, such as the transmission planning studies conducted with funding under the 2009 Recovery Act, should be consulted.[65]

There are also seams between neighboring RTOs (e.g., MISO and SPP) within an Interconnection. RTOs should be encouraged and incentivized to look for opportunities to develop mutually beneficial projects along these seams as well.[66]

FIGURE 6: U.S. Electric Power Grid

NORTH AMERICAN ELECTRIC RELIABILITY CORPORATION INTERCONNECTIONS



Source: Department of Energy (2011)

CONCLUSION

To help stave off the worst effects of climate change, net global greenhouse gas emissions must be approaching zero before mid-century. Building a much larger and 100 percent clean power sector to support widespread electrification is the lynchpin of nearly every economy-wide decarbonization strategy. Key to realizing a reliable and resilient net-zero power sector is putting in place all of the necessary infrastructure.

The much higher levels of variable renewable electricity that will be part of the power system of the future, coupled with the growth of electric vehicles, centralized and distributed generation, and energy storage will dictate (along with other factors) the quantity and type of power infrastructure that is needed. Understanding the implications of these trends and developing policies to minimize the challenges they present will help ensure that the clean, reliable, resilient, and affordable power system of the future actually gets built.

C2ES would like to thank The Bernard and Anne Spitzer Charitable Trust, the William and Flora Hewlett Foundation, the Energy Foundation, and the Intel Corporation for their support of this work. We would also like to thank Dave Grossman for his contributions to this work.

APPENDIX

TABLE A-1: Total Estimated Technical Potential (All Buildings) for Rooftop PV by State

STATE	ANNUAL GENERATION POTENTIAL (% OF SALES)	INSTALLED CAPACITY POTENTIAL (GW)	ANNUAL GENERATION POTENTIAL (TWh/YEAR)	TOTAL ROOF AREA SUITABLE FOR PV DEPLOYMENT (MILLIONS OF m^2)
California	74.2%	128.9	194.0	961
Maine	60.0%	6.3	7.1	45
Vermont	60.0%	3.0	3.4	21
Rhode Island	56.6%	3.8	4.4	28
New Hampshire	53.4%	5.3	5.9	38
Connecticut	49.8%	12.8	14.8	95
Massachusetts	47.0%	22.5	26.0	165
Florida	46.5%	76.2	103.2	557
Michigan	45.9%	42.1	47.3	303
Colorado	44.0%	16.2	23.5	119
Oklahoma	44.1%	19.3	26.4	140
New Mexico	43.4%	6.1	10.0	45
Missouri	42.7%	28.3	35.6	204
Kansas	41.7%	12.5	16.6	90
Nevada	39.6%	8.7	13.9	67
New Jersey	40.4%	24.9	30.1	184
Wisconsin	40.1%	23.6	27.7	169
Maryland	38.7%	19.3	23.9	142
Minnesota	38.5%	23.1	26.4	168
South Dakota	38.7%	3.8	4.7	26
New York	37.4%	46.6	55.3	340
Illinois	37.0%	44.1	52.5	324
Ohio	35.3%	46.8	53.0	338
Iowa	35.5%	14.0	16.6	99
Texas	34.6%	97.8	131.2	715
North Carolina	34.9%	35.0	45.3	252
Pennsylvania	34.5%	43.6	50.4	316
Nebraska	34.1%	8.2	10.5	60
Utah	34.3%	7.2	10.4	52
Oregon	34.2%	14.1	16.3	101
Georgia	33.8%	34.6	44.1	251
Arizona	34.4%	16.3	26.1	114
Arkansas	33.3%	12.2	15.5	88
Virginia	32.4%	28.5	35.8	205
Tennessee	31.9%	24.4	30.9	175
Mississippi	31.2%	11.7	15.2	84

STATE	ANNUAL GENERATION POTENTIAL (% OF SALES)	INSTALLED CAPACITY POTENTIAL (GW)	ANNUAL GENERATION POTENTIAL (TWh/YEAR)	TOTAL ROOF AREA SUITABLE FOR PV DEPLOYMENT (MILLIONS OF m^2)
Delaware	31.0%	2.9	3.5	20
Louisiana	29.8%	20.1	25.6	146
Alabama	29.8%	20.4	26.2	147
Indiana	29.5%	26.3	31.1	188
Montana	28.0%	3.2	3.9	21
Washington	26.6%	22.8	24.7	164
Idaho	26.4%	4.7	6.4	33
Kentucky	25.2%	18.0	21.4	131
South Carolina	25.5%	15.2	20.0	108
North Dakota	24.6%	3.3	3.9	23
West Virginia	22.9%	6.3	7.2	45
Washington, D.C.	15.1%	1.3	1.7	11
Wyoming	14.2%	1.7	2.4	12
Continental U.S. Total	38.6%	1,118	1,432	8,130

Source: National Renewable Energy Laboratory, January 2016

Other Climate Innovation 2050 Resources:

Getting to Zero: A U.S. Climate Agenda
https://www.c2es.org/document/getting-to-zero-a-u-s-climate-agenda/

Pathways to 2050: Scenarios for Decarbonizing the U.S. Economy
https://www.c2es.org/document/pathways-to-2050-scenarios-for-decarbonizing-the-u-s-economy/

Restoring the Economy with Climate Solutions: Recommendations to Congress
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