The Future of Electric Power in the United States – Part 1

By John Benson

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1. Introduction

Occasionally, I come across an information source that is really, REALLY good, but (sort of) overwhelms me. I did so in Early March. The good news is that I have very wide editorial freedom with Energy Central, and can choose what I write about. Or more to the point, feel that I am qualified to write about. In this instance, the subjects I don't feel I should write about are primarily issues that are difficult to quantify (like cultural, regulatory or societal issues) or are difficult to predict (future financial and legal considerations).

The title source is referenced here.[1] This is a monster document, but well worth reading. I completed this task (with much skimming) and will summarize about half of it below. I will also note the sections I am not covering. You can download this document and read both yourself. Note that source is currently a "Prepublication Copy—Subject to Further Editorial Correction." One other comment, you can download a PDF from The National Academies Press at no cost, but they will ask you to register first, and tell them how you intend to use the document.

Note that this review will require three posts and some of the posts (like this one) are rather long.

2. Introduction: Framing the Issues

The groups that are responsible for the referenced document include several subgroups, and are too numerous to list, however they are from various educational institution, utilities, utility industry groups, utility industry vendors, etc. In total there were more than 50 individuals that contributed to the document.

The Charter of these groups is described below by an excerpt from "Statement of Task" in Appendix A of the document:

In its 2018 appropriations for the Department of Energy, the U.S. Congress directed the National Academies of Science, Engineering, and Medicine to appoint an ad hoc committee of experts to "conduct an evaluation of the expected medium- and long-term evolution of the grid. This evaluation shall focus on developments that include the emergence of new technologies, planning and operating techniques, grid architecture, and business models.

In developing its report, the committee will consider: (1) trends in generation resources, their operational characteristics, and what capabilities will be required in energy infrastructure to provide reliable and resilient service; (2) trends in end use, including technologies for intelligent load control, and their implications for grid modernization investments, and (3) interdependencies with other infrastructure systems such as natural gas, telecommunications, and transportation systems. The report will be informed by a broad suite of alternative scenarios for the medium- and long-term evolution of the grid,

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[1] National Academies of Sciences, Engineering, and Medicine 2021. The Future of Electric Power in the United States. Washington, DC: The National Academies Press. https://doi.org/10.17226/25968

and will identify potential "no-regret" strategic federal investments and approaches that will help create a platform for a reliable, resilient, and secure power system including cybersecurity. In its discussions, the committee will consider the evolution of external forces that influence grid investment, planning, and operations, such as evolving technologies in electrification and consumer behavior, the need for community resilience, and the emergence of cyber and physical threats…

In the sections and subsections below I will describe what I feel are important elements of this report. In a few cases, I may also reference additional papers, mainly earlier papers that I posted on Energy Central.

2.1. Basic Constraints

Throughout this report the committee stresses the importance of maintaining and strengthening an electric power system that is at its core safe and secure. About that basic pillar, three other pairs of attributes must be balanced. They are that the electric system must be: clean and sustainable, affordable and equitable, and reliable and resilient.

2.1.1. Safe and Secure

For decades, assuring safety while keeping the lights on has been a bedrock objective for those who operate and regulate the electricity system. Further, making the grid and its components secure has also been central, for both its physical and cyber elements. The electricity industry must continue, and build upon, its outstanding record of past performance. This includes:

- *Developing better technologies and management strategies to ensure public and worker safety in the face of growing numbers and severity of extreme weather events such as wildfires, hurricanes, ice storms as well as geophysical events such as earthquakes and solar storms.*
- *Assuring continued attention to safe operation as a larger proportion of the functions that once fell in the domain of utility operators now fall in the domain of non-utility providers and customers.*
- *Increasing the use of automation and other technologies that are used to build and operate the system, without endangering the livelihood of utility employees.*

2.1.2. Clean and sustainable

The United States must accelerate the transition to a clean electricity system that: produces no conventional air pollution; adds no net greenhouse gas emissions to the atmosphere; minimizes terrestrial and aquatic impacts; and imposes low ecosystem disruption. This must be done in ways that expand the system's ability to generate and move power so as to make abundant electricity available to support the deep decarbonization of all parts of the economy. Advancing this objective will require:

- *Virtually eliminating the emission of conventional air pollution that today contributes to the premature deaths of tens of thousands of Americans;*
- *Developing and deploying a large and diverse portfolio of carbon-free generation technologies, particularly as electrification is pursued as a means to reduce dramatically, and ultimately eliminate, emissions from buildings, transportation and industrial sectors, and improved technologies for storing and moving large quantities of energy across space and time.*

- *Minimizing adverse land and water use and ecological impacts from the power system;*
- *Adopting a longer-term perspective with respect to system planning and decision-making on projects and systems to reduce the carbon intensity of the electricity system so as to avoid major near-term investment in capital stock, and the creation of institutions, which achieve short-term improvements, but make deep decarbonization harder and more expensive to achieve in the long run. Such choices in the near term could both slow needed transitions and give rise to large future stranded investments.*

2.1.3. Affordable and equitable

Moderately priced and universally available electricity service has been a pillar of social and economic development across the country over the last century, and will continue to be essential even as some consumers have the means to adopt their own local technologies to generate, store, and consume electricity. Finding ways to continue to provide such service will be a critical element of assuring continued industrial and personal prosperity. In that connection, this involves:

- *Ensuring that the cost of electric service is affordable will continue to be a key to strong and equitable economic growth.*
- *Making concerted efforts to continue to balance the benefits and costs of system upgrades in a way that ensures that changes in investment and operational strategies result in an increase in net social benefits;*
- *Ensuring that affordable basic electric service is available to all Americans and reducing dramatically the level of energy poverty.*

2.1.4. Reliable and resilient

Electric system planners, operators and decision makers must achieve a better understanding of the concepts of reliability and resilience. In many cases achieving an appropriate level of performance for both of these will require different technologies, policies and strategies. To that end the nation should be:

- *Developing a secure system that can minimize the risks from physical and cyber disruptions and respond in a flexible and adaptive manner when disruptions occur.*
- *Acknowledging that because there is no way to make power systems completely invulnerable to intentional or accidental physical or cyber disruptions and to the effects of extreme weather events, the nation must move aggressively to create systems that can continue to provide basic services as they recover from disruptions.*
- *Implementing technologies and polices that provide high quality and highly reliable power to sensitive digital loads without compromising the quality and cost of service that is provided to regular customers.*
- *Creating a regulatory and economic environment that increases the rate of innovation and its deployment at the level of distribution systems and customers (e.g., distributed generation and storage on both sides of the meter; systems for combined heat and power; microgrids with a variety of different ownership and operational arrangements).*

2.2. Predicting the Future of Electric Power (or not)

What will the U.S. electric power system look like 10 or 30 years from now? No one knows, of course. On the one hand, because so much of the electric system consists of long-lived facilities and other capital stock, one can be reasonably confident that on the surface much of it will still physically look very much the same as it does today. Indeed, many of the same power plants that were in place 30 years ago are still in operation, nearly all of the same giant power lines and substations that span the country remain in the same physical location, and in most communities the poles and wires that bring power to homes and businesses look largely unchanged.

But physical appearances can be deceiving. A closer examination reveals that the electric system has undergone important changes in ownership and control, industry structures, generation technologies and costs, fuel prices, and public policies. Many of the changes evident today were not anticipated, even 10 to 15 years ago…

Given the many forecasts and outlooks published by government agencies, national laboratories, scholars, think tanks, interest groups, and countless others, it can be easy to forget how difficult or impossible it is to accurately predict the future of something as complex and interdependent as energy systems. Retrospective analysis of past efforts to make assessments about the future of those systems have demonstrated that even the best projection efforts have frequently turned out to be incorrect.

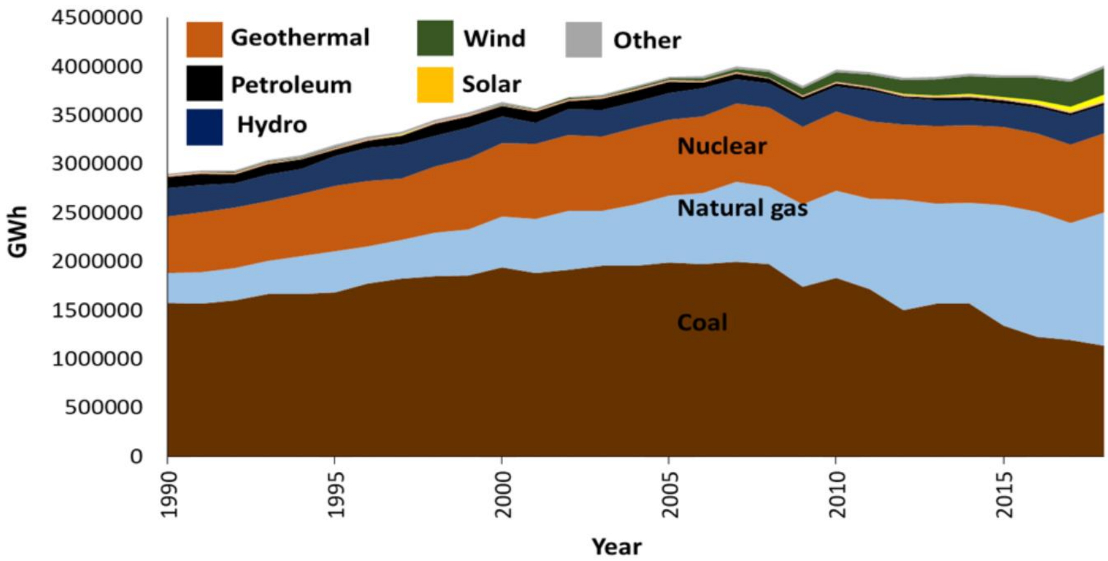
Author's Comment: One of the main wild-cards in predicting the future is the accelerating rate of technological development. Consider the new technologies that were developed, greatly expanded, or those that have become much less expensive over the last 10 or 20 years now impact most electric utility functions. This will be covered in more detail below.

Another factor increasing complexity:

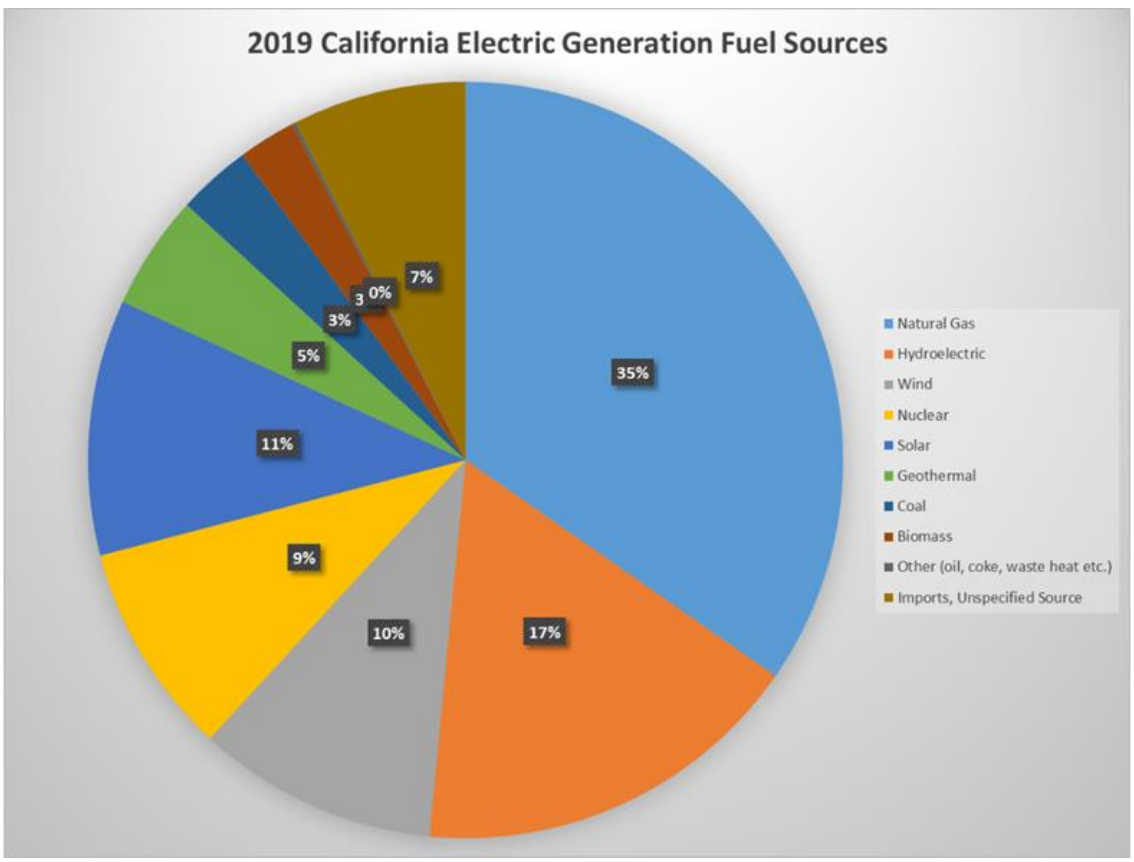
Finding 1.1*: …today the U.S. electricity system consists of a mix of restructured and vertically integrated systems operating in a mix of regulated and competitive market environments. Some systems are investor owned yet regulated in countless ways by public policy; some are publicly owned and regulated more directly through ownership and control (as well as by many state and federal laws). This highly diverse environment makes it very difficult to generalize about many aspects of the system across the country, engage in coherent system-wide long-range planning, develop a common set of recommendations, or to provide advice that is relevant to all parties.*

2.3. Generation Sources in the U.S.

The figure below displays how the energy resources used to generate electricity have changed over the past three decades. The biggest shifts in sources of power supply have occurred since the mid-2000s… In 2019, about 4.12 trillion kWh of electricity were generated at utility-scale generation facilities in the United States. Generation fueled by natural gas (38 percent) has now exceeded generation fueled by coal (23 percent). The drop in generation by coal is partly the result of environmental constraints and pressure to move to a lower carbon generation mix— including the rise of wind and solar power plants that have benefited from incentives at the federal level and other incentives in most states. But the dominant explanation for this shift is rooted in abundant supply of inexpensive natural gas and the associated increase in natural gas-fired electricity generation capacity.



Author: For Comparison the following the current generation mix in California. Note that this chart was used in an earlier paper posted a few months.[2]



[2] Cold Weather Renewables, March 2021, https://energycentral.com/c/cp/cold-weather-renewables ;
Data for the above chart: California Energy Commission, "2019 Total System Electric Generation", https://www.energy.ca.gov/data-reports/energy-almanac/california-electricity-data/2019-total-system-electric-generation

The net output of the fleet of nuclear units has remained relatively stable since the mid-2000s, with upgrades of capacity at existing units over that period and recent retirements of several nuclear units in the past few years. However, the fleet is aging. The EIA's 2020 Annual Energy Outlook estimates a decrease in total U.S. nuclear power generating capacity from 98 GW in 2019 to 79 GW in 2050. Although wind and solar generation grew by 44 times and almost 200 times, respectively, over what it was in 2001, those two technologies still make up a relatively small share of total electricity generation. In 2019 wind accounted for 7 percent and utility-scale and rooftop solar provided 3 percent of total electricity supply. Together with hydroelectric power (which supplied 7 percent of electricity), these three renewable resources provided approximately 17 percent of total power supply. All told, total electricity generation from all fossil fuels—natural gas, coal, and oil—has increased by only 2 percent since 2001, while total electricity production from all resources increased by 10 percent from 2001 through 2019. Fossil generation as a percentage of total power production dropped from 72 percent in 2001 to 63 percent in 2019…

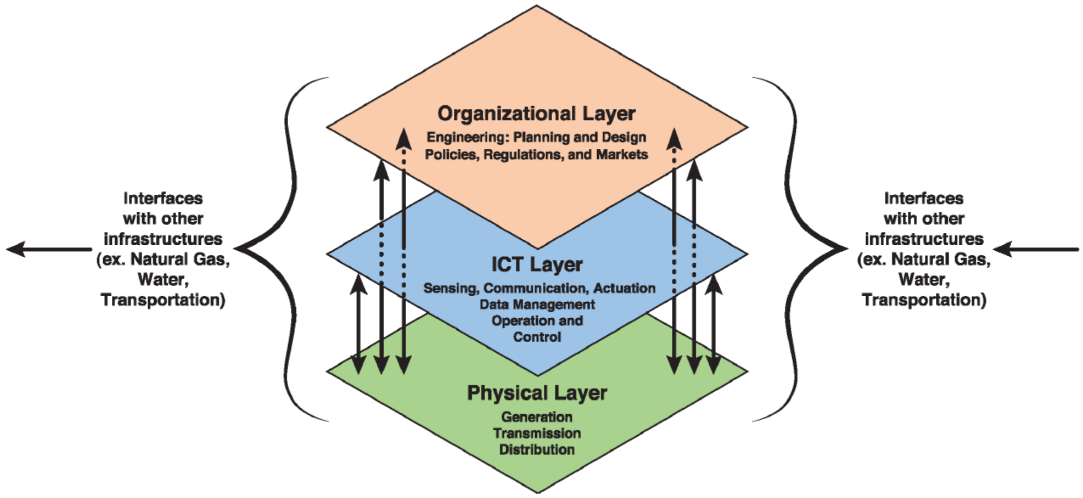
With growing numbers of homes and businesses showing interest in generating their own electricity, the "networking" … continues to evolve: changing electricity systems are creating innovative connectivity models. Rather than just delivering power from power plants to consumers, the distribution system has the potential to become a two-way system as a consequence of decentralized generation… while these developments could lower costs and improve resilience for some higher income customers, they also have important implications for social equity…

A two-way system may offer benefits related to cost and reliability and "energy independence," but it also raises safety concerns related to system controls over energized wires, particularly during periods of disaster response. Widespread deployment of distributed energy resources (and resulting two-way energy systems) have not yet materialized but are becoming more technologically feasible.

2.4. Grid Architecture

The architecture of the U.S. electricity grid has developed organically over more than a century to meet the nation's growing needs for electricity. Its structure has evolved from early islanded systems into its current architecture consisting of several interconnected physical and social systems, often called "layers" in the language of grid architecture (figure below). As shown, these layers encompass the physical components of power systems; the information, controls, and communications components necessary for operations; and the organization components that enable the system to be designed, funded, and provide services to consumers. The committee's motivation in depicting the architectural structure of the grid is to emphasize that the performance of the grid depends upon: (1) the physics of moving electricity from generator to customer; (2) the communications and intelligence for tracking and guiding those flows; and (3) the overall oversight and support to make sure all of this happens in an organized and consistent manner.

Figure below: *The architecture of the electric grid consists of several layers. This complex set of physical, communications, and institutional systems must interact to keep the lights on. The grid's architecture also interfaces with other infrastructure, as indicated. NOTE: ICT refers to Information and Communications Technology.*



While some forms of non-utility generation have been around for a long time (commercial and industrial on-site electricity generation and independent power producers), the need to increase the focus on grid coordination is heightened by the rise in deployment of distributed energy resources (DER), an increase in controllable loads, and ubiquitous connectivity, as well as the fact that distributed generation and responsive demand assets may not be owned or directly controlled by the utility. By calling attention to the need for greater information and coordination, the committee is not passing judgment on the desirability of these changes. Rather, the point is that such transformative changes need to be accompanied by forms of information sharing as part of the architecture of the grid.

The traditional architecture of the grid is a centralized approach in which the transmission system operator (TSO) performs all system coordination and control while the distribution system is relatively passive carrying the power from transmission substations to loads. Although this centralized architecture is accommodating some coordination and control by the TSO of some DER on some distribution systems, it is generally believed that such an architecture will not be adequate to ensure reliability when a large fraction of energy resources are on distribution feeders. In that case it will be preferable, if not necessary, for a layered approach in which the distribution system operator (DSO) has a significant role in coordination with the TSO.

… unlike many central station generators that use rotating machines that contribute stabilizing inertia to the system, many of the newer energy resources—both DER and some new central-station generators like wind and solar, are connected to the system using power electronics and at present do not contribute inertia. Thus, the proportion of rotating mechanical inertia is decreasing in some parts of the system, affecting the synchronizing stability of the electrical grid. As this happens, frequency and voltage controls have to be provided by the power electronic interfaces.

Author's Comment: The source document has quite a bit of discussion on the migration of the grid instrumentation and control function (ICT Layer in the above figure) to the grid edge in order to provide faster response, and autonomous (but coordinated) response. The capabilities for this migration have evolved steadily over the last ten years, and will provide important tools to mitigate potential instability resulting from the changes and challenges described herein. I believe the source document overemphasizes the lack of communication, data and modeling standards. These have been developed, and development continues.

The source document also delves in to problems with the bureaucracy surrounding transmission grid upgrades and other changes. These types of issues are beyond the scope of this paper.

3. Drivers of Change

While it is difficult to anticipate how they will interact, or predict which ones will predominate, we can readily identify a number of social, technical, and economic forces that hold the potential to bring about change in the U.S. power system. Beyond the possibilities being created by new technical capabilities, drivers of change in the electricity system include the drivers described in the following subsections

3.1. Growth in future demand for electricity

While growth in electricity demand has been flat in recent decades, the future will probably not be like the past. The broadly anticipated push for deeper electrification of energy end-uses in a variety of sectors (e.g., buildings, transportation and industry) could lead to very different patterns and levels of electricity demand over the next few decades. Even though only 0.1 percent of current transportation energy use comes from electricity (Figure below), it is widely thought that growing fractions of transportation will be electrified in order to reduce GHG emissions in the United States. Although only 12 percent of energy used by industry came from electricity in 2019, almost all deep-decarbonization studies suggest that electrification of certain industrial end uses will be important. These trends toward greater electrification may be offset in part through the introduction of more efficient appliances and building envelopes…

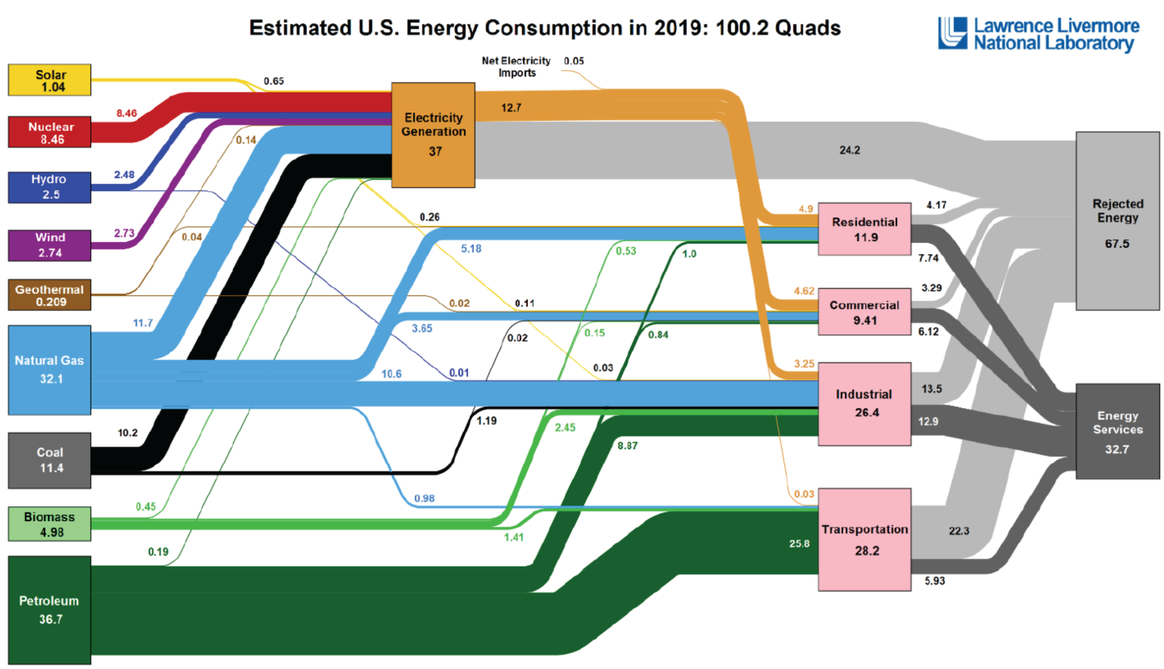


Figure: Energy flows in 2018, U.S. data.[3]

[3] SOURCE: Lawrence Livermore National Laboratory, 2018, "Energy US 2018," Note that the chart is dated March 2019, https://flowcharts.llnl.gov/content/assets/images/energy/us/Energy_US_2018.png

Author's Comment: The source document describes the reasons that estimates of future demand could be increasingly inaccurate over a multi-year time horizon. Although I think they underestimated the number of these factors, there are many, and it is apparent that the effort required to perform this modeling and forecasting will become much more complex and require many more data sources than in prior years. In California where we have very aggressive decarbonization goals, I believe we will start to see side-effects from inaccurate demand forecasting within a few years. Regarding the above chart, a Quad is roughly 300,000 GWh.

3.2. Efforts to Decarbonize the U.S. economy

Efforts to eliminate the emission of greenhouse gases ("deep decarbonization") will require two sets of transitions: (1) a dramatic shift away from generating electricity with conventional fossil fuel technologies to zero- or low-carbon technologies; and (2) replacing the use of conventional fossil fuel technology in buildings, transportation, and industry with zero emission electricity or net zero fuels. In parallel, many of these same activities will also help to dramatically reduce the many conventional pollutants that are associated with the present energy system. Today, the largest immediate externality from electricity generation are the negative health effects from air pollution. Although emissions of air pollutants have been declining, damages from fine particulate matter exposure ($PM_{2.5}$) from the power sector in the United States in 2017 have been estimated to result in about 6500 premature deaths, which comes to just under $60 billion in 2017.

The electric power sector is implicated in the challenge of slowing global warming in two ways:

1. Although the transportation sector's emissions is now a larger and faster growing source of emissions, the power sector is still a prodigious source of emissions of greenhouse gases, accounting for about one-quarter of the U.S. total. Within the sector, most emissions take the form of carbon dioxide, the result of burning coal and natural gas. The sector is also responsible for emissions of methane, from venting associated with production of coal, and from leaks at wellheads and pipeline systems related to the production and delivery of natural gas for ultimate combustion in power plants…

2. Essentially every major review of deep decarbonization scenarios, such as in the most recent major global assessment by the Intergovernmental Panel on Climate Change along with recent assessments of U.S. policy strategies, suggests that least-cost strategies for decarbonization involve massive electrification using low or zero-emission generation across many (if not most) sectors of the economy. Technologically, economically (and probably also politically), it is easier to electrify as many emitting applications as practical, and then supply them with clean electricity, compared with other approaches. An economy that decarbonizes is an economy that electrifies.

These twin, reinforcing logics for decarbonizing the electric power sector have inspired a large amount of research into technological options for decarbonizing the power sector, and numerous studies suggest it should be possible, at reasonable cost, to nearly fully decarbonize the electric power system over the coming two to three decades. This logic has also inspired many different political jurisdictions to experiment with various policy instruments. As of the end of 2020, electric utility companies that provide electricity to over two thirds of the nation's electricity consumers have committed to reducing GHG emissions. Additionally, with pressure from their stakeholders, 37 investor-owned and *publicly owned utilities—including many of the nation's largest electric companies—have committed to reaching net zero emissions by 2050 (and in some cases, earlier). As of the end of 2020, 62 utilities across the United States have publicly stated carbon or emission reduction goals. Of those, 38 have goals of carbon-free or net-zero emissions by 2050.*

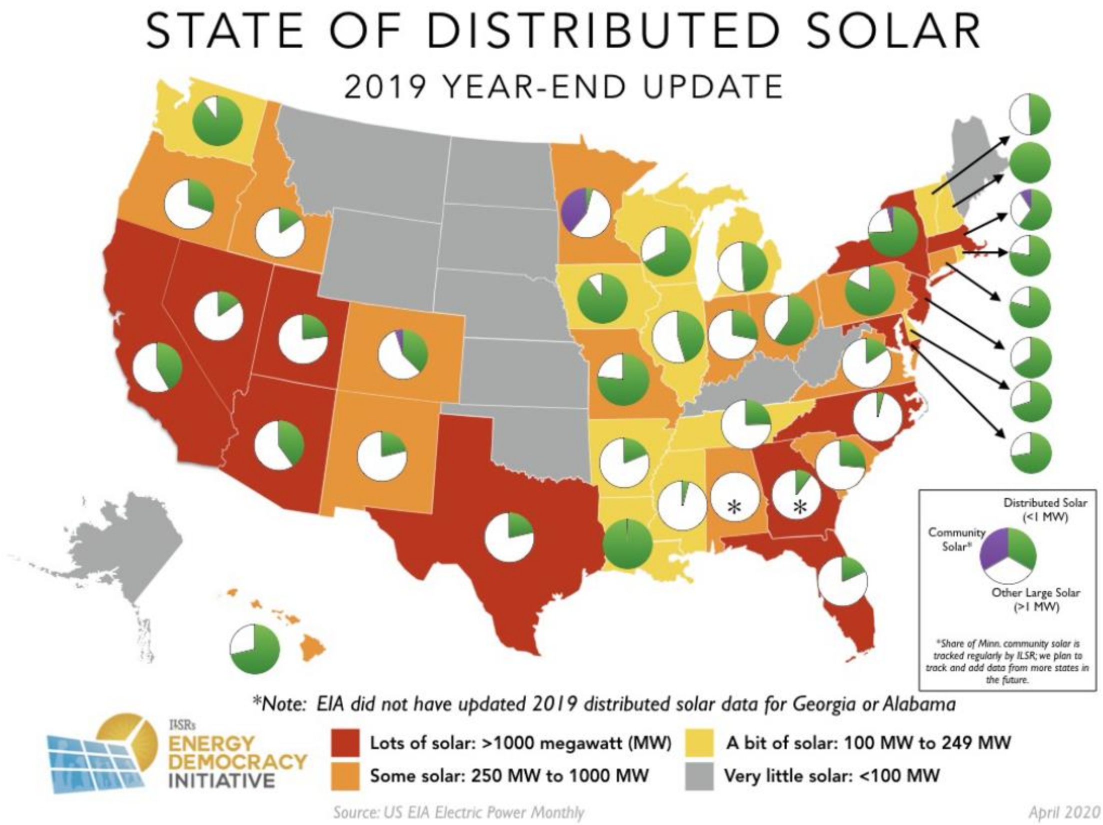
Author's Comment: Note that the source document took a deep dive into policy issues in this section, which is beyond the scope of this paper.

3.3. Developments at the Edge of the Grid

Recent years have witnessed dramatic changes in distribution systems and on the customer side of the meter in at least some parts of the United States. These changes are being driven by:

- *Regulatory and ratemaking policies, along with subsidies, that have promoted consumer adoption of such technologies on consumers' premises;*
- *Availability of commercially ready technologies, such as roof-top PV, battery storage, and highly efficient heat pumps, with equipment sellers offering consumer-friendly services and pricing;*
- *Innovation among manufacturers and sellers of devices and consumer products that can control the timing and/or magnitude of electricity use by appliances or other equipment in customer buildings;*
- *Interest among industrial and other large energy users to increase energy efficiency and decrease electricity costs through deployment of combined heat and power (CHP);*
- *Promising technologies including advanced refrigerants, the use of microwaves to enhance catalysts in chemical production, and various potential developments in other industrial processes using plasma or UV;*
- *A desire to supply local generation to service new high demand facilities such as data centers and fast charger sites for electric vehicles;*
- *The adoption of advanced automation by distribution utilities;*
- *Concerns about climate change and the need to achieve deep decarbonization;*
- *Customer concerns about supply vulnerability in the face of potential natural and human-induced disruptions;*
- *A desire among a few to become completely self-sufficient and disconnected from the grid.*

Distributed energy resources are expanding rapidly. A primary driver of this is residential and small-commercial photovoltaic (PV) generation), and this is in every part of the U.S. (see the map below). Consumers with PV (even residential consumers) are increasing also adding battery energy storage and optimizing controllers.



3.4. Grid Stability Challenges

A primary cause of current grid stability challenges is wind and solar intermittency coupled with the extremely low cost of these renewables.

Because of policy initiatives coupled with technical innovations and expanded supply chains… in the United States at both the federal and state levels, the cost of utility scale wind and solar has fallen precipitously. Today, in much of the country, the cost per kW of new utility-scale solar and wind generation has fallen below that of new gas-fired generation, and well below that of coal and nuclear. These developments… have resulted in major challenges for the industry.

A major challenge associated with wind and solar generation is that at times generation can far exceed demand and require curtailment (intentional reduction of output), which is not an economic use of resources. At other times, renewables can under-produce and require easily dispatchable load-following from other energy resources (e.g., natural gas).

California (and, to a lesser extent other states) have been rapidly implementing battery energy storage systems (BESS), and a major part of their role is mitigating the variability of PV and wind power generation. See the referenced quote below:

To date the CPUC has approved procurement of more than 1,533.52 MW of new storage capacity to be built in the State. Of this total 506 MW are operational. The AB 2514 mandate is procured in three distinct grid domain targets, with some flexibility between the grid domain targets of customer sited, distribution-connected, and *transmission connected. Cumulatively, the three major IOUs have exceeded the AB 2514 target of 1,325 MW and satisfied nearly all domain-specific requirements…*[4]

The following three elements are covered in the source document, but are beyond the scope of this paper:

1. A Desire to reduce social inequities.
2. Concerns about the impacts of the energy transition on employment.
3. A changing international environment including powerful market forces arising from globalization, shifts in the locus of electricity-relevant innovation, and growing concerns about state-sponsored competition and disruption.

At the end of this section (2) there were several scenarios, and some nice charts about how various aspects of the grid might evolve. Although I'm sure the group put much work in on these, since the future is intrinsically more complex and thus less predictable than any amount of analysis can deal with, I consider this stacking imaginary bricks on top of other imaginary bricks.

Also at the end of Section 2 (after the references) was an annex: The Diverse Interests of Electricity Consumers. This is beyond the scope of this summary.

[4] California Public Utilities Commission, Energy, Infrastructure, Energy Storage, Energy Storage Procurement to Date, https://www.cpuc.ca.gov/General.aspx?id=3462