America's ZERO CARBON ACTION PLAN

The Zero Carbon Consortium

2020

5. APPROACHES FOR KEY SECTORS

5.1 Accelerating Deep Decarbonization in the U.S. Power Sector

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5.1.1 Introduction, Context and Goals

Decarbonization of the power sector is essential to overall decarbonization goals, as electricity production alone represents 27 percent of U.S. GHG emissions as of 2018.[1] It is relatively easy to imagine how a decarbonized electric supply system could help achieve multiple social and environmental goals. More complicated is envisioning the diverse political and organizational factors aligning at the needed scale and pace. Thus, much of this chapter looks not simply at technologies and long-term aspirations, but also practicalities. This chapter looks at these issues from four different perspectives: (1) supply of electricity; (2) demand for electricity; (3) the topology of the evolving grid; and (4) policy incentives and implementation.

5.1.2 The Pivotal Role for Electric Power

Nationwide, the bright spot in decarbonization is the electric power sector. While new technologies are appearing in other sectors, such as transportation and industry, emissions continue to rise. In the power sector, however, emissions have been going down modestly since 2005 – about a 33 percent decline in emissions from the sector.[2] That trend might be described as shallow decarbonization, but may be auspicious. So far, decarbonization of the power sector has come from factors partly related to climate policy, the surge in inexpensive natural gas, and rising supply of renewables and energy efficiency. These factors have shrunk the share of power generation from coal in favor of lower to zero-carbon emissions. For the first time since 1885 the share of renewables in U.S. power supply now exceeds that of coal (Figure 5.1.1).[3]

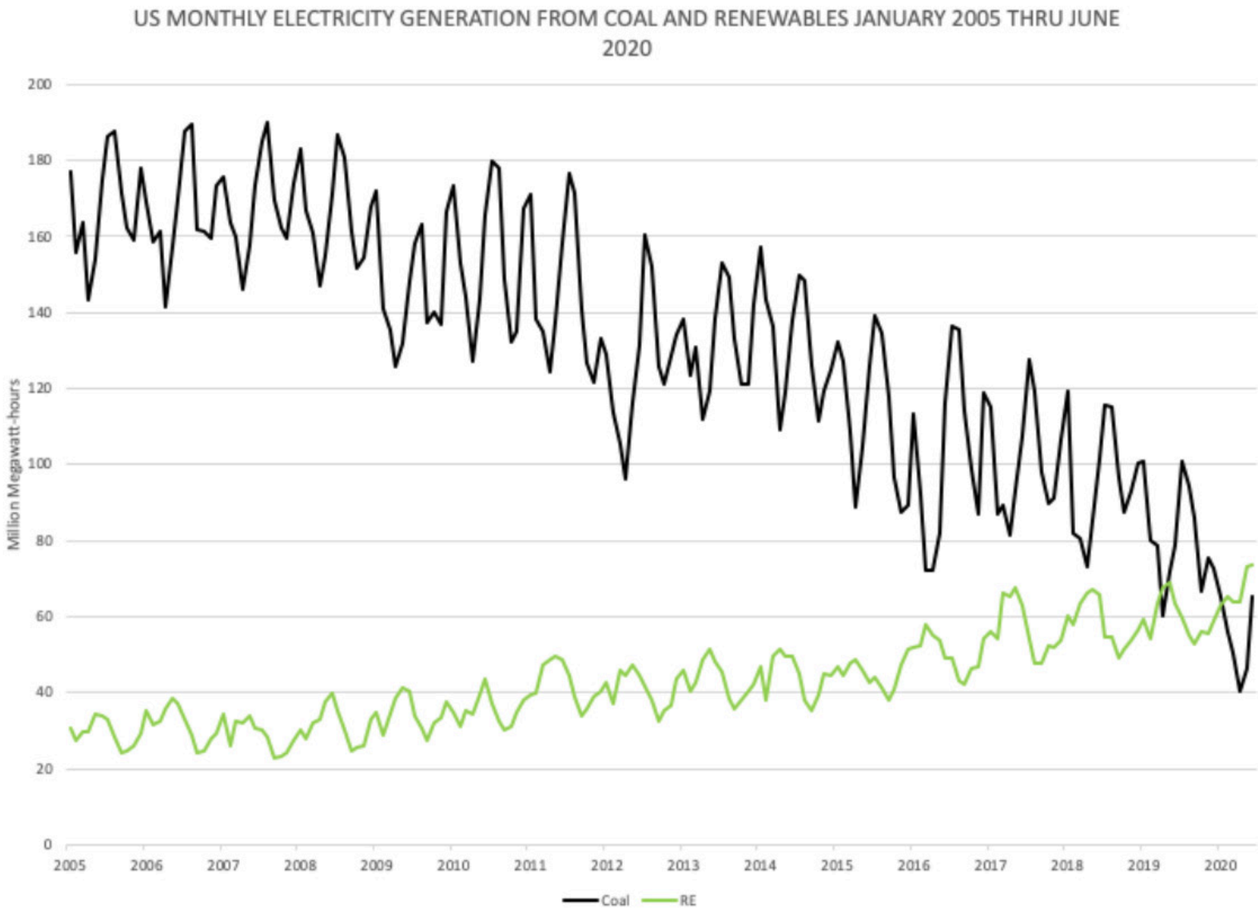

Figure 5.1.1: The contest between coal and renewables on the U.S. power grid (figure original; data from U.S. Energy Information Administration, 2020).

Looking to the future, the rate of decarbonization of the U.S. power sector will need to accelerate (Figure 5.1.2). Some states have visions for that change already—such as California, Hawaii, and New York—but federal policy has not yet been supportive of the speed and extent of change. Moreover, decarbonization of the entire U.S. economy will likely require that many applications that currently rely on direct combustion of fossil fuels—for example, vehicle transportation, heating in buildings and many industrial applications—be electrified. This "electrification" of the economy is one of the most consistent results from large-scale energy models. Electrification of those end uses, while promising, involves a large number of uncertainties including, performance of end-use electric technologies, electricity storage, and the rapid scale up of rival approaches to deep decarbonization (e.g., using hydrogen as an energy carrier).

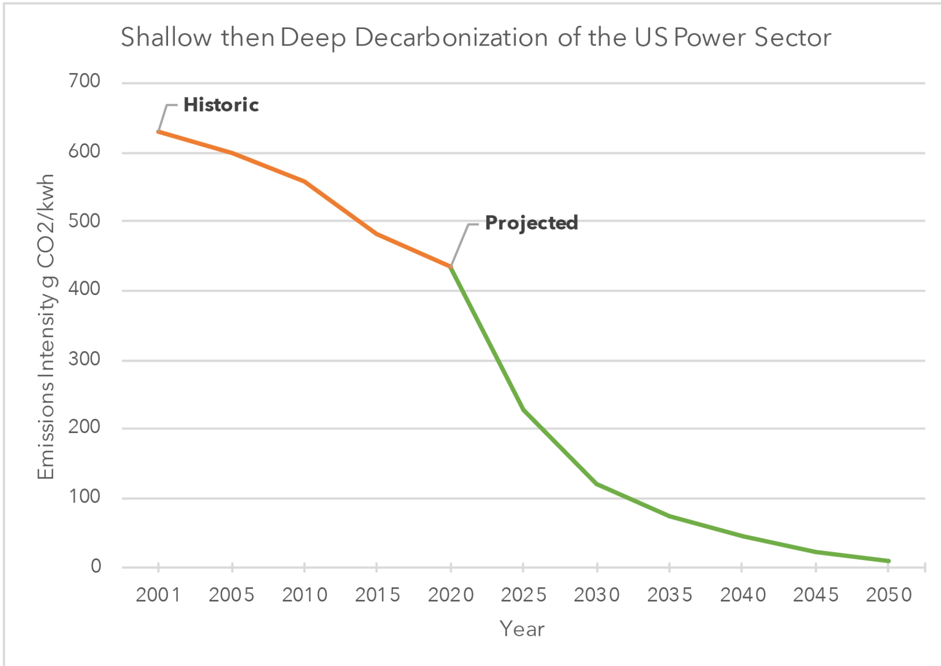

Figure 5.1.2. Shallow then deep decarbonization of the U.S. power sector. (original figure)

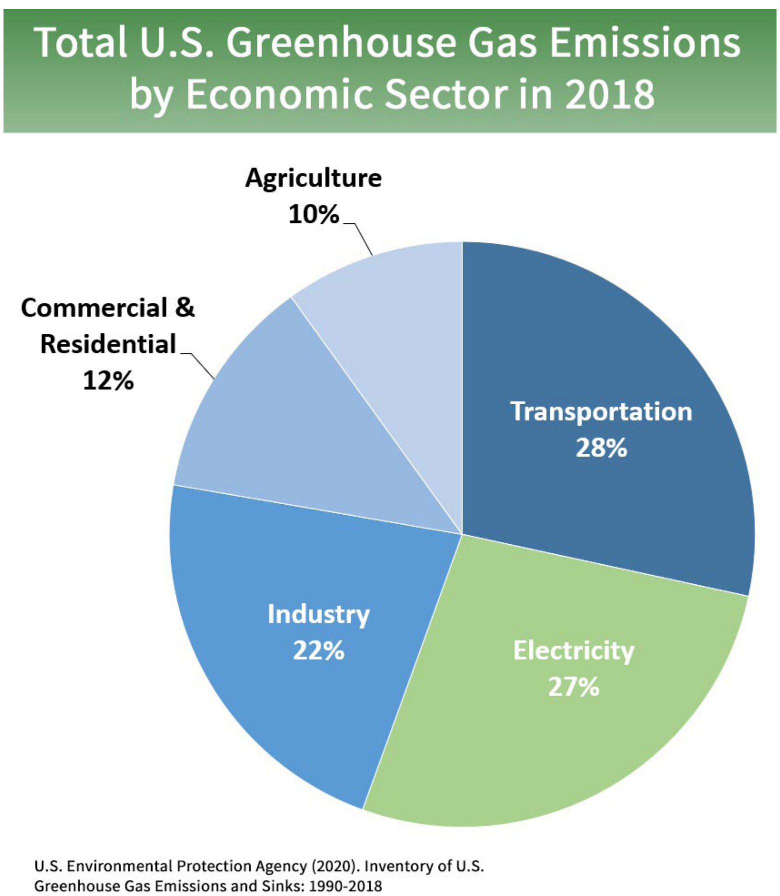

Figure 5.1.3. Total emissions from the power sector (Sources of Greenhouse Gas Emissions, 2020).

This chapter considers how the power sector could play a pivotal role in deep decarbonization of the entire economy. While the focus is heavily on the technological opportunities, transformation of the power sector is not merely a technical question. Instead, it is a matter of industrial organization, socio-economic interactions, and political choice. Organizationally, a key challenge in the U.S. power sector is the sheer number and diversity of owners.

The last century has seen the rise of a large number of investor-owned utilities (IOUs) that provide the backbone of U.S. electric service—as measured by the volume of electricity supplied. All of these companies are heavily regulated due to fears of monopolistic behavior. Within this group there are vertically integrated companies that provide all services—from power generation to transmissions, distribution and marketing—along with firms in markets that have been “restructured” in various ways to unbundle those services. Unbundling has, in theory, allowed portions of electric service that are natural monopolies (e.g., transmission and distribution) to be separated from those where competition is more viable (e.g., generation). In recent decades, unbundling has created more firms and competition where policymakers have allowed. Meanwhile, in the most regulated markets, consolidation has created a smaller number of huge integrated utilities. Looking beyond IOUs, the U.S. also has a number of publicly owned enterprises that provide similar services (e.g., Tennessee Valley Authority), including enterprises owned by states (e.g., NY Power Authority) and a large number of locally owned power enterprises (e.g., LA Department of Water and Power, Orlando Utilities Commission, or Dairyland Power Cooperative). All told, approximately 200 investor-owned utilities and Approximately 2,900 publicly owned utilities (including cooperatives, municipal utilities, and special-purpose utility districts) own and operate the U.S. power supply system.[3] This dispersion in ownership is important because it reflects highly diverse incentives and fragmentation in the imperative and ability to reap the rewards of innovation.

Many trends point to continued, if not accelerating, fragmentation, such as with the rise of community choice aggregation (CCA)—publicly owned local power marketing authorities that are replacing IOUs in some states (Figure 5.1.3).[5]

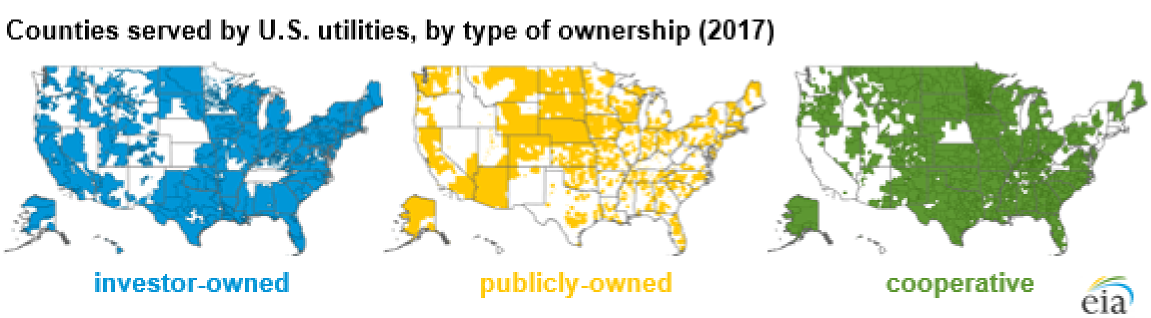

Figure 5.1.4. Load service by ownership type (Darling and Hoff, 2020).

Political choices surrounding the power grid depend not only on how the industry is organized—and its incentives for change—but also what society wants from electric power. Over the last century, reliable and affordable electric service has become pivotal to modern society. It has been the backbone of waves of economic productivity that spanned nearly the whole century. It is vital to modern life—illumination, security, telecommunications and computing. Because of that central role—and because key elements of the grid are natural monopolies—electricity has not been treated as just any industry—it has been regulated (or the means of production state-owned and thus assumed to operate in public interest) in ways needed to assure electricity services align with public interest. This goal takes the form of a "regulatory compact"—that is, a requirement that electricity be available to essentially all households at affordable tariffs and that the grid service be kept at a sufficient level of reliability. Over many decades the "compact" has been extended to include environmental attributes—a clean power system whose environmental burdens do not fall disproportionately on one segment of society.

This background of diverse ownership with diverse incentives, coupled with a social compact that focuses the industry on much more than simply providing a commodity at low cost helps frame the new challenge: decarbonization. Deep decarbonization will need to be seen not simply as an attractive attribute of the grid, but one that reliably contributes to what the society wants from electric power. Failure to do that will create policy pressures that are not deeply sustainable politically.

It is relatively easy to imagine futures for the electric supply system that achieve multiple social and environmental goals. More complicated is envisioning the diverse political and organizational factors aligning at the needed scale and pace. Thus, much of this chapter will look not simply at technologies and visions but also practicalities. Those practicalities arise in at least three dimensions. One is design and implementation of policy in the highly fragmented federalized U.S. system. In that system for decades, policy at the federal level has been largely gridlocked, although some changes have emerged through federal regulatory action, notably at the Federal Energy Regulatory Commission (FERC). So far, FERC action has had mixed implications for deep decarbonization. Some states are more decisively aligned around this goal, but they account for perhaps one third of U.S. electric service. A second dimension is building and sustaining political and community support for decarbonization of a sector that must meet other political goals. Third is how to craft and implement a policy process that addresses seriously the high uncertainties about which technology and investment strategies will be best. This process encourages experimentation and rapid learning, which is efficient about how capital is allocated and also bound to realities about how real firms think about investment under uncertainty.

This chapter will look at these three challenges from four different perspectives: (1) supply of electricity; (2) demand for electricity; (3) the topology of the evolving grid; and (4) policy incentives and implementation.

5.1.3 Decarbonization of Supply

Laws in eight U.S. states require either by goal or mandate the installation of zero-carbon electricity systems by mid-century. Thirteen other states are actively considering similar measures.[6] An even larger group of states have some form of renewable portfolio standard (RPS) in place. While most state targets are between ten percent and 45 percent, 14 states—California, Colorado, Hawaii, Maine, Maryland, Massachusetts, Nevada, New Mexico, New Jersey, New York, Oregon, Vermont, Virginia, Washington, as well as Washington, D.C. Puerto Rico and the Virgin Islands—have requirements of 50 percent or greater.[7]

Given the trajectory of clean energy state policies, multiple technology options are available to deeply decarbonize the supply of electricity. However, due to fragmented federalism, states differ widely on decarbonization goals in the U.S. and consequently necessitate the installation of different types of technologies. Some states have expressed goals for 100 percent renewable energy (Hawaii, Maine, Virginia, D.C., Puerto Rico); others seek 100 percent zero-carbon (California, Washington, New York, Nevada, New Mexico). Some of the states with 100 percent clean goals set sub-goals for renewables, such as 80 percent renewable in New Mexico by 2040 or 60 percent renewable in California by 2030. When combined with supportive regulatory action, such as procurement requirements aligned with integrated resource plans (IRPs), these targets can steer power grids down certain pathways and favor investment in certain groups of technologies. Still, even among the states that are highly committed to action, the diversity in approaches is striking. For example, Washington has no renewables requirement as it relies heavily on hydroelectric with large reservoirs which, like nuclear, is low/zero-carbon but not strictly renewable by most definitions used in RPS, the policy instrument used in most of the country to advance renewable energy. As not all states have hydropower resources, there is no one-size-fits-all clean electricity technology solution for the 50 states. The cost-optimal technology mix differs significantly for different states and targets.

Generation Technology Options

Electricity supplying technologies may be grouped according to their policy definition (whether they fall under renewable, low/zero-carbon, or neither) and also according to the type of service, or functional role they play in the grid. Here we categorize electricity technologies into the following categories: (1) variable renewable energy, (2) firm/dispatchable low-carbon options, and (3) carbon capture utilization and storage (CCUS). We review at a high level below and in Table 5.1.1 some benefits and challenges of each technology option in reaching deep decarbonization goals. Additionally, there are a suite of technologies that are necessary to better enable the use of the aforementioned options which are described later in this section.

Variable renewable energy (VRE) resources refer to resources whose electricity generation profiles are inherently variable due to factors exogenous to the control of electric grid or power station operators (i.e., weather). Specifically, this class includes but is not limited to solar photovoltaic, concentrated solar power, onshore wind, offshore wind, and marine hydrokinetic (under development).

VRE resource potential varies by region. States on the east coast like NY, Virginia, and NJ may ultimately depend on large capacities of off-shore wind to meet zero-carbon targets. Midwest states have the highest quality on-shore wind resources, while southern states have the highest quality solar resources and may depend on these to meet their decarbonization goals. Concentrated solar power resources are even more localized as they benefit from direct solar radiation rather than diffuse radiation that works with photovoltaic (PV).

Table 5.1.1 – Characteristics of Select Low-Carbon Electricity Supply Options.

	Current all-in costs	Projected 2050 all-in costs	Flexibility Score	Typical Capacity Factor	Issue 1	Issue 2	Issue 3
VRE							
Onshore Wind			Medium	40	Variable & regional	Transmission	Offshore cost decline?
Offshore Wind			Medium	50	Currently still more expensive than onshore wind or solar	Floating offshore needed for wide deployment	High capacity factors and close to population centers
Solar			Medium	25	Daytime & regional	Declining value as % rises	Perovskite breakthroughs?
Clean and Dispatchable							
Nuclear		?	Low	90	New plants w/ current tech are economically uncompetitive	Existing plants provide lots of zero carbon e-	How will SMRs evolve?
Geothermal		?	Medium	80	Difficult development pathway	Limited locations for conventional	Large resource base for advanced geothermal, but engineering challenges remain
Hydro			Depends	30-80	Ecosystem conflicts	Many existing non-powered dams could be targeted	Pressure to remove existing dams
Biopower			Medium	65-85	Food/water/ ecosystem conflicts	True lifecycle GHG profile unclear	Relatively high fuel costs and engineering problems operating biogas plants
CSP			Medium	20-40*	CSP with storage adds value	Relies on steam turbine, but potential to reduce overall costs	Operational problems at some plants have damaged the industry's reputation
NGCC			High	50-90	Emits GHGs and local pollutants in air and water	Complements VRE	Social license to operate concerns
Capture							
BECCS		?	Medium	60-80	Food/water/ ecosystem conflicts	Negative emission potential	Alignment of biomass production and geological storage needs
CCUS		?	Medium	60-80	NG CCUS has low CO_2 concentration (costly)	Good target for pure CO_2 streams like ethanol	Backstop for existing coal and hard-to-decarbonize sectors

Note: We use the "green-yellow-red" light classification here, with darker shades indicating intensity of positive/negative attributes. VRE=variable renewable energy, CSP=concentrating solar power, CCUS=carbon capture utilization and storage, BECCS=bioenergy with carbon capture and storage. Source: Synthesized by authors from Lazard, NREL, and BNEF data.

As a class, VRE resources tend to have very low variable costs and no fuel costs, with capital costs for certain VRE resources such as solar PV and onshore wind having decreased rapidly in the past decade and continuing to do so. These attributes help explain why, as the economic depression from the pandemic emerged in early 2020, most countries (including the U.S.) saw the share of renewables rise. Compared with coal or gas-fired power plants, where operating costs were higher, it was less costly to let renewable supply take a larger share of declining total power needs. A recent study reported that VRE resources have the lowest unsubsidized costs in delivering bulk power to two thirds of the globe.[8] The return on investment for these technologies can also depend on the quality of the wind and solar resource in locations where these are installed. However, the inherently variable electricity generation profiles from these resources do not necessarily align with that of the load demand. Therefore, these resources need to be complemented by other resources such as firm/dispatchable generation, energy storage, or demand-side flexibility, each of which entail other costs.

Firm or dispatchable low-carbon resources refer to electricity generation technologies that can be inherently controlled to follow the profile of the electric load demand on a consistent and long-duration basis, in contrast to VRE resources. In a decarbonizing context, this class includes but is not limited to nuclear, hydropower, natural gas with carbon capture and storage (CCS), geothermal, and biomass-and biogas-fuel power plants. Some of these resources are strongly geographically constrained: across the U.S., the Pacific northwest has access to abundant hydropower resources, while conventional geothermal resources are concentrated in some Western locations such as California and Nevada. Biomass and biogas resource potential vary depending on the type of biomass or biogas source and are therefore concentrated in specific areas and entail different environmental externalities (i.e., air pollutant emissions, land or water use).

As a class, firm or dispatchable low-carbon resources tend to exhibit high capacity factors and the ability to provide a diverse array of services for the electric grid in addition to the provision of bulk generation, such as grid reliability and reserve capability. Most of these technologies can operate flexibly within the constraints of their physical capabilities with the exception of hydropower, which must often balance electricity generation with water supply, flood control, and environmental quality priorities. Capital costs for resources such as hydropower, geothermal, and nuclear tend to be high upfront, but the lifetimes of these systems can be long and fuel costs are either low or non-existent. Variable costs can be high depending on the type of resource. By contrast, resources such as biomass and biogas can have relatively lower capital costs but entail continuing and potentially volatile fuel costs. CCS systems added to natural gas power plants will increase costs both through the need for extra equipment and reduction in the efficiency of the power plants that use them. Additionally, it is unclear whether natural gas with CCS is allowed as a zero-carbon compliant technology under regional clean power laws such as California's SB100.

Carbon Capture Utilization and Storage (CCUS) refers to a class of technologies that enable the capture and diversion of CO_2 emissions to either a use or storage that prevents these emissions from entering the atmosphere. Of particular importance are technologies that capture and divert the carbon emissions from primary electricity supply resources such as natural gas and biomass. In a renewable heavy grid, the dynamic operation of fuel-fired power plants can create a technical challenge for CCUS integration. Another alternative is to use CCUS in conjunction with natural gas-based hydrogen production, and use hydrogen as a zero-emission fuel.

Technologies that rely on CCS may be constrained depending on the method of carbon storage—storing in geological reservoirs will constrain the use of these technologies to areas with suitable reservoirs. CCUS allows for continued use of limited fossil fuels (which are easy to store, inexpensive and flexible—especially gas) while also allowing for near zero emissions from the power plants. However, the fossil fuel life cycle processes such as incomplete capture, mining, and leakage will still contribute added carbon emissions. Additionally, the economic viability of CCUS technologies will need to improve before these fulfill any substantial role in a decarbonized electricity system (Table 5.1.1).

Enabling Technologies

In addition to technologies that serve as primary sources of electricity generation, a suite of additional technologies must often be installed to enable the electric grid to utilize the aforementioned low/zero-carbon supply options to serve electric demand and maintain the reliability of the system. These include but are not limited to: short-duration energy storage, long-duration energy storage, and flexible loads from systems such as electric vehicle smart charging and dispatchable hydrogen electrolysis, among others. Particularly, while these technologies do not provide electricity generation on their own, their presence in the system enables functions such as shifting variable renewable generation to coincide with demand, reducing the dynamic requirements of firm/dispatchable resources, and providing short-term grid reliability services. These technologies are varied in their costs, externalities, and functions.

Short-duration energy storage includes various electrochemical batteries (i.e., batteries, capacitors, flywheels) that can store relatively small amounts of energy but can charge from and discharge to the broader electric grid at rapid rates. These enable generation from VRE resources to be shifted over the course of a few hours to one day to better coincide with demand, as well as enable the provision of grid reliability services such as frequency regulation that do not require a significant amount of energy. The costs of battery systems have decreased rapidly over the past decade, partly due to benefitting from improvements in batteries for electric vehicles, and these costs are expected to continue to decrease. However, the need to secure adequate materials supply, implement recycling infrastructure, and improve battery system lifetimes are persisting needs. Although redox flow batteries theoretically could be built for long-duration applications, most are built for short-duration with 1-4 hour storage capabilities. With strong incentives for innovation, which now exist, battery platforms could lead to new systems with much longer storage durations. For example, Form Energy is building a 150 hour battery with metal air chemistry.

Long-duration energy storage refers to technologies that can store very large amounts of energy typically over ten hours. These include but are not limited to pumped hydropower, compressed air, and hydrogen or ammonia (Power-to-Gas-to-Power; PGP) energy storage that charge with otherwise curtailed VRE generation. These technologies enable the electric grid to compensate for relatively long periods of time, such as multiple weeks, seasons, or even multiple years. For example, long-duration storage can fill in for summertime resource gaps in U.S. wind power. Today, more than 90 percent of installed storage on the U.S. grid with these attributes is pumped hydro, although with innovation other technologies may take some of that share. Despite low round-trip efficiencies of long-duration storage systems compared to shorter-duration options like batteries, long-duration storage fulfills a different and distinct grid need.[9] Hydrogen energy storage can provide expandable, relatively geography-neutral long-duration storage.

Currently, hydrogen production and consumption via electrolyzers and fuel cells is cost-effective in reliable wind-solar-battery systems.[10] However, hydrogen energy storage in existing infrastructure such as natural gas pipelines, underground salt caverns, and depleted natural gas reservoirs is even more affordable.[11] Costs of the hydrogen energy long-duration storage system could be improved by replacing fuel cells with hydrogen combustion turbines. Ammonia is another option similar to hydrogen that could emerge as an option to store energy in the future.

Also critical is the need to recognize that storage requirements on a grid depend not just on the ability to install storage systems (and the costs of those systems) but also other attributes of the grid that could be complements and substitutes. For example, expanding the capacity of clean firm generation (nuclear, geothermal, hydropower) would reduce the required storage capacity to meet a given decarbonization target.[12] Additionally, flexible loads such as smart electric vehicle (EV) charging can further reduce energy storage requirements.[13]

Flexible loads

Flexible loads refer to changing the temporal profile of electric loads to better coincide with low-carbon electricity generation. These options are significantly varied in their flexibility and magnitude, but include smart electric vehicle charging (V1G) and vehicle-to-grid (V2G), building demand response, and flexible fuel production loads (i.e., electrolysis to produce fuels for non-grid applications). Grid-responsive electric vehicle charging can provide significant renewable integration benefits for the grid and makes use of already-manufactured battery capacity in the EV fleet. However, this practice is not widely implemented and questions persist as to the willingness of drivers to participate in these programs and the adequate valuation of their services. Additionally, the flexibility of electric vehicle charging loads depends on the travel needs of the driver or vehicle fleet operator and is generally lower than a stationary energy storage system. Building demand response can entail strategies such as reducing lighting and heating, ventilation, and air conditioning (HVAC) loads to reduce demand during times when low/zero-carbon generation is limited, and is limited by building occupant comfort limits and functionality needs. Finally, flexible fuel production entails shaping the load profile of electrolytically produced fuels (i.e., hydrogen or renewable natural gas) for use in non-electric grid applications to better coincide with the low/zero-carbon electricity generation.

Integration of Supply on the Electric Grid System

Deep decarbonization is generally defined as an 80-100 percent reduction in emissions from current or recent levels. Evaluating 40 studies revealed two common paths to deep decarbonization.[14] One electricity sector path depends primarily on VRE supported by grid enabling technologies such as energy storage, flexible demand, and expansion of transmission. A second electricity sector path relies on a wider range of low-carbon resources (i.e., wind and solar) but also ‘firm’ resources such as nuclear, geothermal, biomass, and fossil fuels with CCS.[15]

By mid-century, the U.S. electricity sector should meet zero-carbon emissions, reliability, and affordability. In addition to zero-carbon emission state mandates, the electricity sector must adhere to high reliability and resource adequacy standards of 99.97 percent from FERC and the North American Electric Reliability Corporation (NERC).[16] Achieving about 80 percent carbon-free with solely wind and solar generation is feasible based on current understanding.[17]

Electricity systems transitioning from 50 percent to 70 percent VRE will expand balancing areas, use shorter gate closures and advanced forecasting, build transmission, and increase storage. However, given historical resource gaps in wind and solar resources that can span weeks (especially for wind), the transition to 100 percent carbon-free reliable electricity based only on VRE requires other technologies such as seasonal energy storage, supplemental generation, flexible demand, and transmission expansion.[18] Most of these options, especially overbuilding wind and solar in conjunction with high capacities of Li-ion battery storage increases electricity costs.

Studies indicate that the U.S. electricity sector will expand by 60-110 percent by 2050 due in large part to increased electrification of energy end uses.[19] If decarbonized electricity is not affordable, other sectors such as transportation, heating, and industry will be more likely to continue to use fossil fuels, and therefore affordability of decarbonized electricity is crucial. Using a multi-decadal wind and solar data set, one study showed that long-duration storage, at current technology costs, can improve the affordability of variable renewable electricity systems by filling seasonal and multi-year functional roles.[20] Another recent study demonstrated that the addition of low- or zero-carbon ‘firm’ generators lowers the overall costs of electricity systems with high fractions of VRE sources, and demonstrates the need for both classes of low/zero-carbon electricity generation resources in facilitating decarbonized electricity systems (Figure 5.1.5).[21] That study shows that for two different types of grids (left side and right side of Figure 5.1.5), when clean firm power supplies are utilized optimally, the average cost of electricity is cut in half as emission limits are tightened close to zero. The comparison is with an electric grid that does not allow for clean firm power supplies and thus achieves deep decarbonization entirely with solar, wind and batteries.

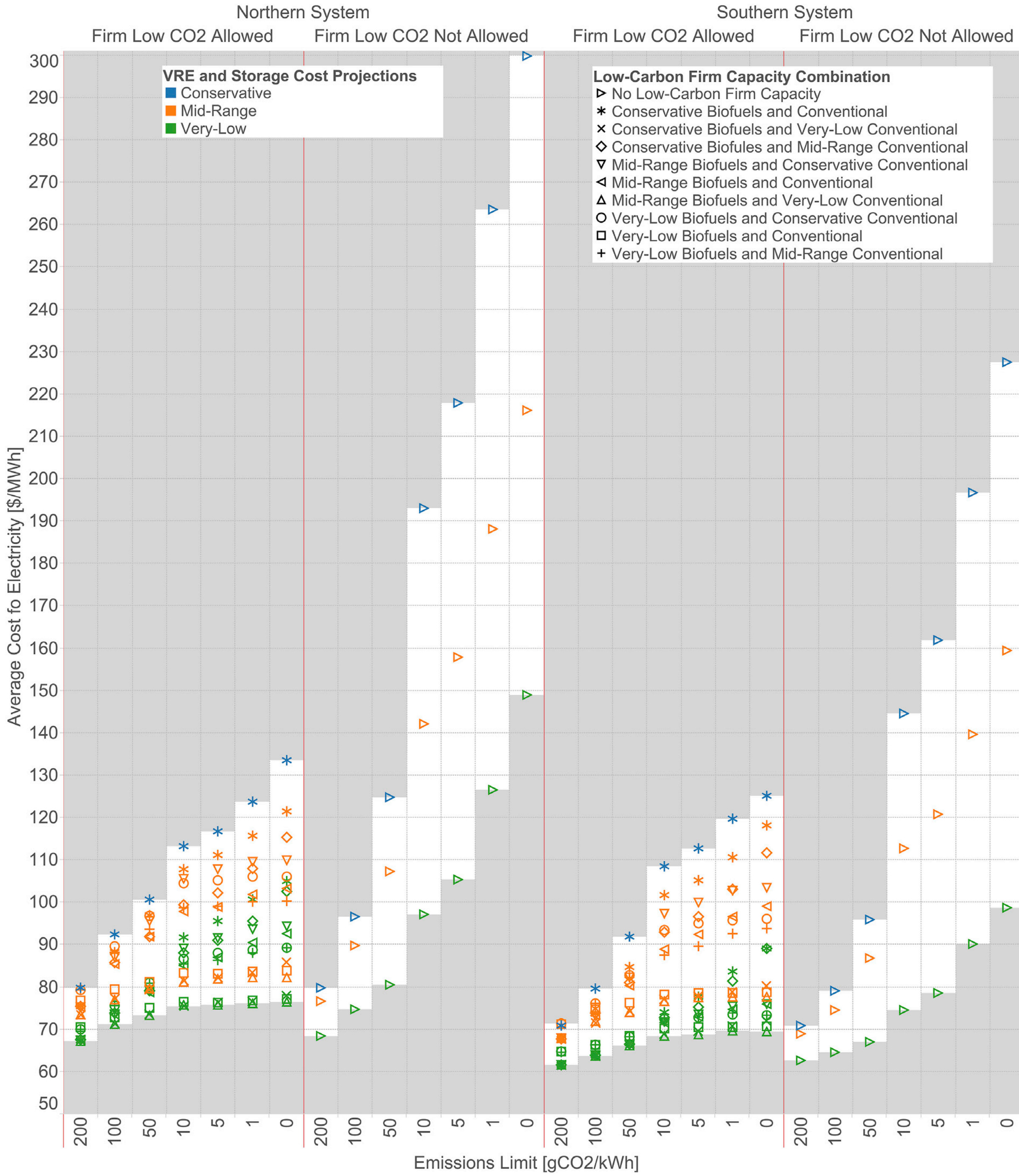

Figure 5.1.5. Cost of electricity associated with different greenhouse gas emissions intensity targets under pathways that include vs. do not include firm low-carbon electricity generation capacity (Sepulveda, Nestor A. et al., 2018).

To best facilitate the development of a deeply decarbonized electricity system, however, decarbonizing electricity supply and managing supply resources is only one part of the needed effort and transformation of the electricity system. Reducing the electric demand through increasing the efficiency of electrified end-uses with technologies such as efficient heat pumps for HVAC systems, improved building envelopes, improved electrified transport efficiencies, and the like will reduce the scale of decarbonized supply capacity and enabling technologies required to provide needed electricity services and the associated costs. Details on these technologies and strategies are the focus of the next section.

5.1.4 Demand for Electricity

Over the last century there has been autonomous expansion of electrification. Applications that did not exist have emerged into widespread utilization (e.g., microwave ovens, the internet, server farms, air conditioning, refrigeration), applications that used to rely on mechanical power or direct combustion of fuels were electrified (e.g., washing machines or elevators replacing stairs for vertical mobility), and demand for useful energy expanded with the economy and population. Combined, these patterns have led to rising demand for electricity overall and a growing fraction of final energy consumed as electricity (Figure 5.1.6). The modeling results in Chapter 2 find that these patterns will continue, resulting in a further doubling of the share of final energy from electricity—starting from 20 percent today and increasing to more than 50 percent by 2050.

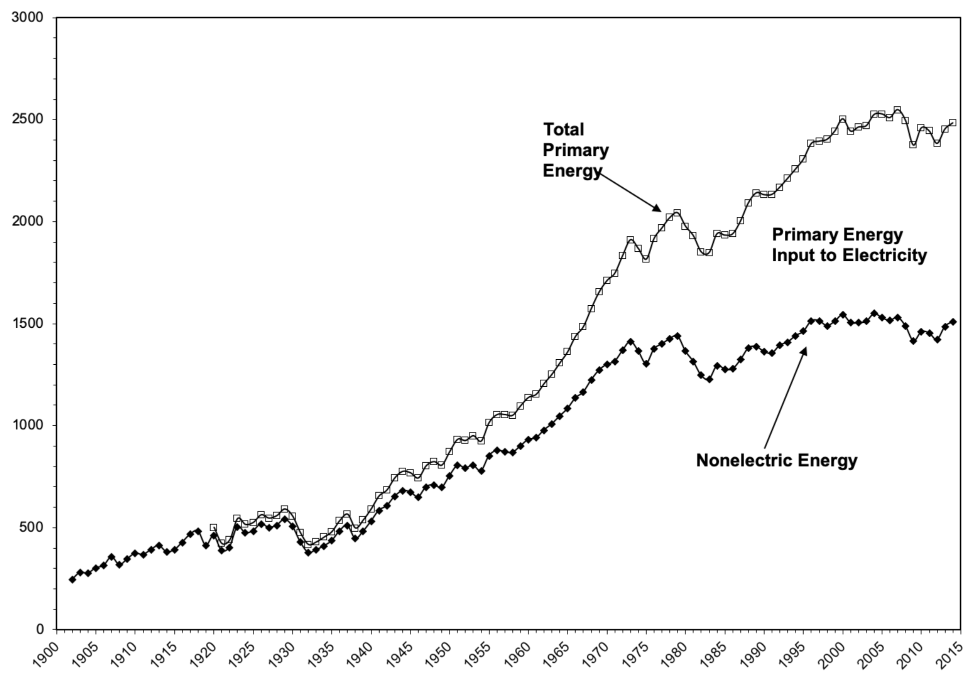

Figure 5.1.6. Long term electrification of the economy. Figure shows total primary energy converted to electricity before consumption over time historically (EIA Monthly Energy Review) and projected into the future (Chapter 2).

Looking to the future, there are at least two major attributes of demand that must be understood: the total level of demand (by region and locality, since that is how infrastructure is planned and built) and the shape of the demand curves (again, by region and locality). As a general rule, the latter is becoming particularly important to understand because peak demand is what drives the needed size and capabilities of transmission and distribution infrastructure and because VRE sources introduce substantial variability in supply. If changes in supply and demand curves are managed well, the needs for infrastructure could be much lower than if supply and demand are out of sync.

A large and growing number of energy uses are ripe for electrification and are often called "easy to electrify." These include low grade heating systems—already, resistance heating is used in water heaters and some space heating—and with more efficient heat pumps there could be more widespread utilization of electricity for these services. Heat pump technology has been known for a long time but has, historically, been costly and unreliable; with ongoing investment the situation is changing quickly.

Most attention is focused on electrification of transportation—a process evident in light duty vehicles in some parts of the world (e.g., Norway, California, Monaco) where active policy support has been combined with wealthy and engaged consumers. Similar patterns may spread to heavier duty transportation (e.g., trucks). Rail systems are already highly electrified, especially where tracks have high usage and the extra cost of power supply systems can be amortized more fully. Whether shipping and aircraft become electrified is harder to fathom, for the costs are higher and rival methods for decarbonization more numerous and competitive.

In terms of overall impact on demand, electrification of light duty transportation has a surprisingly small impact. More interesting is the potential for EV charging to assist in load management and shape demand curves by altering the time and intensity of charging activities. However, as shown in Figure 5.1.7, in the absence of explicit incentives to vary charging behavior—that is, flat tariffs—there is substantial variation across days and over time and people, for the most part, charge when convenient to themselves.[22] This figure, taken from the largest public facing charging network in the U.S. (on the UC San Diego campus), shows that charging ramps up quickly in the morning when people arrive for work, tapers over about four hours (when special access to EV charging spaces expires) and stays lower during mid afternoon when California grid solar supplies are actually peaking. Different incentives could shift those charging blocks around during the day.

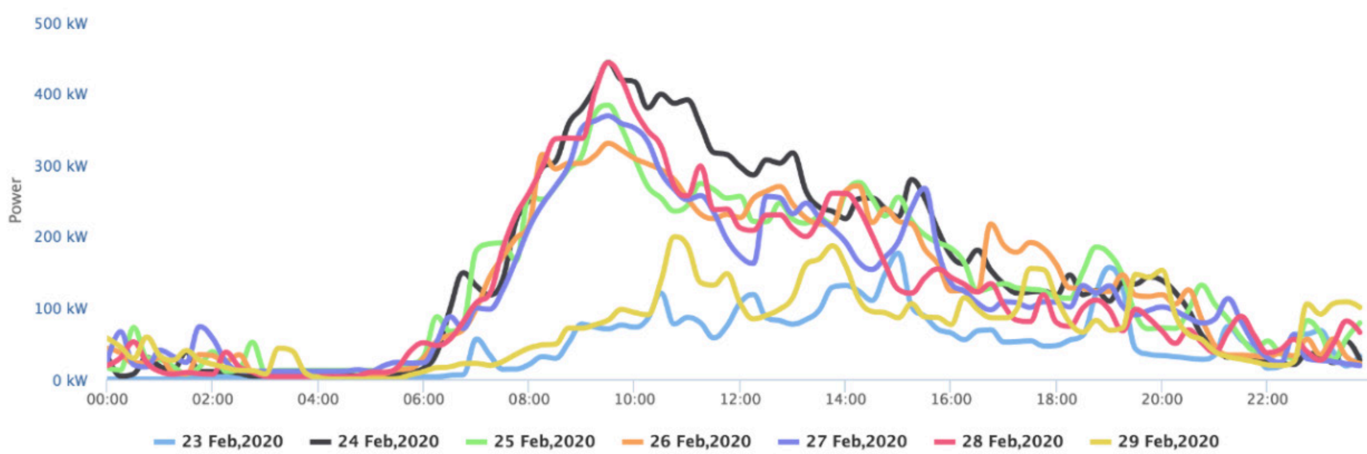

Figure 5.1.7. Daily electric vehicle charging profile (Level 2 chargers only) for UC San Diego during the 9th week of 2020 (February 23-29) (10 hr dwell time, $.15/kWh). (Washom, 2020).

This same logic could be extended to two-way charging—technology is already available, but business models are still being tested—that could pull and reinject power during optimal times.

Looking beyond these easier to electrify options are those that will be much more challenging. In addition to the transportation options already mentioned (e.g., aircraft) a critical set of challenges and opportunities for innovation arise with industrial energy uses such as high heat applications and chemical processing. Here electricity, coupled with CCS, is one of several contenders for deep decarbonization; others include hydrogen and biogas that could replace conventional natural gas.

Electricity is important for deep decarbonization not simply because electric supply is readily decarbonized but also because electrification can contribute to efficiency. Over the last decade (before the pandemic) efficiency has roughly doubled compared with the previous decade. Much of that improvement came from electrification, especially in the emerging economies, and from efficiency improvement in electric generators. That rate of improvement is not as rapid as would be needed globally for deep decarbonization, but is another example of an area where electricity has offered good news for deep decarbonization (Figure 5.1.8).[23] This may be just the beginning—electricity, because it allows for flexible movement of useful energy exactly to the point where it is most needed, can play a big role in more integrated designs that focus on providing services that people need (e.g., illumination, or movement of a person) with primary energy needs that are radically lower than today.

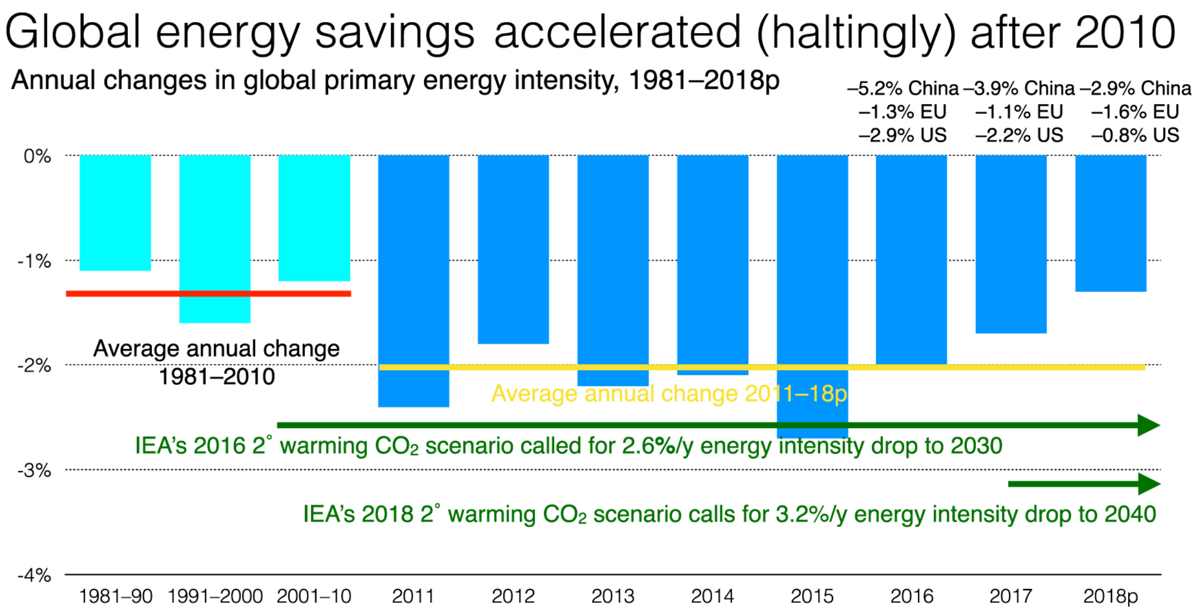

Figure 5.1.8. Improving Efficiency of the Global energy system (Lovins et al., 2019).

5.1.5 Evolution in Grid Topology

Today's power grid was designed to connect a network of large power generators with a large number of end consumers spread over a wide geographical area, creating a linked ecosystem of public and private enterprises operating within a web of government institutions: federal, regional, state, and municipal. Interconnection of the power generation sources and the demand centers is backboned by the complex, often-meshed high-voltage transmission network and typically-radial medium-and low-voltage power distribution systems. While the integrated power grid has been traditionally operated through centralized generation, monitoring and control mechanisms, a transformation to a more dynamic, flexible, and decentralized grid architecture has been emerging driven by:

- rapid proliferation of distributed energy resources (DERs), diverse renewables, and decentralization of the energy production;
- accelerated inclusion of controllable demand-side resources into the grid operation;
- millions of connected "things" to the grid, advancements in sensor technologies, grid-edge power electronics, edge-computing, and evolutions toward distributed intelligence, and;
- intensified requirements for a resilient power grid against natural and made-made extremes.

With the ongoing and future arrival of heterogeneous resources, interactive devices, and additional complexities, the increasingly dynamic smart grids are transforming to a "grid of grids" architecture: a transition from the existing unified network to a collection of smaller networks that can operate in concert or independently as needed.[24] The Grid 2030 is expected to be a fully automated power delivery network that monitors and supports every customer and node, ensuring a two-way flow of electricity and information between the source of power generation and the appliances, and all points in between.[25] Its distributed intelligence through a number of sophisticated sensors, coupled with communications and automated control systems closer to where the data is generated, enables online situational awareness, real-time market transactions, and seamless interfaces among various entities and the electric grid. We here describe several drivers that contribute to such transformations in the grid topology.

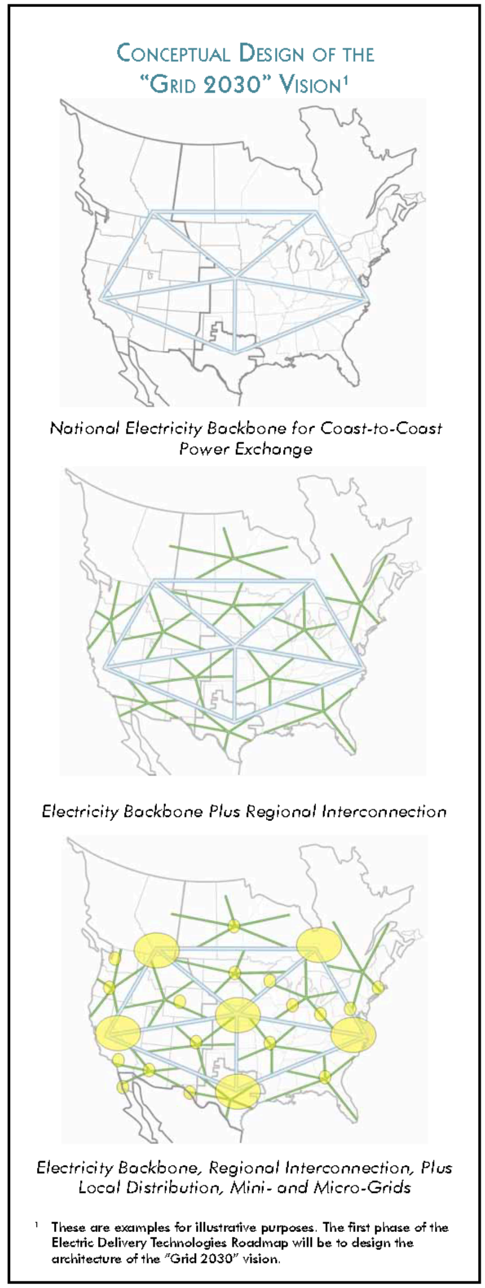

Fig. 5.1.9 Conceptual design of the grid 2030 vision. Transition from existing unified network to a collection of smaller networks that can operate in concert or independently (US DOE, 2003).

Hybrid AC/DC Topology. The increasing deployment of large renewables in power grids, which are typically located at distance from the demand centers, has highlighted the need to build-in additional transmission lines and interconnections with more flexibility to handle the emerging uncertainties. HVDC systems present advantages in bulk transmission networks, namely higher power transferability for transmission lines and better control of power flows across the network (in particular during the transient and emergency conditions that can often lead to blackouts). Thus, the transmission network topology of the future will be made up of a hybrid of AC/DC transmission lines. The other important, but often quiet, driver for such a hybrid structure of the future transmission grid is the rapid growth of DC loads facilitated by the developments in advanced control and electronics technologies to improve the efficiency of energy utilization and control flexibility. A hybrid AC/DC grid topology (i) eliminates the unnecessary AC/DC and DC/AC multi-conversion processes, reducing the total conversion losses; (ii) simplifies the equipment design, reducing the cost of electronic products; and (iii) facilitates the direct connection of the DC loads, making it easier to control harmonic injections into the grid.[26]

Flexible Transmission Grid Topology for Cost Efficiency and Resilience services. The transmission grid is built to be a redundant network in order to ensure mandatory reliability standards. Bulk electric transmission systems have been traditionally characterized with “fixed” and “static” configuration over time except in the cases of faults and forced outages when the topology changes as a consequence of circuit breakers tripping, or due to the scheduled maintenance and operator intervention. Given a fixed system topology with a certain power generation pattern and load profile, the system operator commonly dispatches the committed generating units to optimize the cost while ensuring that the system security and reliability constraints are met. This traditional view does not assume the topology changes during a power dispatch calculation interval. This shortcoming in today’s electricity grid operations needs to be alleviated since it is very unlikely that with all variations in uncertain load and stochastic generation, there exists solely one single optimal network topology for all periods in the operation time horizon.

It is acknowledged that system operators can actually change the grid topology by operating circuit breakers to improve various system conditions and constraints. Power system topology control, often called transmission line switching, is reported as a transmission technology of the future that offers the system operators an opportunity to harness the flexibility of the transmission system topology. By changing the way the electricity flows through the system, transmission switching can be employed during normal operating conditions for higher economic benefits and during emergency conditions for resilience and reliability benefits. Though being performed for decades on a very limited scale with rather focused aims, transmission topology control has recently gained further importance with the increased penetration of renewable energy resources and the growing demand for more reliable operation of power systems. Supported by several national and international directives, this ideology has sparked a series of studies in recent years aiming at discussing the impacts of optimal topology control on the grid operation efficiency and resilience against extreme events.[27] Policymakers should be sure that funding for grid electrification also includes funding for improving grid resilience.

Active Flexible Power Distribution Grids. Both structurally and operationally, power distribution grids are distinct from the high-voltage transmission networks. While a typical distribution grid is made up of a collection of disjoint tree graphs, each growing from substations at the root to customers, its complete layout is loopy, allowing multiple alternative paths to energize operationally. Switching from one layout to another, viable through many switching devices located on different segments of the distribution grid, can take place rather often.[28] The power distribution system was not designed to accommodate an in-mass deployment of DERs while sustaining high levels of electric quality and reliability. In the structurally-changed distribution grid of the future, a growing share of electricity will be produced by an expanding network of diverse more-distributed higher-intermittent DERs—including rooftop photovoltaics and other forms of distributed generation, as well as energy storage technologies and grid-connected electric vehicles—located locally on customer premises (prosumers). Unlike today, where electricity travels "one way", electricity flows bi-directionally, which would necessitate growing needs for local balancing by the distribution grid operator. The local distribution utility will then transform to a "coordinating platform" that enables and supports interfaces and communications among a variety of things including the grid-interactive buildings and appliances, distributed energy storage technologies, as well as transactions between customers, some of whom will be selling excess power from their DERs at certain times.

For resilience, many customers will be able to "island" themselves from the grid, becoming self-reliant as necessary,—the electricity distribution network will be able to instantly disassociate itself into pieces (microgrids) and recombine as needed to handle disruptions. So far, rapidly expanding deployments of DER are connected to the grid but not integrated into grid operations, which is a pattern that is unlikely to be sustainable. To manage this greatly increased degree of operational and transactional complexity and flexibility, it becomes necessary to coordinate distributed resources with utility infrastructure and local autonomous controls (i.e., local optimization inside global coordination),[29] through a massive grid modernization. This would involve reconfiguration of sensors, communications and control systems. Augmenting the present collage of legacy approaches, digitization of the grid will occur by overlaying a set of sensors and cloud-based optimization and command services—some of which will be based on distributed predictive analytics or enabled by blockchain—that facilitates seamless coordination among and between any and all parties that are connected to the grid.

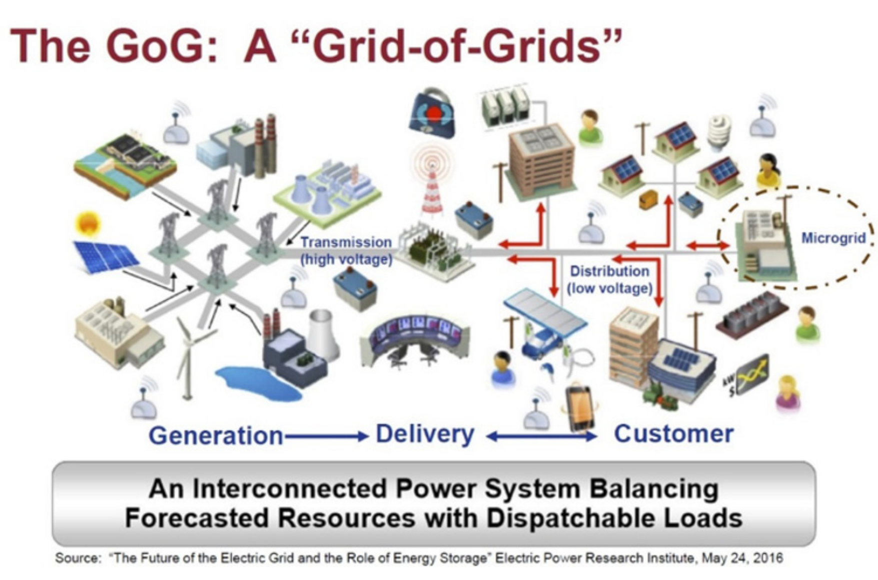

Figure 5.1.10. A "Grid-of-Grids" (EPRI, 2014).

5.1.6 Steering the System with Policies and Markets

There is no single approach or solution to decarbonization. There is, hence, no single policy instrument that is sufficient for reaching electricity decarbonization goals alone, therefore key considerations must be taken into account to develop policies that are effective in promoting progress towards decarbonization goals. These considerations, described in this chapter, are aimed at the development of "no regrets" decarbonization policies, those with significant co-benefits beyond decarbonization and those that may pay for themselves.

On one level, deep decarbonization policy implies navigating and balancing along three dimensions (Figure 5.1.11):

- Environmental Effectiveness: maximizing emissions reductions and reducing air and water pollution associated with a given socio-technical pathway;
- Economic Efficiency: minimizing economic costs in the moment (static efficiency) and across time (dynamic efficiency); and
- Political Efficacy: politically palatable and account for considerations such as distributional and equity concerns.

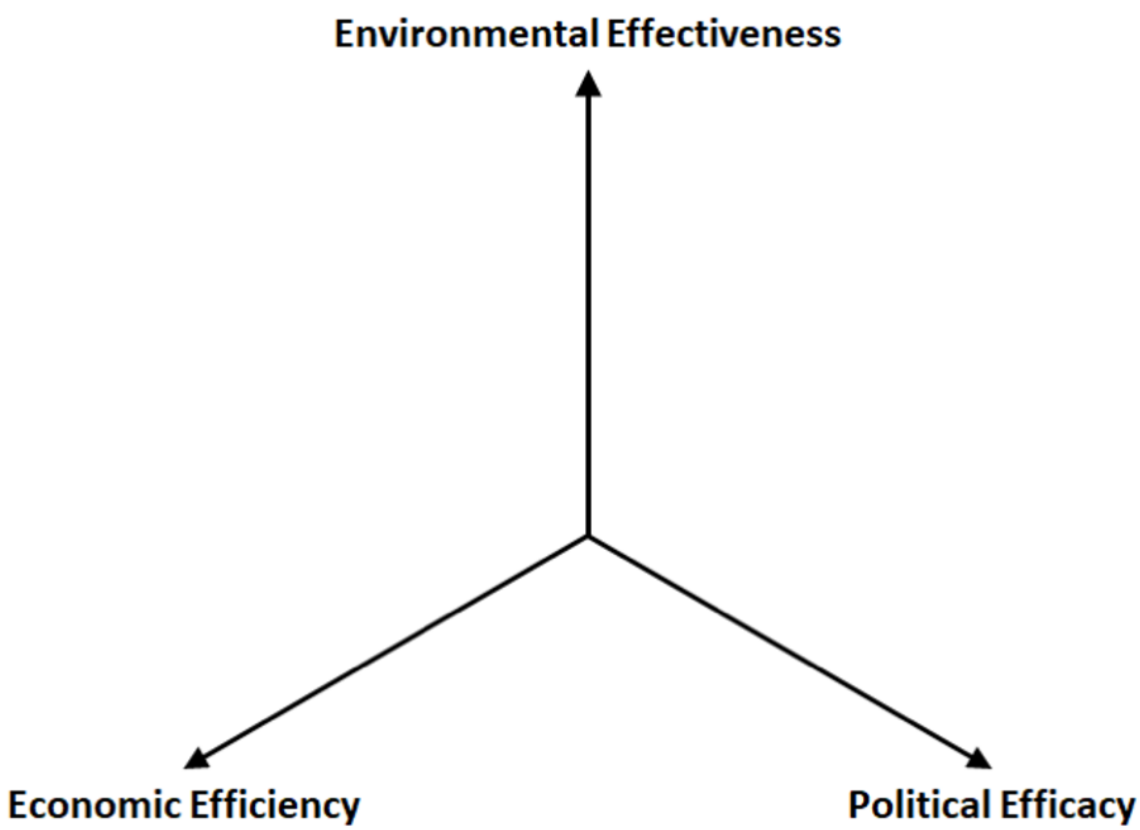

Figure 5.1.11. Competing decarbonization policy priorities (original figure).

All three dimensions are important in designing decarbonization policy instruments and any given instrument often involves trade-offs between these dimensions. Some of the most effective policies make costs explicit, potentially decreasing political efficacy. Politically efficate policies, in turn, may not be among the most efficient or effective, often requiring hard tradeoffs.

Policy instruments fall broadly into three categories:

- Direct regulation: This often takes the form of mandates, standards, and other command-and-control interventions. Examples include state-level Renewable Portfolio Standards (RPS) and building energy efficiency standards.
- Market instruments: These include price incentives and interventions in existing market structures or the creation of new ones. Examples include cap-and-trade systems or the implementation of a carbon tax.
- Technological interventions: These refer to either direct or indirect subsidies on the one hand, or broader industrial policy on the other. Examples include production tax credits.

None of these instruments are exclusive of each other. Many approaches, in fact, span more than one dimension. Reflecting a fine balance of priorities and tools, we here identify three areas of focus where policies will be critical.

First, is the need for policies to promote investing in the electricity network to better support the integration of decarbonizing technologies. Historically, policy has been designed around the characteristics and business models of incumbent technologies, which has meant that the network could expand and risks to investors were low, but incentives for innovation were few. These incentives need to be balanced within existing regulatory frameworks that are often tethered to rate-of-return expectations and state ownership. A key set of questions center around how classic rate-of-return regulations can be repurposed to meet deep decarbonization objectives. For example, which policies need to be reformed so as not to block progress?

Second, is the need for policies to incentivize the adoption of existing decarbonizing technologies and practices. While the need for new technologies in different areas to support decarbonization has been identified, in parallel there will also need to be policies that promote the use of existing technologies to better support electricity decarbonization. Examples include but are not limited to carbon pricing affecting dispatch of known, built technologies for more efficient, lower-carbon emitting operation or adopting currently available appliances to reduce energy consumption and carbon emissions. These policies emphasize static economic efficiency.

The third set of policies focuses on incentives for fundamental innovation and adoption of new technologies--for example, direct investments in RDD&D that contribute to dynamic economic efficiency over time.[30] As examples, such technologies include conventional silicon-based solar photovoltaic, battery energy storage for stationary and mobile applications, and efficient building envelopes and appliances. Currently, while many options for decarbonizing the electricity system exist or are emerging and their adoption rate is increasing, the current rate of adoption must be accelerated to meet regional decarbonization goals.[31] Accelerating the development and adoption of decarbonizing technologies involves building the technological base (and political support) for deep decarbonization over the long term—over decades—rather than only maximizing today's decarbonization potential.

Examples include Germany's and other jurisdictions' subsidies for renewable deployment through instruments such as feed-in tariffs, or U.S. federal tax credits for the purchase of plug-in electric vehicles. The investment in subsidies and learning-by-doing externalities is squarely focused on driving down future costs (Figure 5.1.12).[32]

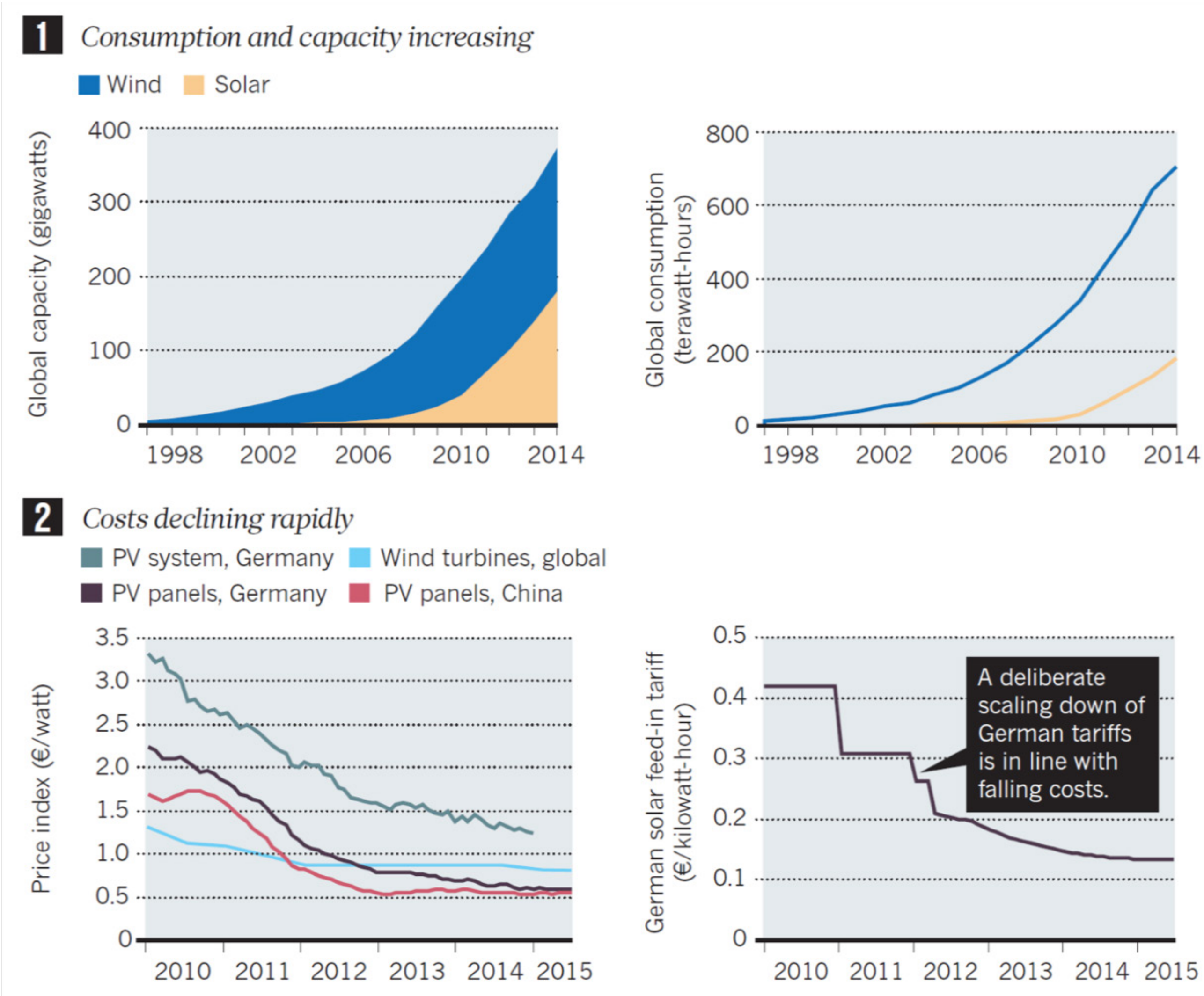

Figure 5.1.12. The rapid solar price decline and global deployment (Wagner et al., 2015).

The design of decarbonization policy must also critically recognize the role of non-carbon co-benefits in either initiating or supporting the incentive for development and adoption of new technologies. The process of building popular and political support for policies aimed at electricity decarbonization will significantly benefit from policy designs that in parallel help to solve tangible issues for different groups. Decarbonization policy is more likely to gain support from populations burdened by local air quality issues or water supply issues if such a policy is structured to adopt technologies and practices that also benefit these issues. Similarly, decarbonization policy must also provide tangible benefits for populations and demographics disproportionately burdened by economic and environmental quality burdens both as a matter of principle and as a means to increase political support and effectiveness.

For example, the initial interest in zero-emission vehicles (ZEVs) in California was based on goals to improve air quality in the state in the early 1990s.[33] In the following years, ZEVs became a powerful means for decarbonization, but due to their benefits for also helping to alleviate local air quality issues, these technologies were able to gain a wider base of support.

There are important considerations, however, regarding the size and importance of co-benefits in designing decarbonization policy. Where does the focus on co-benefits align with decarbonization goals? Where does the pursuit of co-benefits potentially inhibit progress towards decarbonization goals? Other environmental or social externalities can also either initiate or increase the value proposition for developing and adopting new technologies, as well as influencing what types of technologies are developed and deployed. How large does RDD&D spending need to be relative to historic baseline and how can policies be designed to maximize the benefits (decarbonization and otherwise) provided as a result of such spending levels? In a more current context, how much of it can double as post-COVID-19 stimulus spending? Some of these questions have been addressed in previous chapters but the historic spending trends are demonstrated below in (Figure 5.1.13).[32]

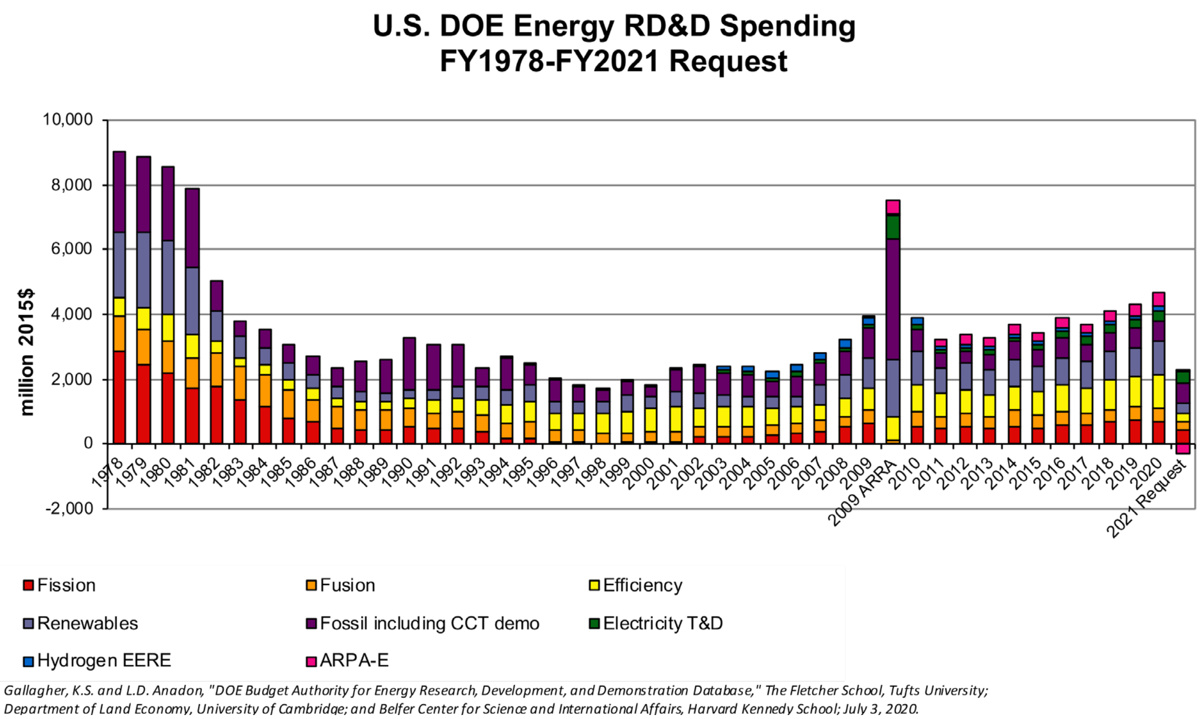

Figure 5.1.13. Historical spending on energy-related public sector RDD&D spending, showing it has largely been flat (Gallagher and Anadon, 2020).

In the end, failure to consider the dimensions, focus areas, and key questions described in this chapter can result in the development of detrimental or ineffective policy designs. Delaying optimal policy design does not just lead to increased costs, it might also lead to different pathways for the evolution of the electricity system altogether.

All that implies that policy design should prioritize looking for “no regrets” pathways towards reaching regional decarbonization goals, and avoid actions with the potential for lock-ins that could lead to more expensive end states.

5.1.7 Conclusions and Policy Recommendations

This chapter briefly considered aspects of the rapidly changing U.S. power sector, first considering supply and demand, then turning to grid typology, and finally markets and policy formulation and implementation.

We noted that, nationwide, the bright spot in decarbonization is the electric power sector. While new technologies are appearing in other sectors, such as transportation and industry, emissions continue to rise. Decarbonization of the grid requires not only dramatic increases in the use of clean energy for supply, but also a focus on energy efficiency across various sectors, and all of this coupled with changes to how the grid is designed, operated, and planned. In concert with decarbonizing the current system, "electrifying" other sectors of the economy to help them move at the pace and scale required by the climate imperative will be crucial.

A large and growing number of energy uses are ripe for electrification and are often called "easy to electrify." These include low grade heating systems. As an example, heat pump technology has been known for a long time but has, historically, been costly and unreliable; with ongoing investment the situation is changing quickly. Considerable attention is focused on electrification of transportation—a process evident in light duty vehicles in some parts of the world where active policy support has been combined with consumer demand. Similar patterns may spread to heavier duty transportation. Electrification of shipping and aircraft is a space for additional innovation as the costs are higher and rival methods for decarbonization more numerous and competitive.

This "electrification" of the economy is one of the most consistent results from large-scale decarbonization models and is clear also in the modelling in Chapter 2. This implies that the economic benefits of focusing on the power sector are significant. Also, finding areas for early and large-scale "wins" tends to provide its own important inertial benefits in the political arena. That said, this section has highlighted that the U.S. power sector is characterized by fragmentation in regulation, ownership, financial incentives, and institutions. This fragmentation can make it difficult to make big changes in short time periods.

Most other jurisdictions do not suffer from this fragmentation. It tends to require a high-level of federal policy mandates to help organise the various actors. As a result, a federal effort that is coherent and well-designed, and aligns with and incentivises state decisions, is likely to be a key step for an administration that prioritizes decarbonization. The electricity sector will need to play a leadership role to help support and motivate other sectors of the economy.

Policy Recommendations

Decarbonization will be achieved through the coordination of varying policy instruments, approaches, and solutions. However, there are key considerations that must be taken into account to help any policy or strategy be effective in promoting progress towards decarbonization goals. Additionally, these considerations, described in this previous section, can aid in developing “no regrets” decarbonization policies that have significant co-benefits beyond decarbonization and may even pay for themselves.

At least three such policies types should be prioritised under this framework:

- Use an expansive Clean Energy Standard or policies like (sector-specific) carbon pricing to price the negative carbon externality. Either policy allows a degree of technological agnosticism, coupled with considerable flexibility in implementation. In the past the states have relied mainly on renewable portfolio standards and federal tax incentives to encourage renewables; those have a role to play in accelerating use of these technologies and will need to be migrated to carbon terms.
- Dramatically increase clean energy RDD&D funding, providing incentives for fundamental innovation and adoption of new technologies. Such a policy would help increase the provision of public goods in the form of new ideas and tested technologies, accelerating the commercial deployment of clean energy systems.
- The third part of this approach would focus on learning and coordination. The states, as they push for deployment of renewables and other low-carbon power generators, will learn a lot about how to integrate these resources onto the grid, especially in the context of other shifts in the power industry such as grid decentralization. An active effort to compare experiences and learn quickly and to identify places of needed coordination--especially between states and federal authorities that have overlapping jurisdiction--will be needed.

These policies all require a new type of grid system as foundational. With the ongoing and future arrival of heterogeneous resources, interactive devices, and additional complexities, the increasingly dynamic smart grids are transforming to a “grid of grids” architecture: a transition from the existing unified network to a collection of smaller networks that can operate in concert or independently as needed. The Grid 2030 is expected to be a much more (if not completely) automated power delivery network that monitors every node, has pervasive yet decentralized controls, and allows multi-directional flows of electricity and information between sources of power generation and users. Its distributed intelligence through a number of sophisticated sensors, coupled with communications and automated control systems closer to where the data is generated, enables online situational awareness, real-time market transactions and seamless interfaces among various entities and the electric grid.

In crafting electricity policy it is crucial to keep the larger context of electric service in mind—including the “social contract” that informs how the sector is regulated. Focusing solely on the technical issues can often be an easier discussion but will not create politically viable pathways if decarbonization is not seen as contributing to other important social goals. Inclusion in decision-making of “just” and equitable transitions will mean policies focused on jobs as well as community benefits—including how decarbonization can help reduce a wide array of environmental ills and not just pollution of warming gases.

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