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CLEAN GRID VISION:

A U.S. PERSPECTIVE

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CLEAN GRID VISION:

A U.S. PERSPECTIVE

Chapter 4. Demand-Side Development

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National Renewable Energy Laboratory

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Fatih Birol	International Energy Agency
Roland Brundlinger	Austrian Institute of Technology
Leon Clarke	Pacific Northwest National Laboratory
Laura Cozzi	International Energy Agency
Paolo Frankl	International Energy Agency
Dolf Gielen	International Renewable Energy Agency
Toni Glaser	German Federal Ministry for Economic Affairs and Energy
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Any error or omission in the report is the sole responsibility of the authors.

List of Acronyms

CO_2	carbon dioxide
DER	distributed energy resource
DOE	U.S. Department of Energy
ECC	economic carrying capacity
EFS	Electrification Futures Study
EPRI	Electric Power Research Institute
ERCOT	Electric Reliability Council of Texas
ESCO	energy service company
FERC	U.S. Federal Energy Regulatory Commission
FRCC	Florida Reliability Coordinating Council
GDP	gross domestic product
HVAC	heating, ventilating, air conditioning
ICE	internal combustion engine
IEA	International Energy Agency
ISO	independent system operator
LCOE	levelized cost of energy
NG-CC	natural gas combined cycle
NO_x	nitrogen oxide
NREL	National Renewable Energy Laboratory
PV	photovoltaic
ReEDS	Regional Energy Deployment System
SO_2	sulfur dioxide
VAR	volt-amp reactive
VRE	variable renewable energy

Preface

The *Clean Grid Vision—A U.S. Perspective* is a part of the National Renewable Energy Laboratory's (NREL)'s 2015–2021 Chinese Programme for a Low-Carbon Future and collaborative research with China's State Grid Energy Research Institute (SGERI). This multiyear program seeks to build capacity and assist Chinese stakeholders to articulate low carbon pathways to achieve energy systems with a high share of renewable energy, energy efficiency, and low carbon emission.

The Clean Grid Vision comprises two major reports: *Clean Grid Vision—A U.S. Perspective*, written by NREL, and *Clean Grid Vision—A Chinese Perspective*, written by SGERI. The former summarizes NREL's lessons learned on some of the main issues in power system transition:

- Power system planning and operational analysis are discussed in Chapter 1, "Clean Grid Scenarios."
- Renewable grid integration challenges and modeling tools at the distribution network level are discussed in Chapter 2, "Distribution Issues and Tools."
- Grid reliability and stability challenges and the technologies to address them at the transmission-network level are discussed in Chapter 3, "Grid-Supporting Technologies."
- Recent dynamics in electricity demand such as energy efficiency, demand response, and electrification are discussed in Chapter 4, "Demand-Side Developments."
- Emerging issues in power market design and market evolution related to the increasing penetration of renewable energy are discussed in Chapter 5, "Power Market Trends."

The scope of *Clean Grid Vision—A U.S. Perspective* is limited to summarizing the main lessons learned and best practices through NREL's power system research in the past 6 years, with a focus on the U.S. power system. It can be compared to and contrasted with SGERI's report that focuses on China's power system.

As a summary report, most of the works cited here were conducted during 2015–2020. While some of the assumptions for these studies, especially the ones related to renewable energy and battery technology costs, are outdated, the main conclusions remain salient and offer valuable insights for planning and operating power systems and power markets with high levels of renewable energy.

More information on the Clean Grid Vision is available at www.nrel.gov/international/clean-grid-vision.html.

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Chapter 4. Demand-Side Developments

Highlights

- Recent dynamics in electricity demand have accelerated the U.S. power system transformation and created tighter linkages between supply and demand.

- Energy efficiency and demand response are low-cost strategies for all countries as they seek to minimize carbon emissions and the cost associated with decarbonization.

- Electrification of end uses (away from fossil fuels) is now considered a hub for economy-wide decarbonization: vehicles, buildings, and industry are potentially capable of large-scale transitions away from direct fossil fuel use while the power sector itself is simultaneously made less carbon-intensive. Some hard-to-decarbonize sectors may need other solutions such as renewable hydrogen, e-fuels, or carbon capture, utilization, and storage.

- Wind and solar may be the largest sources of new generation to meet growing demand under a highly electrified future, but demand flexibility will be crucial to making a highly electrified future feasible.

4.0 Background and Overview

This chapter focuses on recent developments on the demand side of the electricity system, primarily from the United States but also including examples from other countries and regions. After decades of slow-moving changes in power system technology, business models, regulatory structures, and even financing schemes, changes in electricity demand are accelerating rapidly. These changes are also more tightly linking the supply side with the demand side.

We begin with high-level summaries of traditional subjects like demand-side management, which includes energy efficiency and demand response, and then transition to a subject that has gathered increasing attention as the most dynamic change likely to impact power systems in the coming decades: beneficial electrification.[1] In each case, we attempt to address the impacts on system flexibility to the degree possible. These demand-side topics are widely considered to be essential elements of a decarbonized grid strategy. Not included in a comprehensive fashion in this chapter is the subject of distributed energy resources (DERs) (e.g., rooftop solar, behind-the-meter storage, electric vehicles, and other small-scale options). Many of these topics are considered in other chapters of this report.

4.1 Energy Efficiency

Using energy efficiently is a key requirement for a well-functioning, cost-effective, reliable, and clean grid. Efficiency has widely been considered “the first fuel” for ensuring generation matches load in an optimized fashion [1]. Excessive electricity use requires not only more generation, but more transmission and distribution infrastructure as well. Efficiency is also an essential element in meeting future sustainability and climate goals [2].

Given the long history and rich literature of energy efficiency, this section stays at a high level and reviews key points of effective energy efficiency programs and strategies. One of the main impacts of

[1] Beneficial electrification refers to the shift from a non-electrically driven end use to one that relies on electricity in order to achieve economic, pollution, and/or climate benefits. Examples include the shift from fossil fuel ICEs to electric vehicles, and the change from natural gas-fired furnaces to electric heat pumps.

energy efficiency on system flexibility is both the reduction in peak load that offsets the need for sharp ramps to balance supply and demand, but also lower overall load—which can provide flexibility benefits. Demand response is another main tool on the demand side that is reviewed in Section 4.2.

4.1.1 Benefits and Challenges of Energy Efficiency

Historical studies have illustrated the power of energy efficiency to save energy and natural resources, thereby reducing money spent on energy bills, water used for power plant cooling, and health and ecosystem impacts associated with harmful emissions [1], [3]. For example, a 2009 study found that if U.S. energy productivity[2] had remained constant at 1970 levels, the country would have consumed over 203 quadrillion BTUs (quads) of energy by 2007, instead of the 102 quads it actually consumed over that time period [4]. These energy savings have resulted in significant cumulative benefits on national energy security, monthly household energy bills, water withdrawals and consumption, utility investment in new capacity and peak load management, air quality, and greenhouse gas emissions. While approximately two-thirds to three-quarters of the reduction noted above is attributed to improved energy efficiency, the remaining portion is due to structural shifts in the U.S. economy, resulting in less energy-intensive manufacturing, for example [5]. A subset of those savings includes a reduction in the size of energy-intensive manufacturing industries, such as steel and cement production.

While its benefits are well documented [1], [6], [7], energy efficiency may not have met its full market potential, known as the "energy efficiency gap" [11]–[13], due to some complex and enduring challenges. First, metrics used to quantify energy efficiency savings can be complicated to define and put into practice. This is not just because energy savings that accrue over time lack an established counterfactual baseline scenario for comparison purposes, but also due to attributional and comparative factors. Using primary energy consumption and gross domestic product (GDP) are the most common metrics to track and compare economy-wide energy efficiency trends over time, yet, as the example above from Metcalf [5] shows, other changes in the economy (like structural change) can interfere with understanding the drivers and impacts of energy efficiency behavior [6]. A more complete discussion of how primary energy demand may change under highly electrified futures is presented in Section 4.3.

Beyond metrics to characterize efficiency, a host of market failures and incentives prevent uptake of energy efficiency. Subsidies that promote use of energy are probably highest on the list, but high transaction costs for small projects, asymmetric information, and principal-agent problems such as the landlord-renter[3] dilemma provide other examples [8]–[10]. Some of the barriers to energy efficiency have been overcome through innovative financing measures described below, but others endure, and the remaining potential to achieve higher energy efficiency is significant in most countries [1]. Indeed, global improvements in energy efficiency have been declining since peak improvement occurred in 2015, as shown in Figure 4- 1.

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[2] Energy productivity is generally measured as GDP divided by energy use and is the inverse of energy intensity (energy use divided by economic activity).

[3] If the tenant pays utility bills, the landlord has little incentive to invest in energy efficiency [14].

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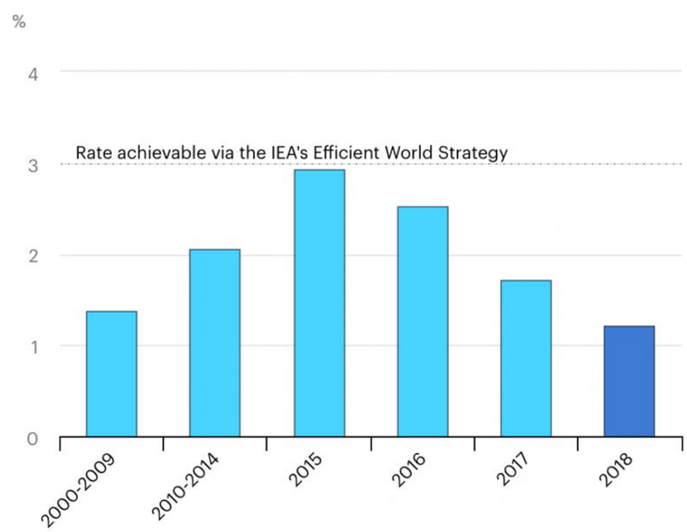

Figure 4- 1. Global improvements in primary energy intensity, 2000–2018

Source: [1]

Before we look specifically at the role that energy efficiency has played in the United States, it is instructive to review and categorize select measures available and stakeholder roles involved in pursuing energy efficiency around the world.

4.1.2 Measures to Promote Energy Efficiency

At least six broad measures have evolved to advance the level of energy efficiency in industrialized economies around the world.[4] Each of these is briefly discussed below, including examples from each category. Then, the role of stakeholders and capacity required is also described. Many energy efficiency measures can require simple levels of institutional capacity (incentivizing the use of LED lightbulbs, for example), but others may require sophisticated financial markets and industrial capacity.

Policy Directives: At the highest level, countries or subnational jurisdictions can pass requirements for energy efficiency throughout the economy. Examples of these measures include funding levels for research, development, and deployment budgets at home or through international organizations; energy efficiency resource standards that require utility jurisdictions to achieve specified levels of customer energy savings [15]; or codes and standards that set minimum performance levels for vehicles, buildings, and the equipment within. Policy directives set through legislation are typically operationalized through government agencies or regulators.

Delivery: These include programs and actions to physically replace or modify existing buildings, equipment, or other electricity-consuming devices. For existing buildings and industrial sites, stakeholders can take steps to improve the overall energy performance of the unit and equipment within. Utilities, in partnership with state regulators and others, often deliver energy savings to such customers [16]. Weatherization is an attempt to reduce energy demand from space conditioning by lowering heat loss during colder months and improving cooling performance during hot periods. Weatherization efforts for low- and medium-income households are particularly popular in cold weather climates [17]. Other types of energy efficiency program delivery might rely on home energy audits conducted by the utility to prioritize potential investments to improve energy efficiency and estimate benefits. Commissioning

[4] This is a synthesized list of select measures. Additional measures to advance energy efficiency are listed here and here.

programs can also be used to ensure a building's systems are installed and operating correctly through all phases of the building's life.

Finance: While energy efficient investments often demonstrate lifetime cost savings compared to traditional options, they may have high upfront costs, or consumers might not be prepared to invest in efficiency measures even if they will save money over the long term. A large number of financial incentives and new business models have been adopted to address these barriers [18]–[20]. For example, low-interest loans can enable homeowners and commercial businesses to invest in energy efficiency. Utilities can offer "on-bill" financing so that customers can pay back the utility for investing in energy efficiency measures in a simple way. Likewise, energy service companies (ESCOs) offer industrial and commercial building owners a no-upfront-cost way to upgrade their energy-consuming equipment and practices by agreeing to share with the ESCO a portion of the monthly energy savings.[5] Finally, regulators can require that utilities "decouple" electricity sales from revenue so that they are more likely to encourage the use of energy efficiency [21].

Consumer Education and Outreach: Consumers often are not aware of life cycle cost accounting methods when making purchases. They might choose a refrigerator that costs $50 less than another, but that uses $60 more electricity each year—all other factors being equivalent. Educating consumers through labeling and disclosures has been a powerful set of tools to influence consumer behavior. Most jurisdictions must now clearly label annual energy use in a transparent way so that consumers can make more informed decisions. In the United States, this includes vehicle miles per gallon labeling,[6] appliance energy use through ENERGY STAR®,[7] and, in some locations, a home energy score[8] indicating how efficient the building is compared to its peers. Attempting to alter consumer behavior has also recently become a more popular approach to overcoming energy efficiency barriers. For example, utilities can inform residential and commercial ratepayers of their monthly energy use compared to a typical user to help motivate improved efficiency through behavioral psychology [22].

Institutional and Human Capacity Building: Training staff and institutions on how to conduct long-term energy planning that incorporates energy efficiency can add value, so many bilateral and multilateral assistance programs have been building capacity around the world for decades [23]. The full life cycle of energy efficiency options requires at least some individual and institutional capability, as exemplified in the stakeholder discussion below.

Evaluation: Careful post-evaluation of energy efficiency programs against their intended goals and objectives is a key element of any effort to maximize impact and minimize cost. Effective evaluation is not an afterthought in the supply chain of energy efficiency delivery but an important component of project planning and goal-setting from the start [17]. As energy efficiency is a continuous process, efforts to evaluate, monitor, and verify can help jurisdictions improve program delivery in future phases [24].

4.1.3 Stakeholders in the Energy Efficiency Value Chain

Government: Federal and local governments are responsible for enacting the policies and legislation that influence activity along the energy efficiency supply chain. As noted previously, these measures can

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[5] For more on ESCOs, see this International Energy Agency (IEA) resource.

[6] The National Highway Traffic Safety Administration regulates how far vehicles must travel on a gallon fuel through the Corporate Average Fuel Economy program. Congress first established Corporate Average Fuel Economy standards in 1975.

[7] ENERGY STAR is a government-backed symbol for energy efficiency operated by the U.S. Environmental Protection Agency.

[8] This "miles per gallon" home energy rating system is administered by the U.S. Department of Energy's (DOE's) Office of Energy Efficiency and Renewable Energy.

cover a variety of topics, with implementation often left to a federal or state agency or regulator. In the United States, the government role in energy is often much more decentralized than in other countries, with states having most of the authority in setting energy goals and regulations. The federal government does play an important role, however, in establishing minimum performance levels for equipment, appliances, and vehicles, and in appliance labeling through the ENERGY STAR program.

Utilities: In the United States, utilities can play key roles in advancing energy efficiency and demand response (see Section 4.2), but they may require some encouragement from government or other stakeholders. Utilities can administer public benefit fees or “wire charges” on top of electricity tariffs to help fund energy efficiency and other social programs. There is generally a wide range of desires and capabilities among utilities to design, implement, and evaluate energy efficiency programs [16]. Decoupling of regulated utility profits from electricity sales is one measure to encourage utilities to play a more active role in energy efficiency.

Private Sector: For-profit companies not only design, manufacture, and sell efficient technologies such as LED bulbs, refrigerators, and furnaces, but they also finance and install upgrades at a variety of consumer facilities. ESCOs are well-known for creating thriving businesses in many regions of the world, including the United States and China. These companies can bring large energy savings to industries and commercial buildings by identifying energy-saving options, and then financing and installing the new equipment in exchange for sharing future monthly energy savings. This helps overcome some of the traditional financing barriers, although they may also introduce a few new hurdles if regulators classify ESCOs as lending institutions, for example.

Nongovernment Organizations: Nongovernment organizations can be key stakeholders in many energy efficiency supply chains because they are independent and trusted by end-use consumers. Nongovernment organizations often help administer low- and medium-income energy efficiency programs across the world, and also convene stakeholders to identify and promote best practices. Finally, they conduct research on barriers and how to overcome them, paralleling the roll that academics often play.

Academia: One need look no further than the wide collection of scholarly journal articles on energy efficiency to understand one of the important roles of academics and others in the research community. Universities and research organizations push the boundaries of knowledge on energy efficiency and also conduct evaluations that provide feedback for further improvement in its delivery.

As shown in Figure 4- 2, both the energy efficiency programmatic measures and the stakeholders involved can evolve over time to create increasingly sophisticated value chains for energy efficiency that can improve effectiveness and replicability [17]. Although this illustration was created for low- and moderate-income populations, the same mechanisms and stakeholders exist for the larger population. Decades of experience have made some jurisdictions in the United States very effective at delivering energy efficiency, even if the United States is only ranked tenth in the world overall.[9]

[9] The American Council for an Energy Efficient Economy publishes a regular international scorecard of energy efficiency capability. The United States lost two places in the 2018 version of the report after lapsing in several areas (from eighth place down to tenth) [25]. The American Council for an Energy Efficient Economy also publishes an annual scorecard on which domestic utilities are most effectively promoting energy efficiency [16].

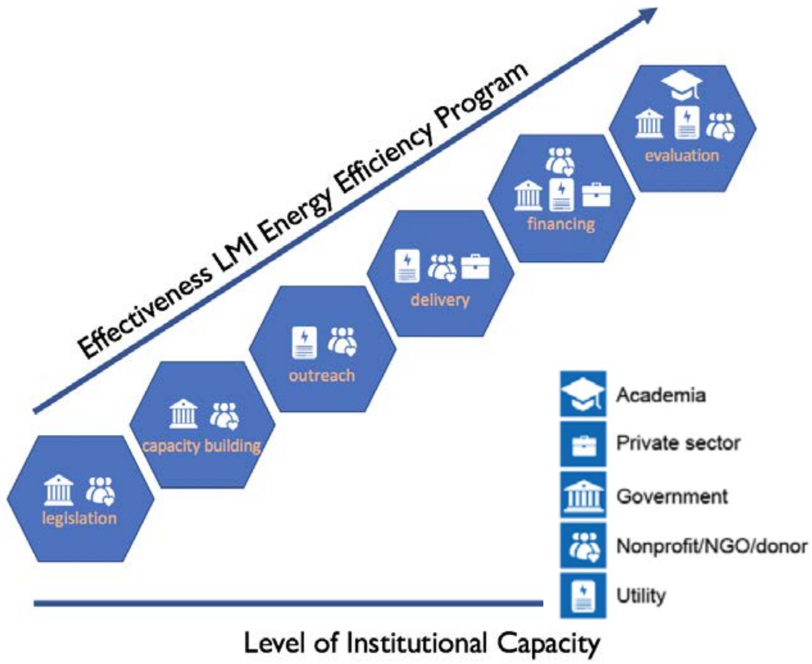


Figure 4- 2. Level of institutional capacity in carrying out effective energy efficiency programs

Source:[17]
Note: LMI=low- and medium-income

The next section presents an overview of the history of energy efficiency in the United States and metrics characterizing trends in energy use.

4.1.4 History of Energy Efficiency in the United States

After the first oil crisis hit the United States in 1973, the federal government began to take action by passing legislation on vehicle and appliance efficiency standards, conducting public education on the benefits of energy efficiency, and establishing loan guarantees for both energy efficiency and renewable energy in public and commercial buildings [26]. It also established a low-income home weatherization program to both support greater energy efficiency in the poorest households and help fund payments on monthly energy bills. While subsidizing monthly energy bills often works against energy efficiency efforts, the social cost of cold homes is very high for the poorest households [17]. Federal and state laws also prompted utilities to begin offering demand-side management programs in the late 1970s that included energy audits of buildings to prioritize steps to cutting residential, commercial, and industrial energy waste.

Through the 1980s, interest in additional energy efficiency measures generally waned as the impact of fuel economy standards began to be felt and energy insecurity became less intense with the stabilization of global oil markets [26]. But efforts to promote efficiency in the power sector and buildings continued through the following decades, with many utilities required to perform least-cost planning exercises that included integrated resource plans, and to add public benefit charges to electricity tariffs that funded further efficiency efforts. States had widely divergent efforts to promote energy efficiency, with California, the northeastern states, and some mid-Atlantic states achieving the most, while some of the southeastern states were less engaged [16]. California, in particular, has been a leader in requiring efficient performance standards for transport and buildings, and its actions have helped pull many other parts of the United States forward [102].

Energy efficiency was a major target in the 2009 American Recovery and Reinvestment Act, an economic stimulus package that aimed to relaunch the country after the financial crisis of 2007–2008. Retrofitting buildings to be more energy efficient, for example, creates new sources of employment rapidly, and contributes to long-term energy savings, two objectives of the stimulus.

Most recently, U.S. electricity demand has remained largely flat or has fallen since 2007[10] after steady growth since the 1950s and despite continued growth in GDP, building space, and population (Figure 4-3). The stabilization of electricity demand growth has contributed to the recent fall in carbon dioxide (CO_2) emissions. A combination of new technologies (front-load washing machines, LEDs), business models (utility decoupling, distributed generation tariffs), policies (state and regional climate targets, energy efficiency resource standards) and structural changes in the economy are thought to have contributed to the slowdown in electricity demand growth [28], [29].

[10] Net generation did increase by nearly 4% in 2018, but this was largely considered to be for weather-related reasons rather than efficiency or structural reasons. Minor increases in net generation occurred during several other years, but the total still remained below the 2007 peak at the end of 2019 [60].

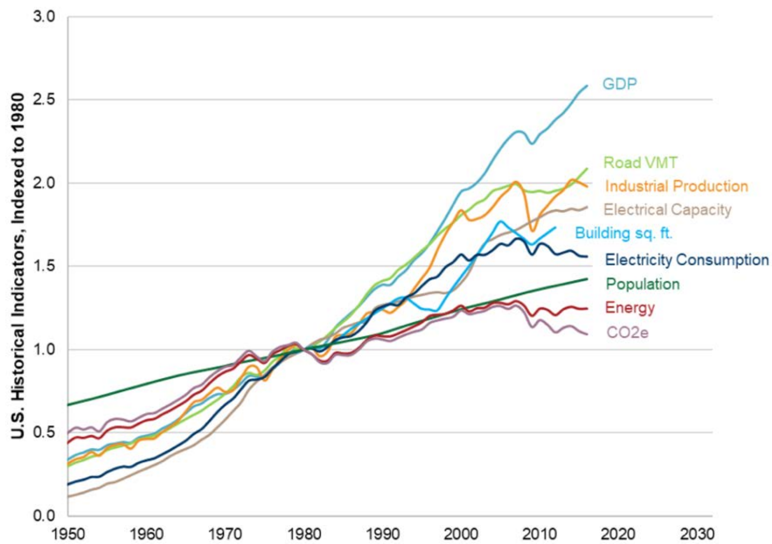
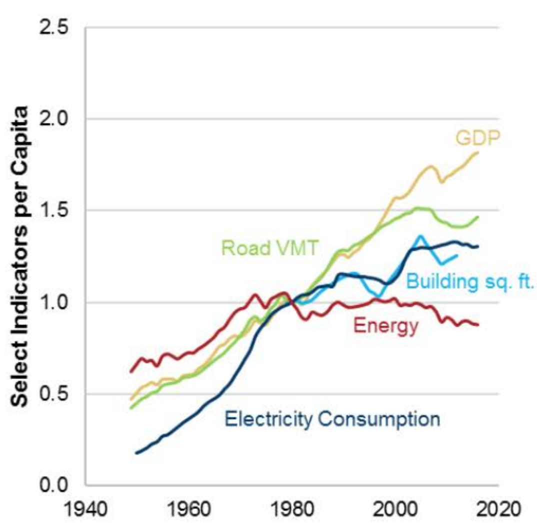


Figure 4- 3. Indicators of the U.S. energy economy

Source: [27]

Note: VMT=vehicle miles travelled; sq. ft.= square feet; $CO2_e$= CO_2 equivalent.

On a per-capita basis, the picture remains similar (Figure 4- 4). Electricity demand per capita has leveled off since 2010 after decades of growth, while overall energy demand has fallen since 2000. On a per-GDP basis, all indicators have been falling—as expected—although electricity demand plateaued around 1980 and has fallen since. As will be seen in Section 4.3, however, some observers believe that trend is set to change largely due to increased electrification [30], [31].



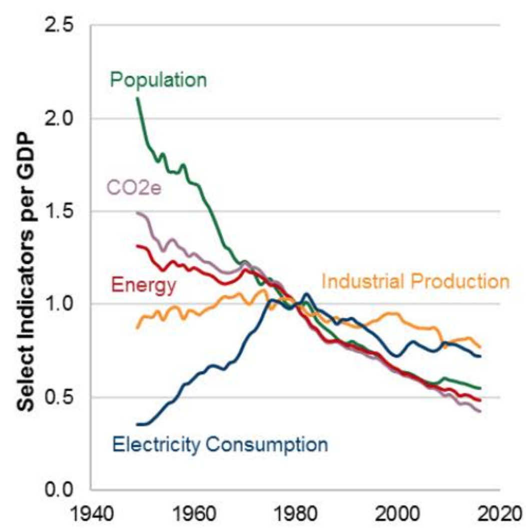


Figure 4- 4. Selected normalized indicators (left) per capita and (right) per dollar of GDP

Source: [27]
Note: VMT=vehicle miles travelled; sq. ft.= square feet; $CO2_e$=CO_2 equivalent.

4.1.5 Outlook

A large number of studies in the literature point to the potential role that energy efficiency could play in helping to achieve sustained economic growth, increasing flexibility in many transforming power systems

[32], and meeting United Nations Framework Convention on Climate Change goals [1], [33], [34] and the United Nations Sustainable Development Goals [35]. All countries have room to make greater use of energy efficiency, and all can benefit from its impacts.

Meeting the United Nations Sustainable Development Goal #7[11] requires, inter alia, a strong focus on energy efficiency, including an annual reduction in global primary energy intensity of 3% on average through 2030. Achieving this target will provide numerous benefits, including: (1) energy access for the over 800 million people who still do not have electricity connections; (2) healthier environments for human development; (3) energy security; and (4) overall sustainability. Not achieving the target will put greater strain on other clean energy options.

The role that energy efficiency can play in maintaining flexible and resilient power grids is notable. Three examples below illustrate how energy efficiency and demand response can help cut costs of keeping supply and demand in balance in the United States (Figure 4- 5).

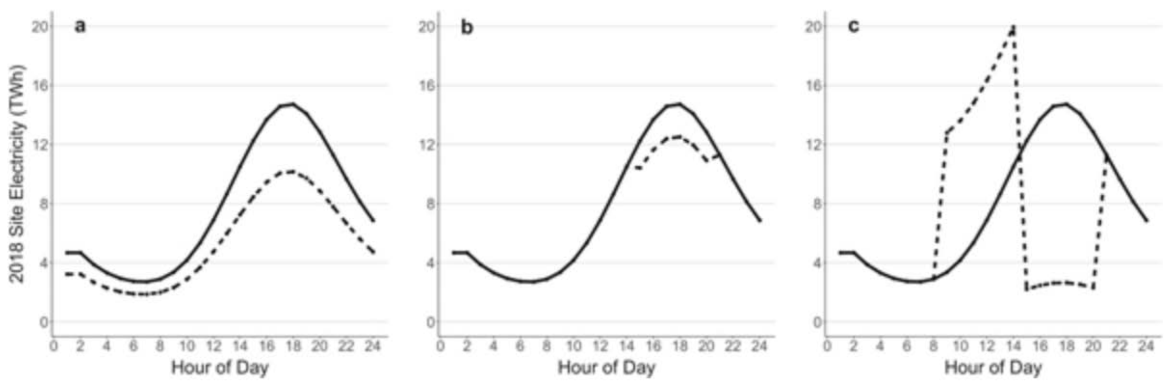


Figure 4- 5. Hourly load shapes representing hypothetical energy efficiency and demand response measures, including: a) static cooling efficiency measures applied across all hours, b) dynamic cooling load shedding that reduced peak demand from 2 p.m. to 8 p.m., and c) dynamic cooling load shift that reduces load from 2 p.m. to 8 p.m. (assuming no energy penalty)

Source: [36]

Nearly all studies that attempt to define energy pathways that comport with the "under 2°C" scenarios show an increasingly strong role for energy efficiency depending on targeted mitigation. Figure 4- 6 shows primary energy intensity (a proxy for energy efficiency) over time from over 200 studies collected in the Intergovernmental Panel on Climate Change Assessment Report 5. In scenarios limiting change to below 1.5°C (blue), primary energy intensity would decline by an average of 2.6% annually, while in scenarios limiting change to below 2.0°C (grey), primary energy demand declines slightly less rapidly at 2.3% per year. Energy efficiency will play an important role in any country's attempt to eliminate carbon emissions: without including it in their strategies, more resources will need to be dedicated to zero-carbon infrastructure and enabling options.

[11] Defined as "Ensure access to affordable, reliable, sustainable and modern energy for all"; https://sustainabledevelopment.un.org/sdg7.

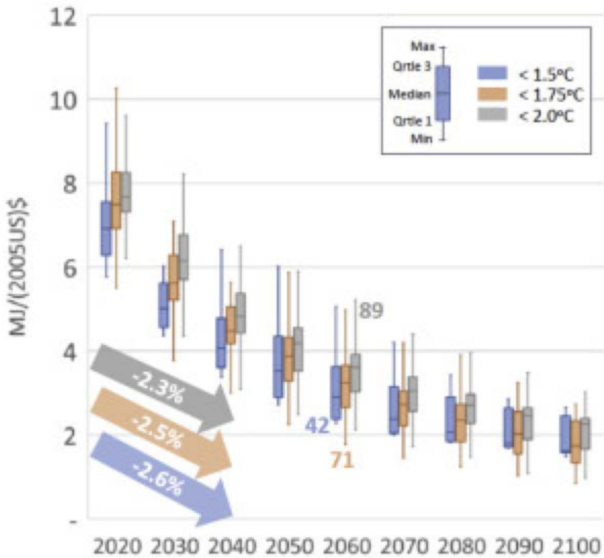


Figure 4- 6. Change in global primary energy demand in meeting various temperature change targets, 2020–2100

Source: [37]

4.2 Demand Response and Other Forms of Demand-Side Flexibility

Utilities have been asking customers to reduce load during peak demand times and compensating them for that service for decades. There is currently interest in understanding what additional roles the demand side could play in future clean electricity grids: might emerging communications and control technologies enable a wide variety of end uses to take a more active role in bulk power supply-demand balancing, distribution system operations, and/or microgrid-enabled outage ride-through?

In this section, we describe: (a) how electricity demand can be incentivized to operate more flexibly; (b) the grid services such flexible demand might provide; and (c) results of previous research on the ability of demand response to reduce system costs and help integrate variable renewable generation.

4.2.1 Types of Demand-Side Flexibility

The term "demand response" is sometimes used in a limited manner to refer only to event-based reductions in electricity use; however, in the remainder of this section, we will use the term broadly, to indicate any change in demand-side operations undertaken for the purpose of providing a grid service. [11], [12] take a similarly broad view by categorizing demand response as shed, shift, shape, or shimmy.

The "shed" category aligns with the traditional use of demand response to reduce load during peak times, as might be done by large commercial or industrial customers as part of an interruptible load program. The reduction might be achieved by shutting down an energy-intensive process, or by starting up a small on-site generator. Typically, this type of demand response is only called on a few times a year, and only for one hour to a few hours at a time. Events may be communicated semi-manually up to a day ahead of time, through phone calls, emails, and text messages; or they may be communicated directly to demand-side control systems with as little as 10 minutes notice. The latter may be required by the grid operator or necessary to achieve acceptable performance when shed demand response participates in formal spinning reserves markets [38], [39].

Demand-side "shifting" can be implemented for a variety of end uses by scheduling services like clothes drying, water pumping, or car charging; or by using the thermal storage inherent in buildings and refrigeration systems to partially schedule heating and cooling operations. Shifting can also be implemented in a variety of ways—via direct load controllers, programmable communicating thermostats, other types of controllers visible to and (partially) operable by an aggregator or a utility; or via site-level controllers that respond to a static (e.g., time-of-use) or dynamic (e.g., real-time pricing, critical peak pricing) price signal.

In [40], "shape" demand response refers to shifting achieved via price responsiveness or behavioral campaigns. In practice, shift demand response may be achieved via "shape" methods. For example, an aggregator may compute a fictitious price signal that a site-level controller can use to modify operations in a way that achieves the aggregator's shifting goal [41].

Finally, "shimmy" refers to demand response used to even out the supply-demand balance on the seconds to hour scale. In an independent system operator (ISO) context, these types of services might be referred to as regulating (seconds-scale) or ramping (hour-scale) reserve [42]. Flexible demand providing regulation reserve is fairly uncommon, as the size of these markets is relatively small [40], [42], and implementation is technically complex [43]–[47]. Nonetheless, PJM reported in 2017 that their registered providers of regulation reserve included water heaters, heating, ventilating, air conditioning (HVAC), manufacturing, and refrigeration [48]. Looking forward, ramping reserve may be a better fit for shimmy demand response, based on a moderately larger expected market size[12] and a longer time constant, as compared to regulation [40], [42].

At the distribution level, inverter-based demand-side resources can provide voltage and reactive power support by implementing constant power factor or more sophisticated volt/volt-amp reactive (VAR) controls. For example, researchers at SolarCity, San Diego Gas & Electric, and the National Renewable Energy Laboratory (NREL) have demonstrated smart inverters associated with solar photovoltaic (PV) systems providing such support both in the field [49] and in simulation models [50]; however, while smart inverters can provide this service, it is unclear to what extent these functionalities will be enabled and/or compensated. Per [40], the size of this flexibility market is expected to be small, as demand-side resources "must compete against cost-effective supply side resources including transformers, fixed capacitor banks, and line regulators." Indeed, [50] finds the voltage impact of 700 kW of controllable PV to be similar to that of a 1,200-kVAr switched capacitor installed at the substation.

Larger-scale distribution-level deferrals, beyond using smart inverters to achieve voltage control, as well as transmission deferrals, can sometimes be achieved by reducing peak net load relative to a baseline planning forecast. Often referred to as "non-wires alternatives," both distributed generation (e.g., from PV) and load flexibility/dispatchability (e.g., from shift demand response and/or behind-the-meter storage) may be able to defer network upgrades in this way [51]. One well-known example, the Brooklyn-Queens Neighborhood Program, deferred a $1.2 billion substation upgrade through a combination of energy efficiency, demand response, and distributed generation [52].

Paired with one or more generation sources (e.g., diesel generator, solar PV), controls that limit consumption to critical loads and perhaps dispatch energy storage and other forms of flexibility to best match on-site electricity supply and demand can provide additional value by extending the length of time over which a site can ride through an outage. For example, [53] estimate that adding 1,287 kW of PV

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[12] For example, currently in the California Independent System Operator and Midcontinent Independent System Operator, spinning reserve requirements are more than twice as large as regulation reserve requirements, and ramping reserve requirements are about twice as large as spinning reserve requirements [42]. These sorts of ratios may become typical for large power systems as variable generation penetrations increase.

along with 215 kW/1,557 kWh of battery energy storage to an already existing 500-kW/250-gal fuel storage diesel generation system could extend outage survivability from 0.9 to 3.0 days for an example New York City building with a critical load of 155 kW. They estimate that the value of the extra survivability is worth approximately 4% of the system life cycle costs (capital, fuel, operations and maintenance) and demonstrate that monetization through business interruption insurance premium reductions could comprise up to 9% of the revenues attributable to such a renewable energy hybrid system.

In the remainder of this section, we focus on the value flexible demand can provide by way of bulk-level services, especially firm capacity/peak load reduction and energy shifting. This focus is in line with the qualitative value and market size findings of [40]. It is further supported by a variety of findings[13] that while voltage support, transmission and distribution deferrals, and resiliency value can be considerable, their value tends to be location-, utility- and/or customer-specific, and often smaller than (that is, best thought of as an add-on to) the value of providing basic capacity and energy services.

4.2.2 Grid System Value and Cost Savings

Compared to no demand response, the presence of demand response always represents an additional degree of freedom for the grid operator and therefore always lowers overall system costs if the power system is planned and operated in a least-cost manner. Thus, the question is not whether demand response will provide grid system value, but rather, how much will it provide, what form it will take, and are those benefits sufficient to cover the costs of enabling that demand response?

For example, [55] examined the value of demand response in a production cost model of a Colorado test system and found that the 12 end uses shown in Figure 4- 7 were able to reduce annual production costs by $7.9 million by providing energy arbitrage and ancillary services (i.e., flexibility, contingency, and regulation reserves). Enabling these end uses to provide demand response would only make sense if the costs of enablement—including any hardware, software, utility marketing and programmatic costs, and opportunity costs of foregone energy services—total to less than the $7.9 million savings.

[13] For example, [54] finds that adding distribution-level service requirements to an energy storage system that was otherwise allowed to provide bulk-level services reduced its 10-year net present value from $1.11 million to $191,000. Also, [53] attributes significant resiliency value to PV plus battery systems when a critical load is present, but they also find that normal condition, grid-connected savings are 2.2 times larger than the value of riding through a 3-day outage. In general, [53] demonstrates how resiliency value scales with critical load size and importance, as well as the probability of experiencing a long-term outage event.

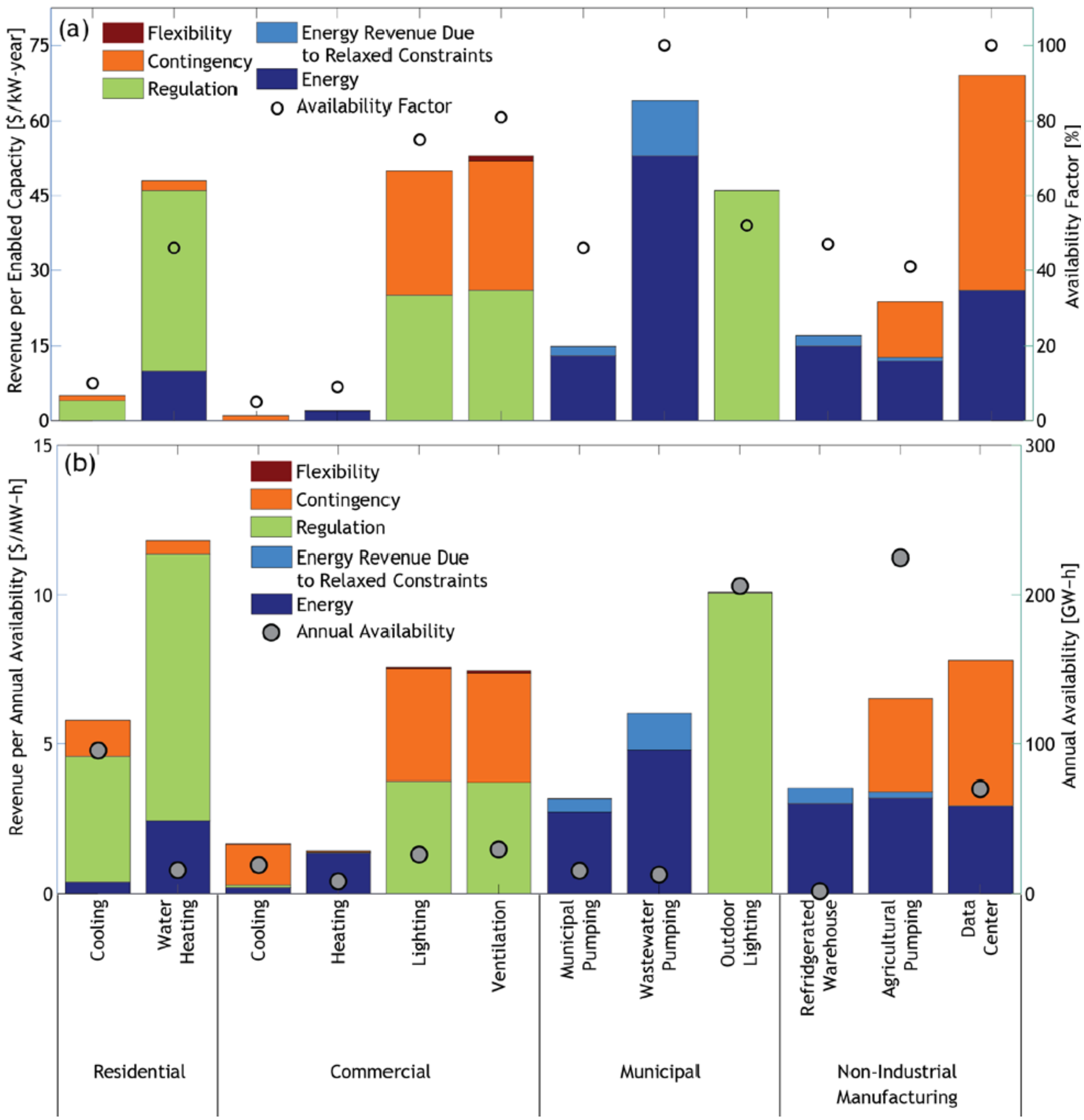

Figure 4- 7. Average annual revenue (left axis) from the day-ahead market per: (a) total enabled capacity and (b) annual availability for each type of demand response resource in the Colorado test system as modeled in [55]

Ideally, cost-effectiveness would also be measured on a per-program basis, rather than for demand response as a whole. One way to look at that question is to examine model revenues for the flexible demand resources. In production cost modeling, model revenues—measured by multiplying service provided by marginal service price and summing over the year—are typically less than the production cost savings computed by subtracting the production costs for the system with the resource in question from the production costs for the same system *without* the resource in question. This happens because the additional resource suppresses prices for the services it provides. Nonetheless, model revenues provide a way to compare the value of demand response from different end uses.

Figure 4- 7 depicts average model revenues per flexible end use, normalized by capacity (MW) and annual availability (MW-h). Total revenue for these resources in the Colorado test system would be $5.4 million, but as is apparent from the figure, that revenue would not be split evenly among the end uses. Highly available (nonseasonal and often operating) end uses are equipped to provide regulation and contingency reserves (e.g., residential water heating, commercial lighting, commercial ventilation, and outdoor lighting do well by these normalized metrics), as are highly schedulable and/or interruptible loads (e.g., wastewater pumping, agricultural pumping, data center). To get total revenues, we multiplied the normalized revenues in $/MW-h by the annual availability in GW-h. Thus, while residential water heating is very valuable per MW-h of availability, in this set of results it captured less revenue than outdoor lighting or commercial ventilation, because it had less annual availability than those other end uses. [55] also estimated that the capacity value of these resources would fall between $8.7 million and $23.7 million, that is, similar to or up to four times higher than, the estimated operational value.

[38] examined the interactions between demand response, other flexibility options (operational flexibility and battery energy storage capacity), and a wide range of PV penetrations in a production cost model of the Florida Reliability Coordinating Council (FRCC) power system. The capacity composition of the test system for a subset of the scenarios modeled is shown in Figure 4- 8.

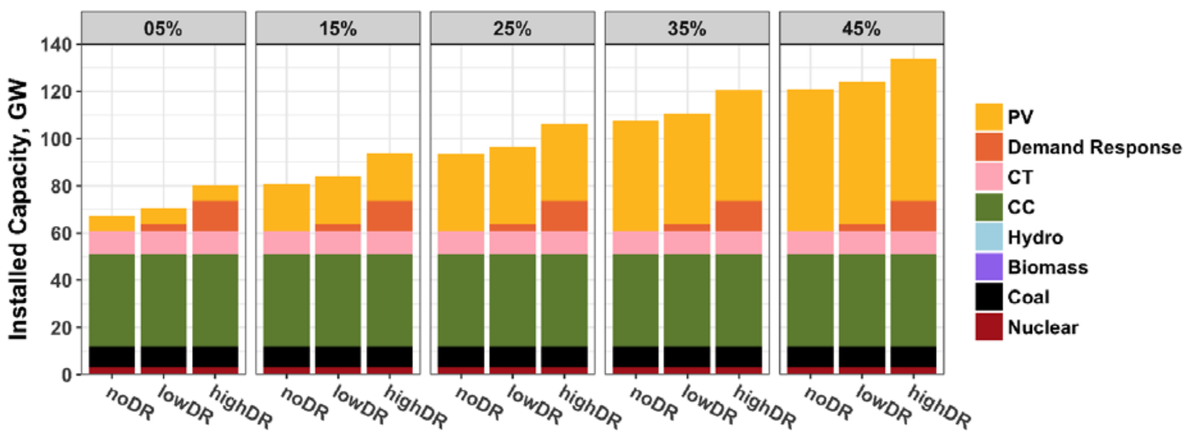

Figure 4- 8. FRCC model installed capacity by solar PV penetration and demand response scenario. The battery capacity included in some of our scenarios, which amounts to either 1 GW or 4 GW spread throughout FRCC, all with 6 hours of storage, is not depicted.

Source: [38]

In the test system, demand response could shift energy use from higher cost to lower cost hours, as well as provide ancillary services. Figure 4- 9 depicts how annual generation by generator type changes when different portfolios of flexibility measures are added to the FRCC system. All differences are with respect to the base scenario (least-flexible case) for the same PV penetration. The impact of demand response alone could be seen by comparing the first column across the three rows, where the bottom row contains no flexibility measures, the second row has limited demand response capacity, and the first row has high demand-response capacity (high demand response scenarios). Because these difference bar charts are shown for the full range of PV penetrations modeled (5% to 45% by annual energy, precurtailment), we can see that the impact of demand response (and the other flexibility measures) changes as we move from a low-PV to a high-PV system. Focusing on the Base-High Demand Response scenario (upper left corner), at low PV penetrations, demand response operations resulted in less natural gas combustion turbine and more coal generation; but at high PV penetrations, the main effect was to reduce solar curtailment and NG-CC generation.

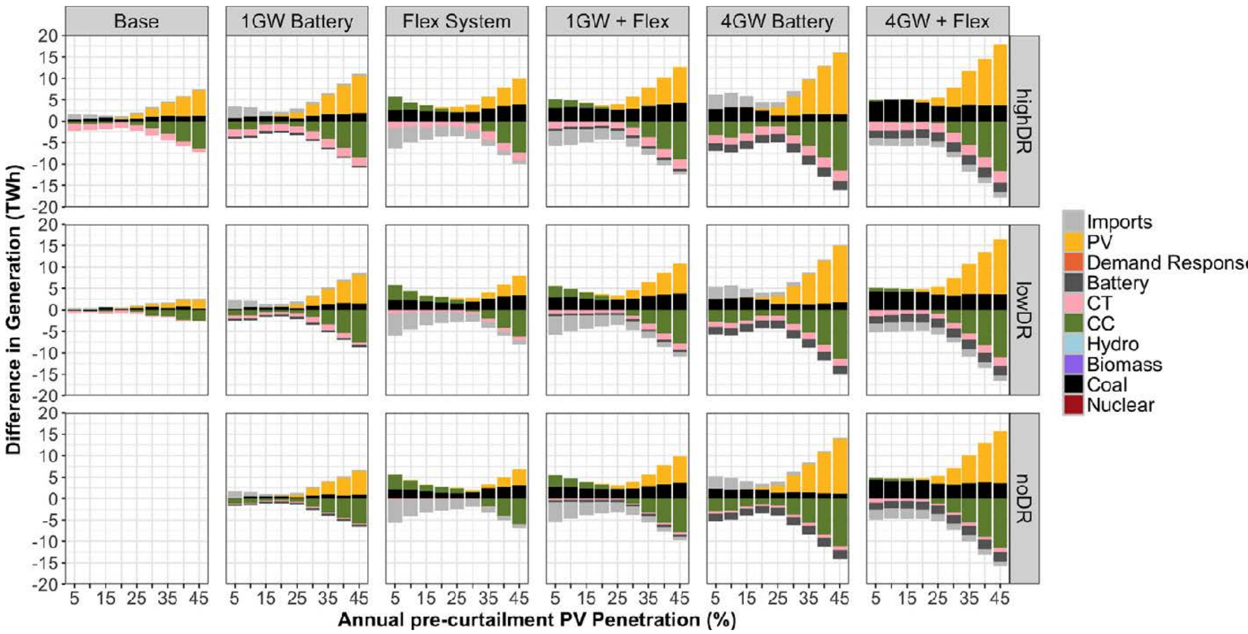

Figure 4- 9. Differences in annual generation from the baseline scenario at each PV penetration, using mid-gas prices in the Florida study

Source: [38]

Figure 4- 9 also lets us compare demand response energy shifting to other forms of flexibility. For example, the impact of Base-High Demand Response was similar to that of 1-GW Battery-No Demand Response in both magnitude and type of impact, especially at high PV penetration where both resources offset natural gas combined cycle (NG-CC) generation by reducing solar curtailments. On the other hand, while the magnitudes of Base-High Demand Response and Flex System-No Demand Response's impacts were similar at high PV penetrations, the resulting generation mix was not, as the Flex System package increased coal generation nearly as much as it reduced PV curtailments. Flex System also had a much larger impact at low PV penetrations, when it reduced imports in favor of more in-FRCC gas and coal generation. These outcomes resulted from the complex interactions between the system generator fleet, fuel costs, and the details of the DR capabilities, battery capacity, and/or package of system flexibility measures.[14]

Demand response could also provide value by reducing thermal generator starts (Figure 4- 10) and the amount of time spent at minimum generation levels (Figure 4- 11), both of which increase generator efficiency and reduce wear and tear.

[14] Flex System is defined as a package of four flexibility measures: (1) Curtailed PV is allowed to provide regulation and contingency reserves; (2) The minimum generation level of all FRCC NG-CC units is reduced from 50% to 40%; (3) All hurdle rates (extra costs for transferring power between the model's six balancing authorities) are removed; and (4) Regulation and contingency reserves requirements are set and met at the FRCC level, not by individual balancing authority.

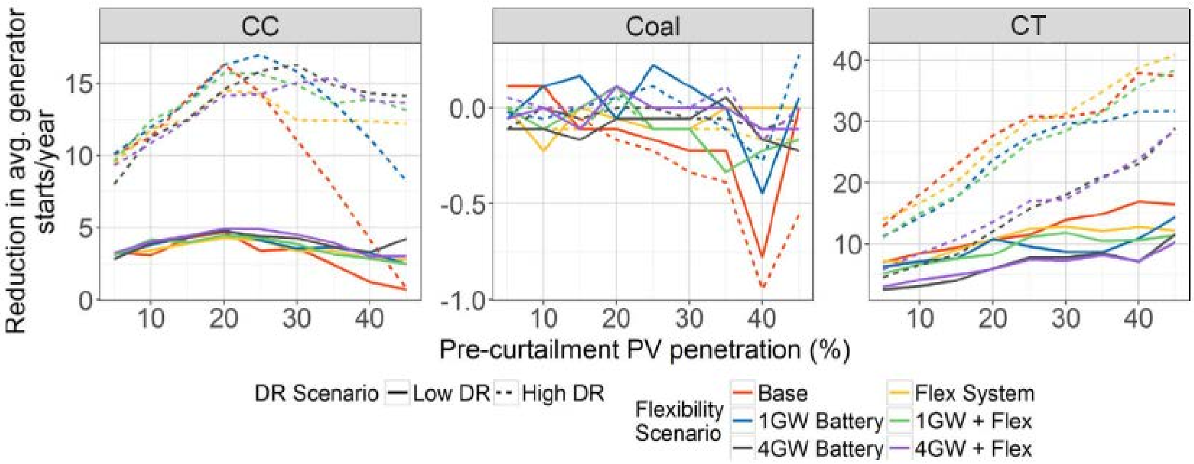

Figure 4- 10. Reduction in the mean generator starts per year for each generator category in the Florida system by demand response, for all flexibility options [56]. Differences are between the plotted Low Demand Response or High Demand Response scenario and the corresponding No Demand Response scenario at the same PV penetration.

With regards to generator starts, demand response fairly consistently reduced the number of natural gas starts (compared to the least-flexible, Base-No Demand Response scenario), especially for combustion turbines, which are just listed as “Gas” in Figure 4- 10. For non-Base scenarios with additional flexibility measures enabled, the other flexibility measures (especially 4 GW of battery) had already suppressed the number of natural gas starts in most cases.[15] This left fewer starts in place for demand response to mitigate; nonetheless, the actions of the other resources often made it easier for demand response to suppress some of the additional combined cycle starts induced by high PV penetrations, perhaps by reducing the amount of energy that must be shifted to bridge over some of the low net-demand periods. The interactive effects were more competitive in the case of combustion turbine starts; demand response was not able to eliminate as many of those when other flexibility measures were also in place.

Coal generators typically start up and shut down much less often than gas generators. [56] reported average coal unit starts falling in a tight band between 6.5/yr and 7.75/yr across the entire range of modeled PV penetrations (5% to 45% by precurtailment annual energy). As such, there were few consistent trends across either PV penetrations or flexibility options, including demand response (Figure 4- 10). Consistent with coal generators being on for long stretches of time so as to avoid being unavailable for their minimum down time (which can be a week or more), demand response was able to consistently reduce the amount of time coal plants spend at their minimum stable level, see Figure 4- 11.

[15] At low PV penetrations, average combined cycle starts are about 50/yr without 4 GW of battery and 25/yr with 4 GW of battery; gas/combustion turbine starts are suppressed from about 25/yr to 8/yr by 4 GW of battery capacity. Higher PV penetrations increase both combined cycle and combustion turbine starts to about 150/yr and 75/yr, respectively, in the base case. Adding 4 GW of battery capacity reduces combined cycle starts to about 130/yr and combustion turbine starts to about 50/yr.

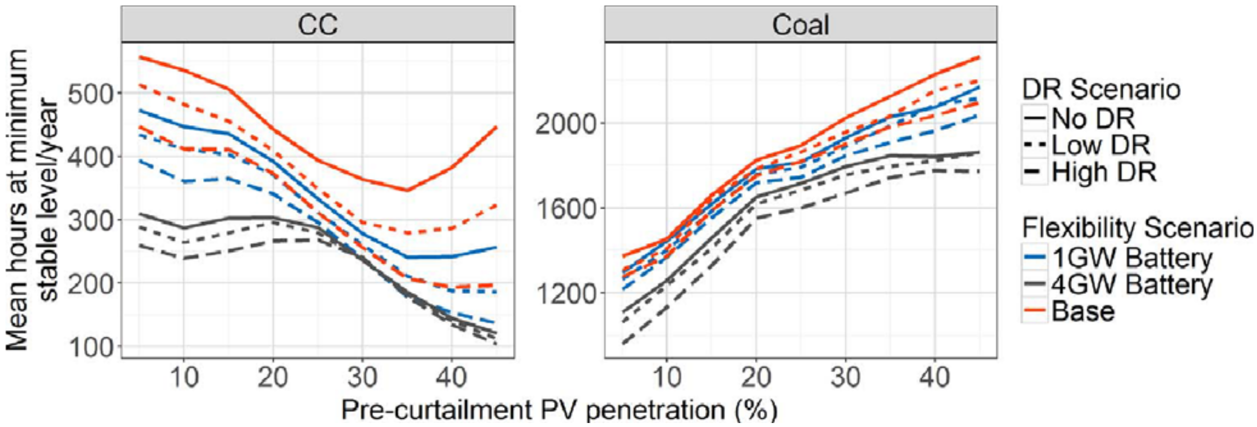

Figure 4- 11. Mean number of hours two generator types spent operating at their minimum stable levels for each PV penetration and several flexibility scenarios

Source: [56]

The impact of demand response on NG-CC units' time at minimum stable level was more complex. The directional impact was consistent—demand response reduced NG-CC units' time spent at this minimum output point, but the magnitude of its impact changes dramatically with both PV penetration and the presence of other flexibility options. For example, the High Demand Response scenario had its biggest impact on the Base flexibility scenario at 45% PV, but hardly any impact at all when 4 GW of battery capacity was already deployed and PV penetrations were 30% or higher (Figure 4- 12).

4.2.3 Integration of Variable Renewable Generation

It has come to be understood that increasing amounts of variable renewable generation (e.g., from wind and solar) create a demand on the rest of the system for more flexibility [57], [108].

Above we showed the ability of demand response and other forms of flexibility to reduce PV curtailments in an FRCC test system production cost model (Figure 4- 9). We can also quantify this impact in terms of the system value of the next increment of PV, which was computed by summing the operational value of PV[16] along with its capacity value[17] and the value of avoided emissions.[18] Compiling this information across PV penetrations and flexibility scenarios yielded Figure 4- 12, where we can see that PV value consistently declines with increasing penetrations. This trend was due to later increments of PV: (a) replacing less expensive generation and (b) experiencing higher marginal curtailment rates because there was insufficient flexibility to turn enough other units down or off to accommodate all of the available solar generation.

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16 Production costs before minus the production costs after the next PV increment is added.

17 PV capacity times capacity credit (fraction of nameplate capacity that contributes to meeting peak demand) times capacity price. Capacity credit is calculated based on how much the PV reduces the sum of the top 100 net-load hours [58]. [38] assume a capacity price of $75/kW-yr.

18 Incremental reduction in carbon emissions multiplied by an assumed social cost of carbon. [38] assume $50/metric ton CO_2 in the base case and consider sensitivities of $0/metric ton CO_2 and $100/metric ton CO_2.

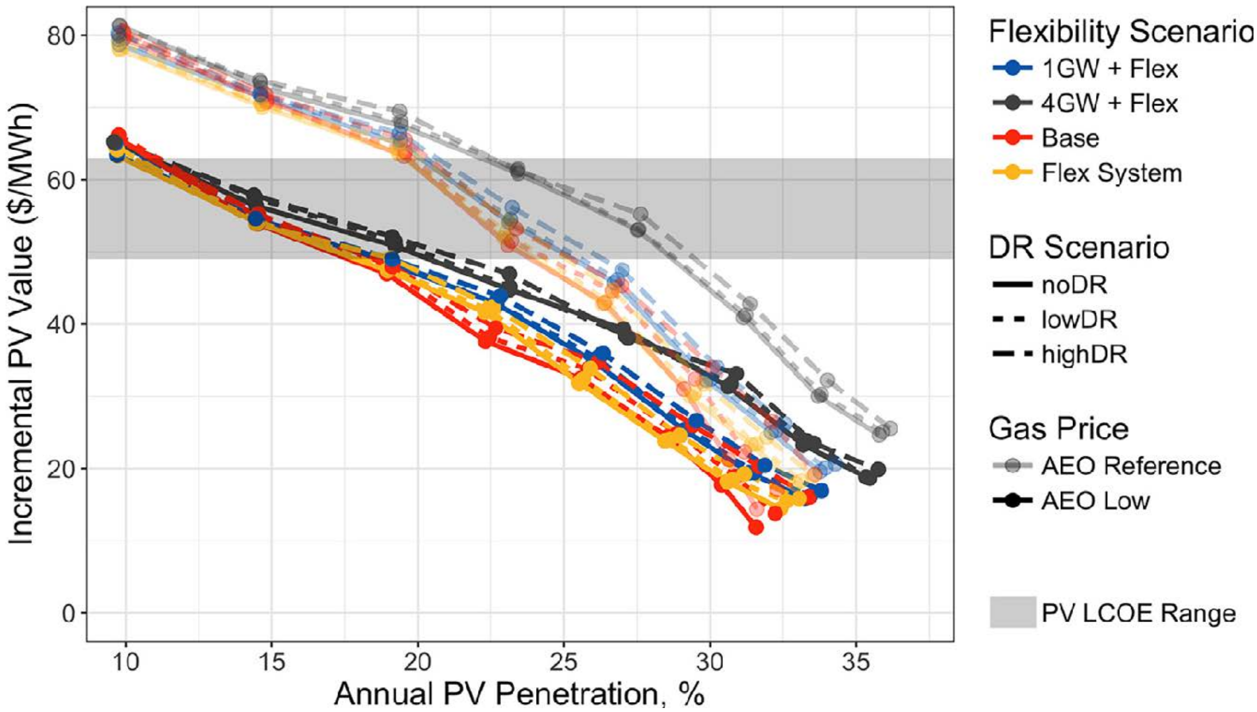

Figure 4- 12. Incremental value of PV in the FRCC test system [38]. Results are shown for both low (darker) and mid (lighter) natural gas prices. The PV levelized cost of energy (LCOE) range represents the mid- to low-PV price trajectories for 2026 in NREL's 2016 Annual Technology Baseline [59].

In addition to declining solar value, Figure 4- 12 shows that system flexibility, in all the available forms, is able to mitigate the value decline. The exact impact varies by flexibility measure, PV penetration, and natural gas price. One way to measure this impact is to compute the system's economic carrying capacity (ECC) of PV as a function of PV system cost. The ECC is the maximum penetration of PV economically justified by its incremental value. That is, if we draw a horizontal line on Figure 4- 12 corresponding to the precurtailment PV LCOE, and then draw a vertical line down to the PV penetration axis at the point where the horizontal line intersects the incremental value curve, the resulting PV penetration is the ECC, that is, the maximum penetration supportable by current system conditions based on energy values.

If for the same assumed PV LCOE we subtract the baseline ECC from the ECC obtained when flexibility measures are in place, we obtain a metric that describes how well different flexibility measures enable the integration of more PV generation. Figure 4- 13 shows this metric for the mid-natural gas price data in Figure 4- 12. Focusing on the High Demand Response line, we see that demand response increased the PV ECC in this test system anywhere from 0.5 percentage points (at a PV LCOE of $75/MWh) up to 2 percentage points (at PV LCOEs $30/MWh or less). Similar to what we saw in Figure 4- 9, this impact was comparable to that of a 1-GW battery. Also similar to what is depicted in Figure 4- 9, 4 GW of battery had considerably more impact.

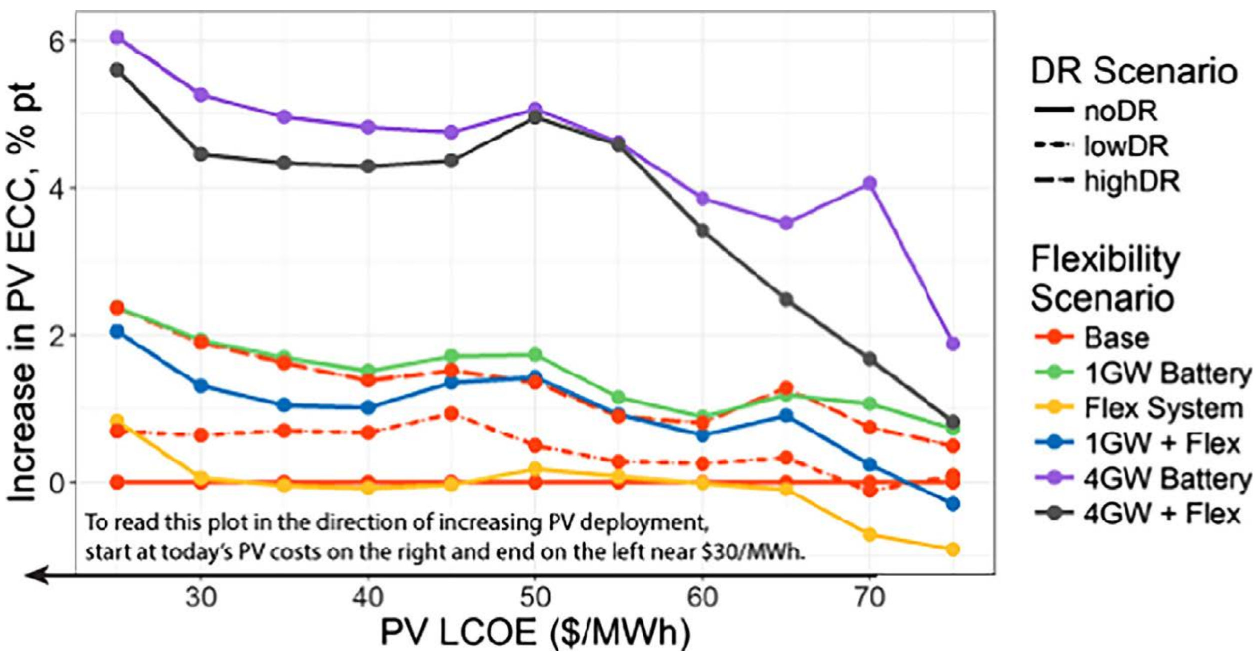

Figure 4- 13. Increase in the ECC of PV under mid-gas prices [38]. Increases are shown for select flexibility packages, compared to the Base scenario.

One way demand response helps integrate PV is by utilizing energy that would have otherwise been curtailed. The results we have looked at so far have shown this overall impact, but in considering what kinds of demand response would be most valuable to enable in the future, it is also helpful to understand exactly which types of demand response are best able to provide this service. Figure 4- 14 shows that, even if they are all providing energy shifting, different end uses have different abilities to actually make use of otherwise curtailed PV generation. Understanding exactly how shiftable different end uses may be and representing that accurately in bulk power system models remains an open research question. And demand response would be competing against other flexible technologies such as battery storage. [56] demonstrates that nonseasonal end uses with a high degree of shiftability (e.g., industrial manufacturing, municipal wastewater pumping, and residential water heating) are generally able to absorb more otherwise curtailed PV generation as compared to more seasonal and/or less shiftable end uses (e.g., residential and commercial heating and cooling, data centers).

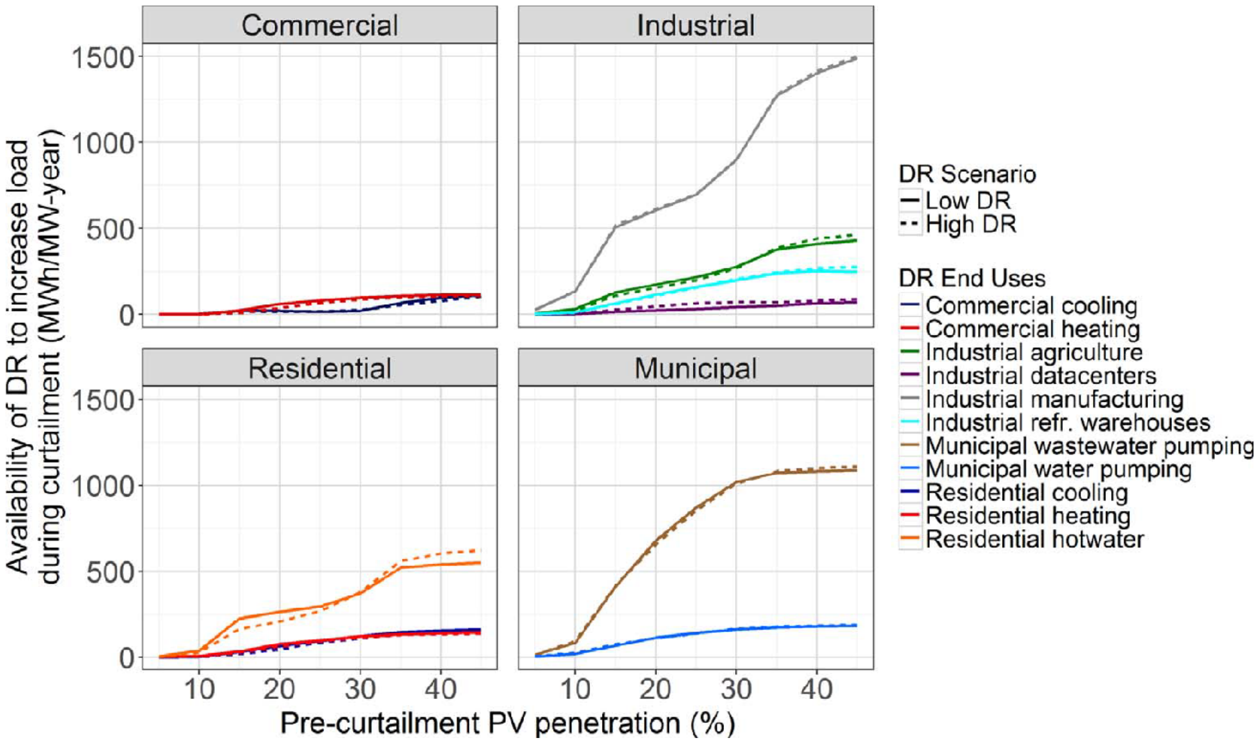

Figure 4- 14. Demand response end-use load increases during the No-Demand Response scenario's hours of curtailment, normalized by end-use peak demand

Source: [56]

4.2.4 Summary

Demand response and other forms of demand flexibility are increasingly recognized as potentially valuable providers of various grid benefits. Although a number of different services may contribute to a particular resource's value stack, it is generally recognized that the most consistently valuable services demand-side resources can provide are bulk-level capacity and energy.

By reducing generation needs during times of peak load or other forms of grid stress, demand flexibility can defer generation, transmission, and/or storage investments that would otherwise be needed to maintain reliability. If high levels of demand shifting can be enabled through advanced communications and controls, demand response can also reduce grid energy costs and potentially help integrate more renewable generation, primarily by making use of energy that would otherwise have been curtailed.

The value of demand flexibility varies considerably depending on end-use availability and flexibility parameters, control capabilities, and grid system conditions. While many control demonstrations, demand response and DER pilots, and grid integration studies have been completed, resource aggregation, business model, human behavior, and grid system value are still active areas of demand response research.

4.3 Electrification

Beneficial electrification is the substitution of electricity for fossil (or biomass) combustion at the end-use application while simultaneously lowering carbon intensity of electricity generation. It has demonstrated increasing interest among stakeholders since at least 2015. Electrification holds the potential to accelerate the current energy transition and enable systems to achieve deep decarbonization more efficiently.

4.3.1 The Next Energy Transition?

Humankind has gone through a number of energy transitions, ranging from the mastery of fire around 250,000 years ago—which had profound implications for our lifestyles, diet, and physiological development—to the birth of sedentary agriculture about 8,000 years ago, to the harnessing of fossil fuels that led to the industrial revolution 250 years ago [60], [61]. While the occurrence of numerous other transitions over the years can be debated, we enter the second decade of the 21st century on the edge of a new transition that includes a combination of renewable energy, digitization, decentralization, and other enablers of a low-carbon energy transition. The emergence of abundant quantities of lower-cost natural gas is also a driver of change in some economies, especially North America, but it is still viewed as a shorter-term phenomenon unless a solution for its carbon emissions can be found soon [62], [63].

A growing number of voices see beneficial electrification as a key element of the current transition [64]–[66]. The shift from internal combustion engine (ICE) to electric vehicles is the poster child of beneficial electrification, but other examples include electric heat pumps replacing natural gas-fired boilers and furnaces, induction cooktops replacing natural gas burners, and electricity-derived "green hydrogen" replacing natural gas and also potentially providing longer-term energy storage.[19] How this transition ultimately plays out remains unknown, although its impacts are already shaking markets and decision halls around the world.

Energy efficiency has played a role in grid planning and operations for decades and is well understood, but now there is more beneficial electrification and more demand response to think about. Loads are growing and shifting across time in new ways. The changes create both opportunities and challenges in providing the needed flexibility to operate the grid reliably.

4.3.2 Why Electrify Now?

The choice of whether to use electricity to power end-use devices emerged, perhaps surprisingly, in the late 1880s when Westinghouse and Edison jockeyed to advance their respective AC and DC technologies to run the grid in New York City and beyond [67]–[69]. Shortly after that not-so-friendly "war of the currents" was waged, battery electric vehicles were in serious contention to power the ascendant passenger car. Their competition? The steam engine and the ICE, among others [70].

Despite the eventual victory of the gasoline-powered ICE, newly improved electric cars now stand poised (over a century later) to again transform the market for passenger vehicles. In parallel fashion, heat pumps, induction cooktops, and other electric-powered end-use technologies may play an increasingly important role in replacing natural gas, fuel oil, propane, bioenergy, and coal in our buildings and industrial sectors. Indeed, electrification is now viewed as the hub to decarbonize many other sectors of the economy.

Although a handful of studies have been carried out over the past decades envisioning a much larger role for electricity in helping to decarbonize the economy [71]–[73], it wasn't until 2012 with the publication of a short report by a team of California researchers [74] that a strategy of using newly improved electrically powered devices combined with a lower-carbon electricity mix was even considered feasible as a way to address the climate challenge from an economy-wide perspective. Since then, several studies

[19] Green hydrogen is derived from zero-carbon electricity that splits water into hydrogen and oxygen using electrolysis; "grey hydrogen" is the traditional process of using steam reformation to separate natural gas (methane) into H_2 and CO_2; "blue hydrogen" takes the grey hydrogen process one step further by using carbon capture and storage to offset a portion of the produced CO_2.

have emerged to consider the benefits, challenges, and policy options associated with economy-wide electrification [27], [31], [75]–[78].

Lithium-ion battery price estimates show a nearly 85% reduction since 2010, as shown in Figure 4- 16. These price reductions have made lifetime operating costs for electric vehicles to be within striking distance of the ICE in some markets.

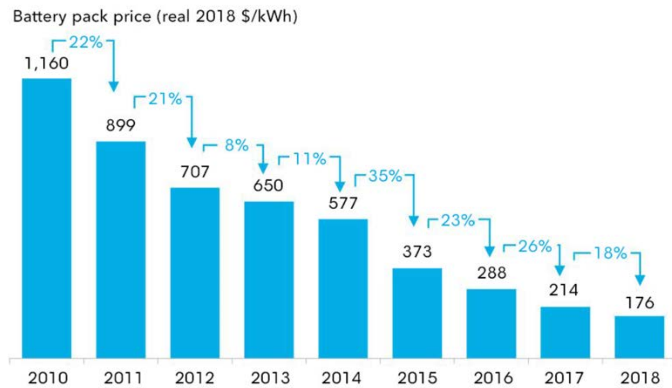

Figure 4- 15. Lithium-ion battery price survey results: volume-weighted average

Source: [79]

While heat pumps and other electrically driven end-use devices have not seen equivalent drops in costs yet, they have been engineered to higher performance levels, especially in cold climates, and could become more affordable through greater innovation and scale-up of manufacturing.

The other reason why electric utilities, environmentalists, and other stakeholders are interested in electrification is the rapidly declining carbon intensity of the U.S. electricity grid (Figure 4- 16). The emergence of cheap and plentiful shale gas and dramatically falling costs for wind and solar has resulted in the accelerated retirement of over 100 GW of coal-fired generation over the past decade [80]–[82]. The carbon intensity of the U.S. grid has fallen by 35% since 2008 [104], and most analysts expect it to continue falling as variable renewable energy (VRE) (and batteries) become increasingly low-cost, driving further coal retirements [105-107]. In 2018, total U.S. power sector CO_2 emissions rose for the first time in years as the growth in emissions from natural gas generators exceeded the decline in emissions from coal-fired generators [83]. Emission intensity still managed to decline, however, as total generation also grew rapidly. Data for 2019, however, showed a continuing decline in both total generation and CO_2 emissions [84]. Preliminary data for 2020 saw an economy-wide decline in energy-related CO_2 emissions of 11% [103].

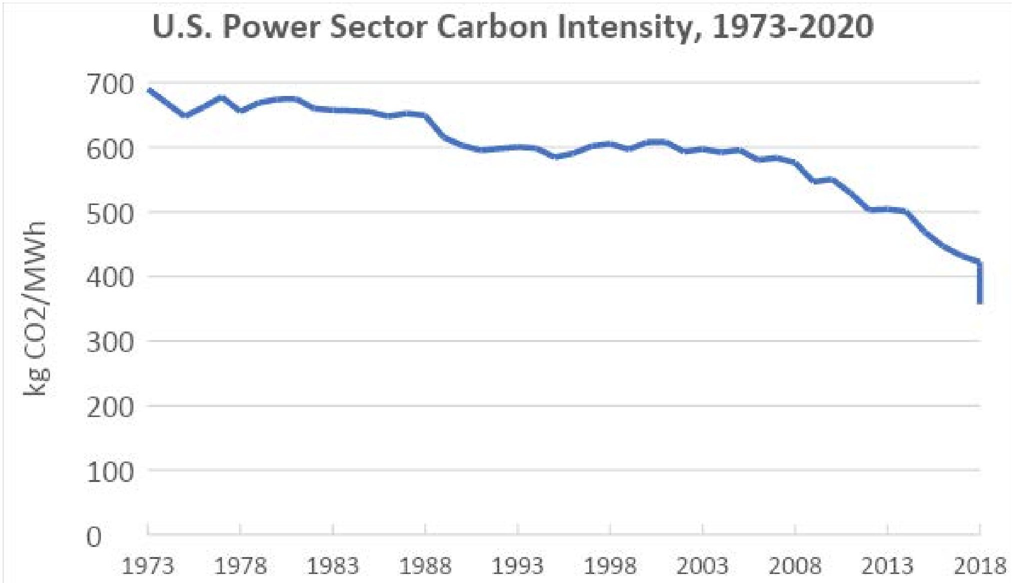

Figure 4- 16. Carbon-intensity changes in the U.S. power sector

Source: [104]

4.3.3 Benefits and Challenges of Electrification

One advantage that most electrically driven end-use devices offer is their improved efficiency. Electric vehicles and heat pumps are far more efficient than ICEs and furnaces, respectively. Their efficiency is high enough to even offset the 40%–70% losses associated with generating electricity at natural gas- or coal-fired power plants. Electric light-duty vehicles are approximately three times more efficient than ICE counterparts from the "tank/battery" to the wheels [85]. Likewise, air-source heat pumps that can be used in place of furnaces and boilers to heat buildings have average efficiencies about three times greater.[20] These higher efficiencies result in less energy use, fewer emissions of local criteria pollutants and (usually) a reduction in CO_2 emissions (depending on the composition of the local electricity generation mix).

Other typical benefits of electrification include: (1) quieter and safer[21] operation; (2) simpler end-use devices[22]; and (3) increasing flexibility for replacement renovations, including the ductless split-unit heat pump that can more easily replace a traditional furnace or boiler. More subjectively, many owners of electric vehicles say they are more fun to drive than traditional vehicles because they have better acceleration and handling.

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[20] Heat pumps use a metric called "coefficient of performance" to rank their efficiency. Typical air-source heat pumps operate with coefficients of performance of approximately 200-400, compared to boilers and furnaces that can reach the low 90s (measured in standard percentage terms). In cold weather (below 10° F), heat pumps can suffer a loss of efficiency, although recent advances have reduced efficiency losses at colder outdoor temperatures. An electric resistance heater, which an air-source heat pump resembles at temperatures below -4° F, has a coefficient of performance of 100. Ground-source heat pumps have higher coefficient of performance ratings (300-500) because they gather heat from below the surface where base temperatures are higher and relatively constant [86].

[21] Electricity can still be dangerous due to the potential for electrocution, but limited anecdotal information suggests that accidents due to natural gas leaks and incomplete combustion are more serious problems. Lithium-ion batteries are also known to catch fire or explode if damaged.

[22] The powertrain of a conventional ICE vehicle has an estimated 2,000 moving parts compared to an electric vehicle with 20 [87].

Electrification also faces a variety of challenges. On the technology side, some high-temperature processes in industry do not currently have electrical options; some climates may be too cold to rely entirely on current heat pump technologies for efficient heating services. On the infrastructure side, charging stations would be needed for greater electric vehicle adoption, and some homes and distribution systems might need to be upgraded to handle the increased electricity load of replacement heat pumps or new vehicle charging equipment. On the supply chain side, current lithium-ion battery supply chains rely on cobalt and lithium, which could experience supply shortages in certain future growth scenarios [88]. From the perspective of consumers and stakeholders, consumers may not understand the benefits of electro-technologies; some worry that building reliability might be compromised if all energy comes from one source (no gas line to serve as potential backup if the electricity goes out[23]); some may experience range anxiety with electric vehicles. Contractors who lack familiarity with electro-technologies would be less likely to provide consultation, installation, and maintenance services on them. Finally, incumbent energy providers may use their vested interests to oppose electrification. Time will tell if these challenges are enduring or can be overcome.

4.3.4 Sectoral Overview

Electrification analysis is often broken down by sector (transportation, buildings, industry) as technologies, applications, and challenges may be unique to each. Figure 4- 17 shows the amount of electricity and other energy sources in 2015 that each U.S. sector used. Transportation currently uses the least percentage of electricity in its mix, while commercial buildings use the most.

[23] When a typical residential home loses electricity, gas furnaces and boilers are also typically shut down, as they need electricity to operate.

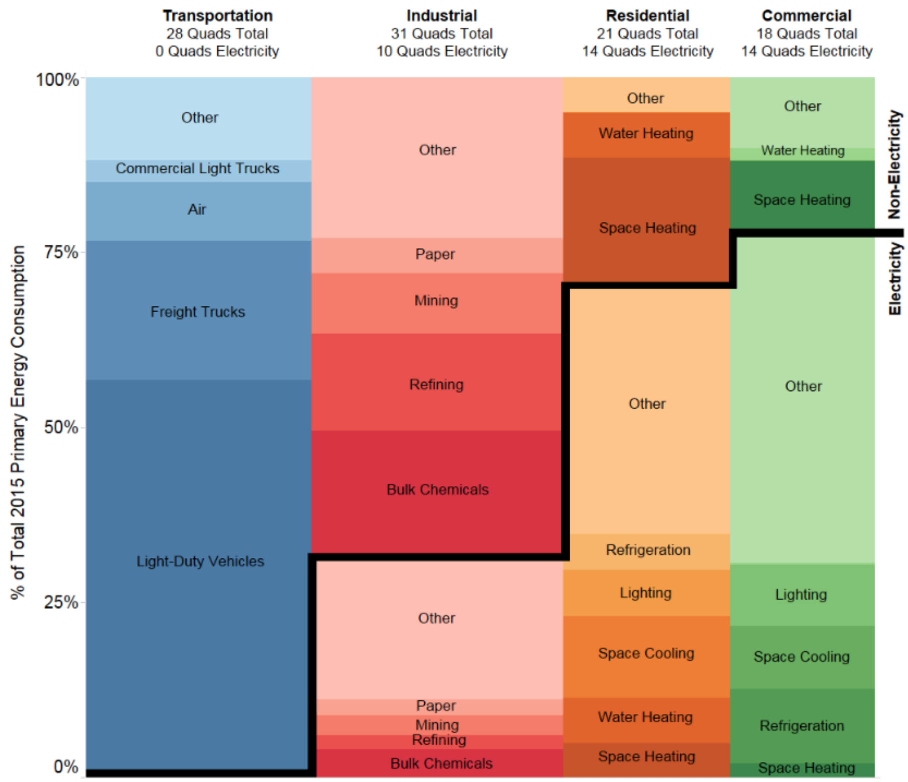

Figure 4- 17. U.S. primary energy consumption shares in 2015 by sector

Source: [27]

4.3.5 Opportunities and Potential for Electrification

The following sections use results from a recent study published by NREL on the "demand-side scenarios" for electrification [27]. The NREL Electrification Futures Study (EFS) is a multiyear, multistakeholder, and multipublication undertaking to better understand the national potential for electrification in the United States, and used a suite of high-resolution models to simulate the evolution of the energy sector under different sets of assumptions. More background on the methodology and products associated with this study program is available at https://www.nrel.gov/analysis/electrification-futures.html.

4.3.5.1 Electrification of Transport

The EFS study looked at three scenarios for how electrification could occur in the U.S. transport sector: a reference case assuming no significant changes, a Medium scenario with moderate improvements, and a High scenario with transformational vehicle electrification. Results for the light-duty fleet of vehicles in terms of annual sales share, vehicle penetration, and miles traveled are shown in Figure 4- 18. As illustrated, in the High scenario, electric vehicles sales accounted for more than 90% of all light-duty purchases in 2050.

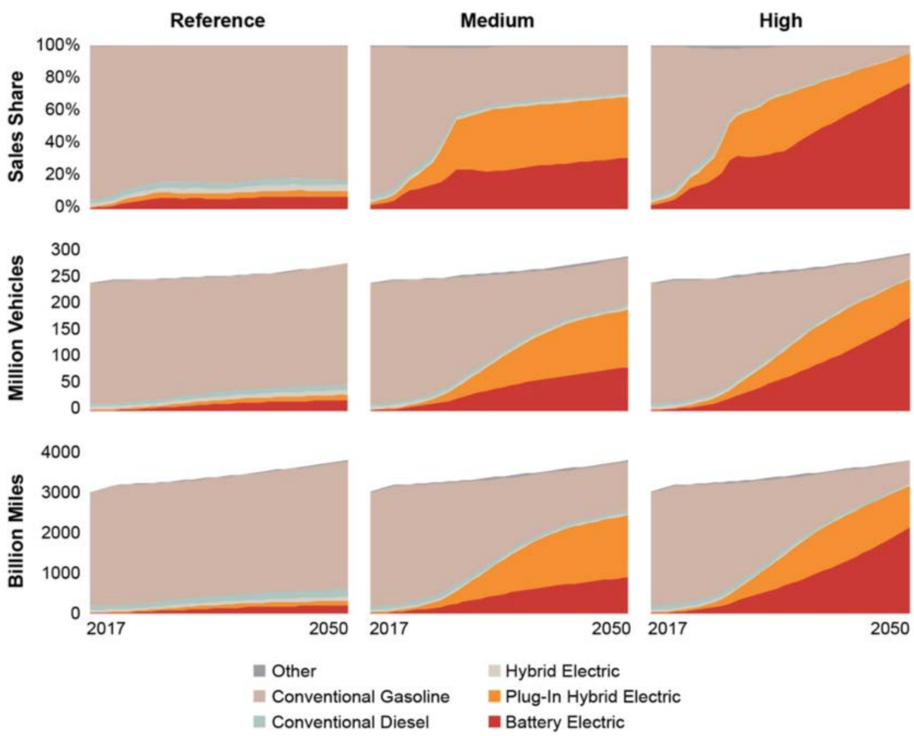

Figure 4- 18. Scenario results for light-duty U.S. vehicle fleet evolution through 2050

Source: [27]

4.3.5.2 Electrification of Buildings

In the buildings sector, air-source heat pumps have made enough incremental progress to now operate efficiently at temperatures as low as -4°F (-20°C), much improved from earlier models that would switch to "electric resistance" mode when the temperature fell below 30°F. Heat pumps can run more efficiently than a boiler or furnace, but they can also provide both heating and air conditioning and be integrated into domestic hot water production. The split-unit offering that allows heat pumps to be used in existing home retrofits without installing new duct work also broadens the market opportunities. These advances have encouraged some municipalities to consider banning (or actually ban) the use of natural gas connections for new residential and commercial buildings [89]. Solving the challenges around electrifying residential and commercial space heating and cooling will be central to achieving a zero-carbon future.

Figure 4- 19 presents results from the NREL EFS study for the residential and commercial buildings sector. Residential space heating using electric options in the High scenario showed similar penetration to the light-duty vehicle sector, with about 80% penetration by 2050, while electric options for water heating remained more constrained, reaching only about half in that year. Similar results were observed in commercial buildings, although cooking in that sector was shown to shift completely to electric by 2050 due to the advantages that electrical induction stoves offer.

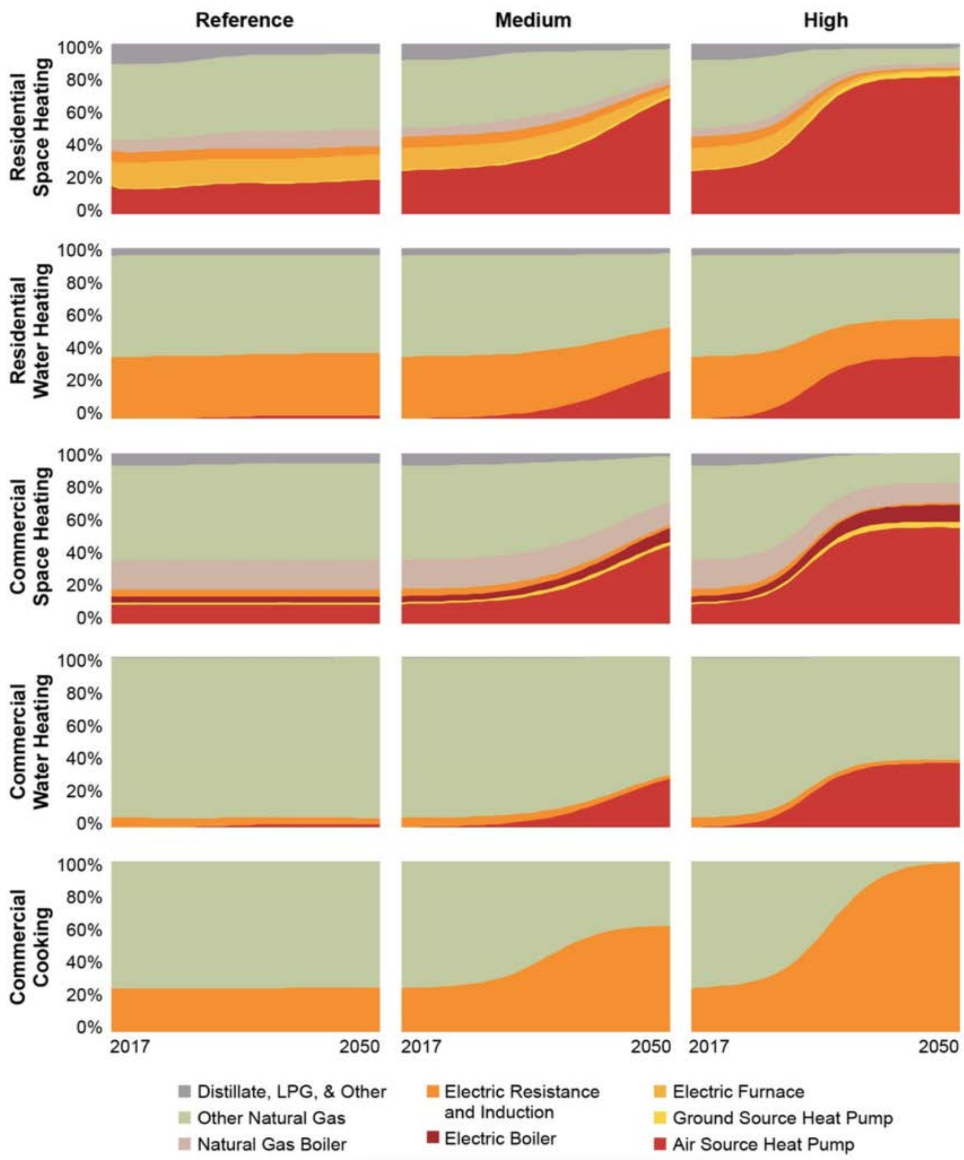

Figure 4- 19. U.S. buildings technology sales shares by electrification scenario

Source: [27]

4.3.5.3 *Electrification of Industry*

While progress on and understanding of electrified applications in the industrial sector remains murky at best, a large number of low- to medium-temperature process heat services can clearly be converted from fossil to electricity. The industrial sector will no doubt see new efforts to understand the potential for electrification in the coming years.

The NREL EFS study results for the industrial sector are shown in Figure 4- 20. A wide assortment of energy would be needed in industry, with natural gas currently playing the dominant role in most. As noted, low- and medium-temperature process heat used for drying and curing products could see significant penetration of electrified alternatives in place of natural gas. Space heating of industrial locations using heat pumps is probably one of the lowest-hanging fruits for electrification of industry.

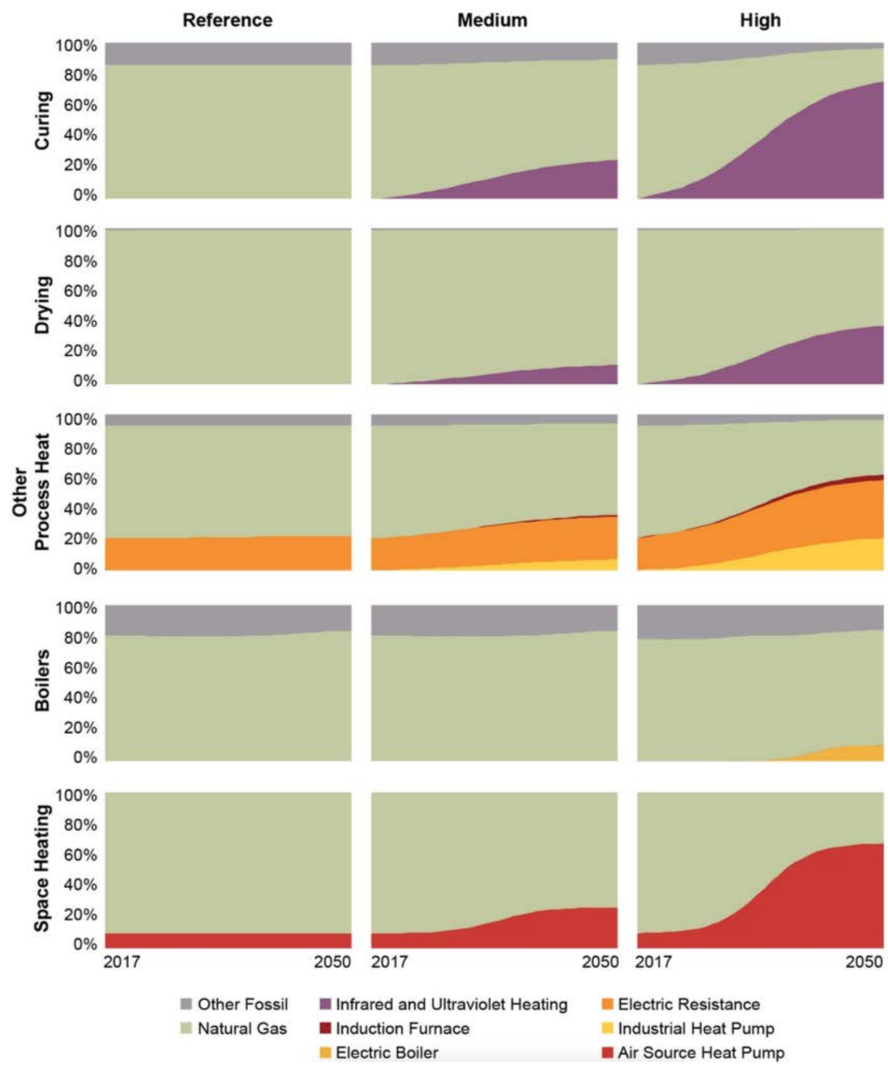

Figure 4- 20. U.S. industrial technology sales shares by electrification scenario

Source: [27]

4.3.6 Overall Impact on Electricity Demand

Electrification increases the total quantity of electricity demand, increases the magnitude of the peak demand, and changes the temporal shape of the electricity demand, making more U.S. regions winter-peaking or dual-peaking (see Section 3.4.8). In the High scenario, total demand in 2050 would increase by approximately 35% compared to the Reference case (Figure 4- 21). The vast majority of this new demand would come from the transportation sector.

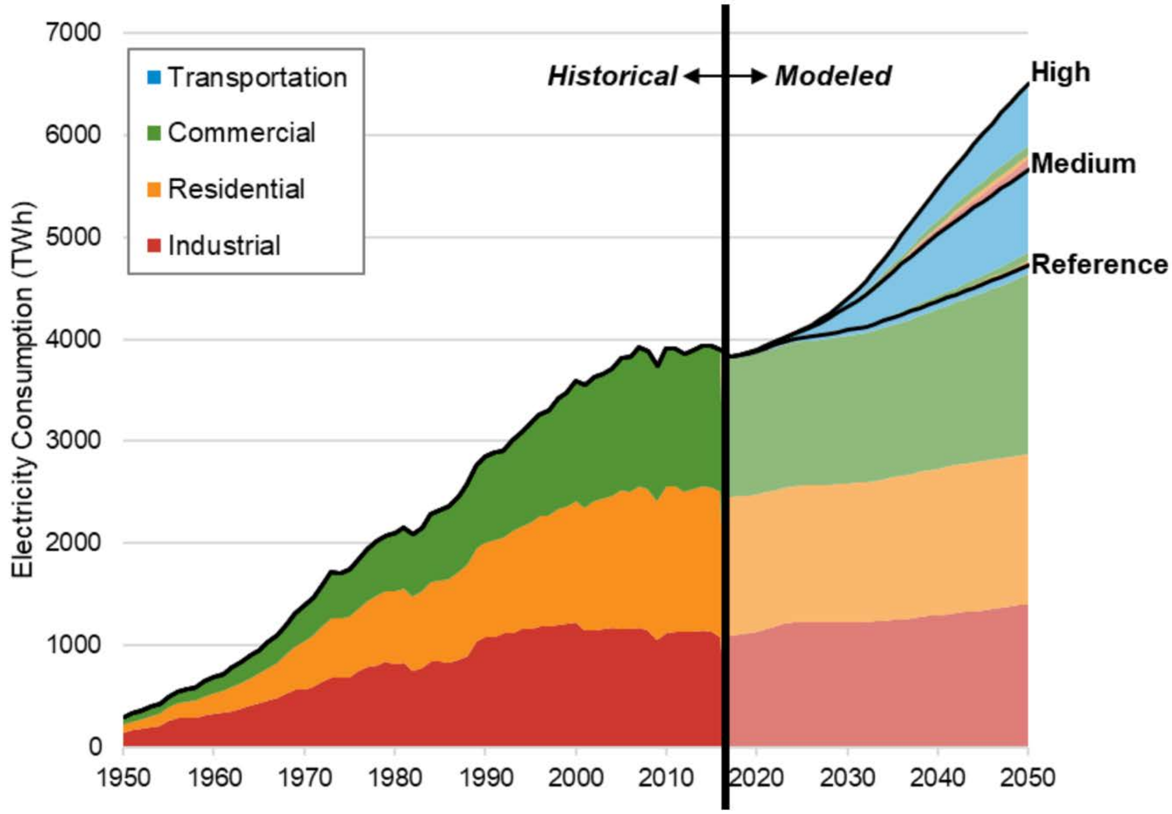

Figure 4- 21. Historical and projected electricity demand growth by scenario and sector

Source: [27]

4.3.7 Impact of Electrification on Primary Energy Consumption and Emissions

Increased electrification affects the energy use and emissions associated with both service demand and the broader energy system. Electricity can displace other fuels in end-use applications, but this may correspond to an increase in fuel consumption in the electric sector. This section explores the net impact of electrification on primary energy consumption—which includes end-use energy consumption and the energy losses incurred from converting fuels to electricity—and on direct-air emissions. We present results from the EFS and summarize the key trends [90].

As noted previously, one major benefit of electrification is the increased efficiency of electric technologies compared to the alternatives. Greater efficiency gains are possible with projected technology improvement [91]. The increased efficiency achieved through electrification results in a decrease in final energy[24] consumption as more electricity technologies are adopted.

The impact of electrification on primary energy and emissions is more complex, because energy and emissions are shifted away from the various end uses to the power sector. Therefore, the net impact heavily depends on the generation mix used to produce electricity. Electrification eliminates direct end-use emissions as electricity displaces a fossil fuel or biomass alternative. For example, using electricity in place of petroleum in the transportation sector results in zero CO_2, nitrogen oxide (NO_X), and sulfur dioxide (SO_2) emissions at the point of use, which can lead to decreased emissions in heavily populated

[24] Final energy is the energy supplied to the end users for consumption (i.e., gas at the pump, electricity in the household). Primary energy is energy in the form that it is first accounted, such as coal or crude oil, before any transformation.

urban areas; however, the potential for total emissions reductions—considering both end-use and power sector emissions—varies based on the generation fleet. In some central and upper Midwest regions in the United States, driving a gasoline powered hybrid electric vehicle has less associated emissions then driving a battery electric vehicle, due to higher emissions intensities of regional grids [92]. But the carbon intensity of the power sector is declining, largely driven by the replacement of coal with natural gas and renewable resources, such as wind and solar, a trend which is expected to continue, as described in Section 4.3.2. In addition to emissions, the generation mix also determines the impact on primary energy from electrification: increased efficiency of the generation fleet results in greater primary energy reductions.

Text Box 1. Accounting for Primary Energy of Renewable Generation

The primary energy consumption of thermal generators is calculated based on the total fuel consumed to produce electricity. Because electricity production from renewable, noncombustible resources—such as wind, solar, hydro, and geothermal—does not consume fuel, calculating the associated primary energy consumption is less straightforward. Methods for estimating the primary energy of renewable generators vary across organizations and analyses [93] [94] [95]. Some leading energy research organizations assume 100% efficiency, whereas others (e.g., the U.S. Energy Information Administration) assume primary energy equivalence of an average fossil fuel plant (30%-40% efficient), also referred to as "thermal equivalence" or "fossil fuel equivalence." These alternate methods yield differing results when comparing total primary energy consumption, and the divergence becomes more prominent in scenarios with higher penetrations of renewable energy.

In the case of electrification, the methodology used can affect the estimated net impacts on primary consumption in high electrification scenarios. For example, if the incremental generation capacity needed to meet the increased load is primarily met with renewable energy, then the "thermal equivalence" methodology would show lower primary energy reductions compared to the assumption of 100% efficiency. For consistency with the U.S. Energy Information Administration, the EFS followed the "thermal equivalence" approach, but attention should be given to which methodology is employed in other analyses.

To illustrate these trends in energy use and emissions, we focus on results from the EFS [90]. The EFS projected three levels of electrification—Reference, Medium, and High—with each reflecting the same level of service demand but with increasing electric technology adoption. Layered onto these electrification scenarios, the EFS explored a range of potential future conditions on the power sector, including fuel prices, technology costs, and system constraints. EFS found that electrification always reduced economy-wide emissions, though the magnitude of emission reduction was sensitive to power sector characteristics and could be limited or enhanced depending on the cost-competitiveness of generators and operational and policy constraints, among other factors.

Final and primary energy results for base-case scenario EFS assumptions are shown in Figure 4- 22.

Electricity's share of final energy reached 36% under high electrification in 2050,[25] corresponding to a 21% reduction of final energy use compared to the Reference electrification scenario. As described previously, this final energy reduction was due to the higher efficiencies of electric technologies. Most of the decrease was attributed to the transportation sector, where electric vehicles displaced petroleum-fueled conventional ICE vehicles. Primary energy, which included the energy associated with the increased electricity generation, decreased only 10% under High electrification compared to Reference;

[25] All results correspond to the Moderate Technology Advancement scenarios unless otherwise noted.

reductions ranged from 8%–12% across the EFS base case power sector scenarios. Results also showed primary fossil fuel use to decrease by 18%, but across base case power sector scenarios, the decrease ranges from 16%–32%. Net fossil fuel use reduction is primarily driven by the displacement of petroleum for transportation end uses; however, electrification also impacts natural gas use: consumption of natural gas across residential, commercial, and industrial end uses decreases, but system-wide natural gas use is moderated by the increased demand of natural gas within the electric sector. For example, the EFS estimated a reduction in natural gas end use, but an *increase* in primary energy consumption under base scenario assumptions, as shown in Figure 4- 23. Natural gas prices would likely influence the dynamics of natural gas consumption; in the EFS, assuming higher natural gas prices resulted in lower total natural gas consumption under High electrification (compared to Reference).

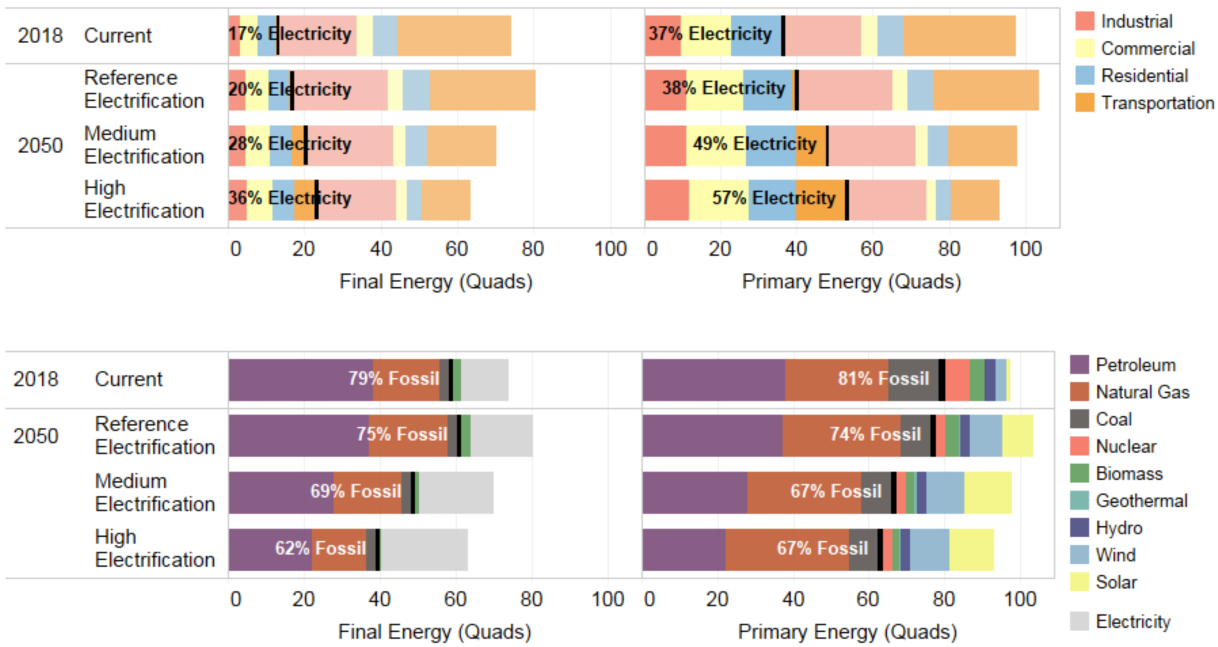

Figure 4- 22. Final and primary energy use in the base case electrification scenarios in the EFS

Source: [90]

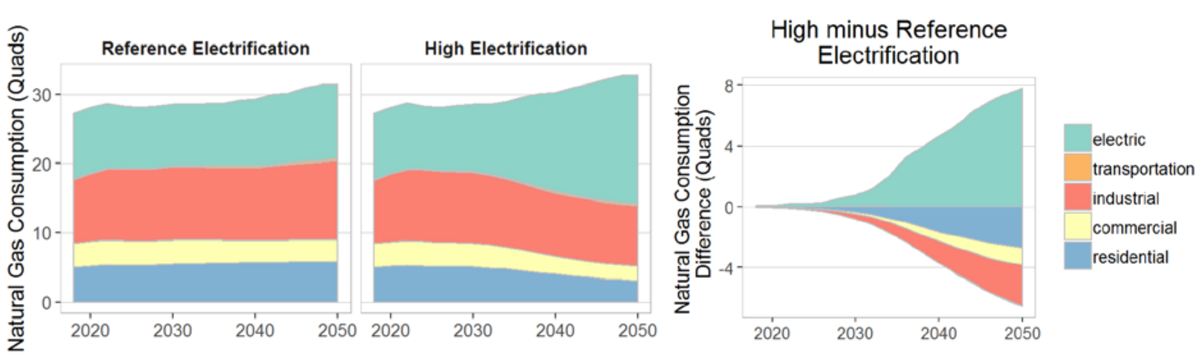

Figure 4- 23. National natural gas consumption by sector under Reference electrification (left) and High electrification (middle) and the difference between the two scenarios (right) in the EFS

Source: [90]

Electrification can also lead to reductions in energy sector emissions.[26] The impact on net emissions depends on the trade-off between the emissions intensities of the displaced nonelectric end uses and on the associated power sector emissions for the electrified end uses. Even without electrification, the future emissions intensity of the grid is expected to decline; however, electrification may accelerate this trend as natural gas and renewable generation replace coal-fired generators. Figure 4- 24 shows CO_2 emissions for the EFS base case scenarios, which resulted in a 23% reduction of CO_2 emissions compared to the Reference scenario in 2050, varying between 23%–37% across scenarios. As with final energy, much of the reduction was attributed to the transportation sector. Electric sector emissions increased under high electrification, but this was driven by the increased need for generation, which was not completely offset by the declining emissions intensity. The EFS also estimated similar trends in NO_x and SO_2 emissions. NO_x declined primarily as a result of transporation electrification, while SO_2 reductions were driven by electrification of the industrial sector.

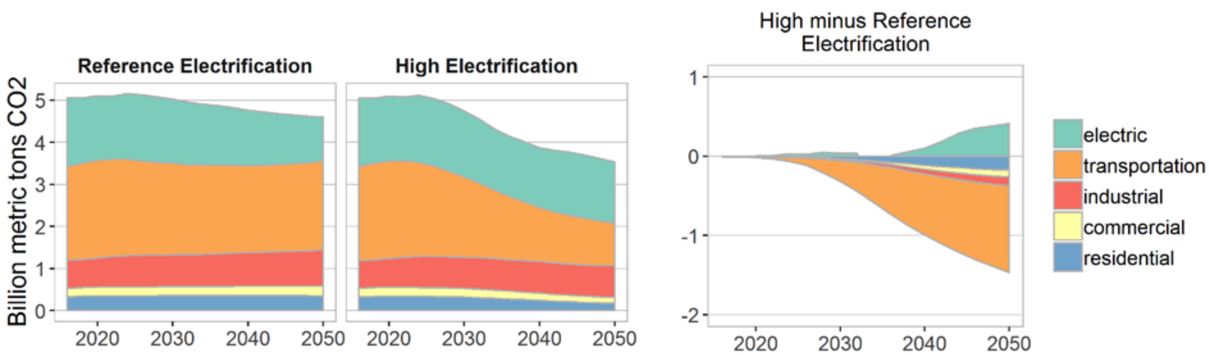

Figure 4- 24. Energy-sector CO_2 emissions for the Base Case scenario with Reference and High electrification levels scenarios in the EFS

Source: [90]

Other options are available to further decarbonize sectors that are not directly suitable for electrification. For example, in long-range air transport options, synthetic fuels can be derived from CO_2 waste streams and other inputs, including electricity, although research and development improvements are needed to make them commercially viable. Hydrogen is also viewed as an option in industrial sectors that are considered hard-to-decarbonize. Producing “green” hydrogen directly from renewable energy in electrolizers or “blue” hydrogen using traditional natural gas methods combined with carbon capture and storage are options, although cost and technical challenges remain to be solved. Finally, CO_2 removal options can be used to help fully decarbonize sectors where fossil fuel use cannot be fully removed. These include direct air capture with sequestration, reforestation of existing land, bioenergy with capture and sequestration, and advanced agricultural techniques, among others [101].

4.3.8 Impact of Electrification on the Power System

The electrification trends described in the previous sections could have wide-ranging impacts on the power system. To explore these impacts, part of the EFS study focused on how electrification could drive changes in the generation and transmission infrastructure, generation mix, system costs, and air emissions

[26] Here we focus only on direct air emissions and do not include all life cycle emissions (e.g., from battery manufacturing), which impact results differently.

[90]. This section draws mainly from the EFS study supply-side scenarios and will be supplemented by other electrification literature.

4.3.8.1 Electrification Can Lead to Massive Growth in Electricity Demand and at the Same Time, Change the Load Shape

Estimates of future electricity demand as a result of electrification vary in the literature, ranging from 52% over the current level to more than doubling the demand today [74], [31], [96]–[98]. The EFS study explored a range of scenarios based on different electrification levels, technology advancements, demand-side flexibility, and technology costs. The 2050 electricity demand in the EFS Reference electrification scenario was about 30% higher than in 2018, and 2050 demand in the High electrification scenario was 80% higher than in 2018 (Figure 4- 25). The High electrification scenario also sees a doubling of electricity's share of final energy.

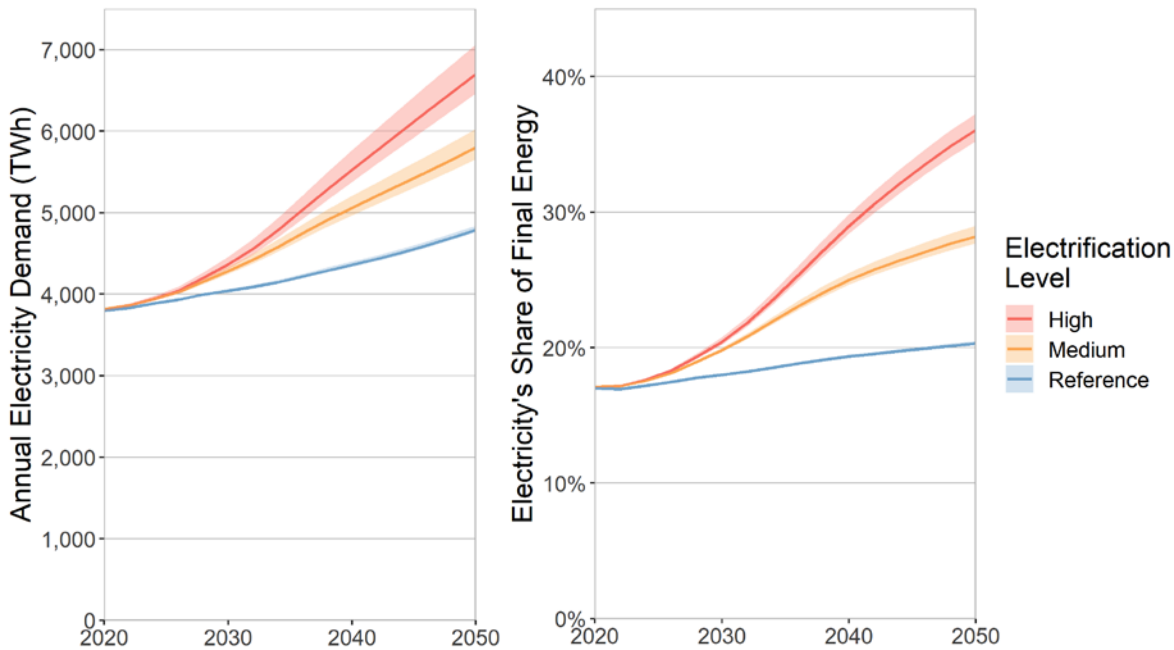

Figure 4- 25. Annual end-use electricity demand (left) and electricity's share of final energy (right) for the three electrification levels evaluated in the EFS study (thick solid lines) [90]

Electrification not only increases the total electricity demand, but also changes the diurnal and seasonal shape of the load profiles as the end use shifts to include more vehicle charging, heating, and other electric loads [31]. Among other changes, the Northeast region is expected to shift into winter-peaking due to the electrified heating loads [27].

Rapid demand increases from electrification would require significant investment in new generation capacity, as we discuss in the next section, and increase reliability concerns if the additional load is left uncontrolled. [99] shows that electrification can significantly impact the reliability of supply as it increases both the demand and its variations, which would be another issue for consideration outside the scope of this report.

4.3.8.2 Meeting Electrified Loads May Require Greatly Expanding the Generation Capacity by 2050

Our analysis shows that meeting the electrified load would require doubling the generation capacity across all regions of the continental United States in the High electrification scenario (Figure 4- 26), reaching about 2,400 GW in total capacity in 2050, compared with 1,100 GW in 2018. Under the Medium and High electrification scenarios, natural gas and renewable energy generation would grow in all regions. The reduction of natural gas usage in the other sectors as a result of electrification suppressed the price of natural gas, making it more competitive in the power sector. Electrification also amplified the growing deployment of renewable energy, reaching 784 GW of solar and 336 GW wind in the High electrification scenario in 2050. Lower renewable energy cost assumption or carbon constraints could drive the amount of VRE even higher.

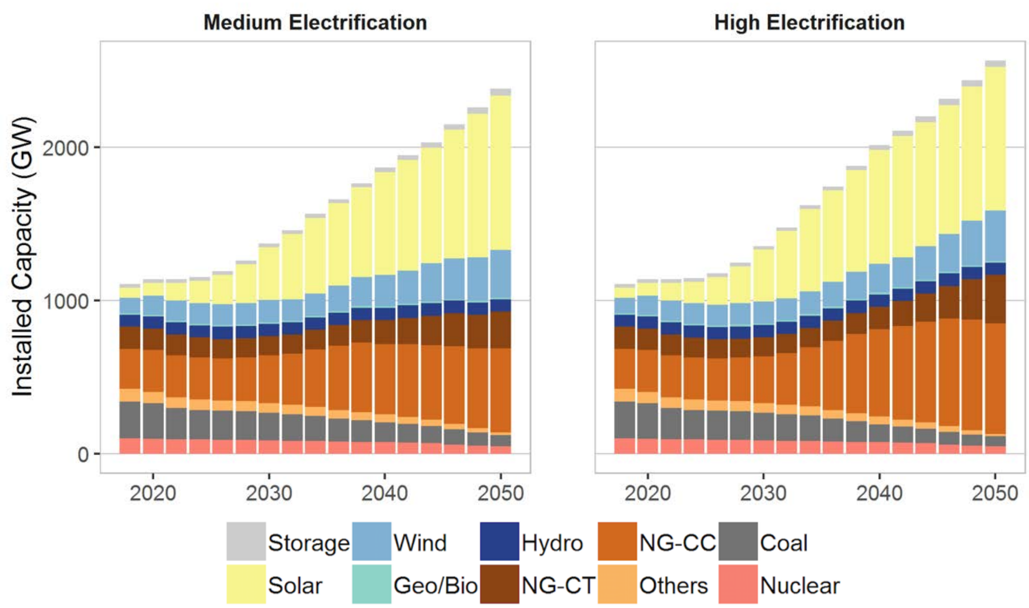

Figure 4- 26. Cumulative installed capacities for the Medium and High electrification scenarios

Source: [90]

4.3.8.3 Synergy Between Electrification and Transmission Expansion

The Regional Energy Deployment System (ReEDS) model used for the analysis co-optimizes generation expansion with transmission (including long-distance transmission and intra-region spur lines) expansion. While transmission expansion is typically associated with large-scale VRE integration (see Chapter 1), electrification on its own may not drive the expansion of the long-distance transmission grid because the VRE penetration level remained relatively stable from Reference to High electrification if the renewable technology costs assumptions remained the same. The Reference electrification scenario had an 11% increase in long-distance transmission capacity by 2050 relative to 2018 levels, and the number was between 11% and 14% in Medium and High electrification. The spur line capacity scales with electrification level, and it accounted for the majority of the incremental new transmission capacity by 2050 under High electrification. The similar amount of long-distance transmission growth across different electrification levels was attributable to the greater utilization of local or nearby resources. However, an operational analysis of the power system envisioned in the EFS showed increased flows between regions, greater line utilization, and more frequent interface congestion under High electrification, indicating that the increased transmission capacity was necessary for the operation of high electrification systems [100].

4.3.8.4 Electrification Increases Capacity Factors of Coal and NG-CC Plants, but VRE Penetration Is Insensitive to Electrification Levels

The load growth under electrification drove an additional 1,200 TWh and 2,000 TWh of generation in 2050 in the Medium and High electrifications scenarios (respectively) relative to the Reference electrification scenario. Similar to the capacity growth, the additional load was met primarily by NG-CC, wind, and solar generation (Figure 4- 27). Due to the suppressed natural gas price under electrification, coal generation tended to decrease with electrification despite the growing load. Coal capacity factors, however, driven by steady retirement of coal plants over the study period, increased from 73% under Reference electrification in 2050 to 83% under High electrification. NG-CC capacity factors also increased, partly due to the natural gas price reduction, from 37% under Reference electrification in 2050 to 44% under High electrification.

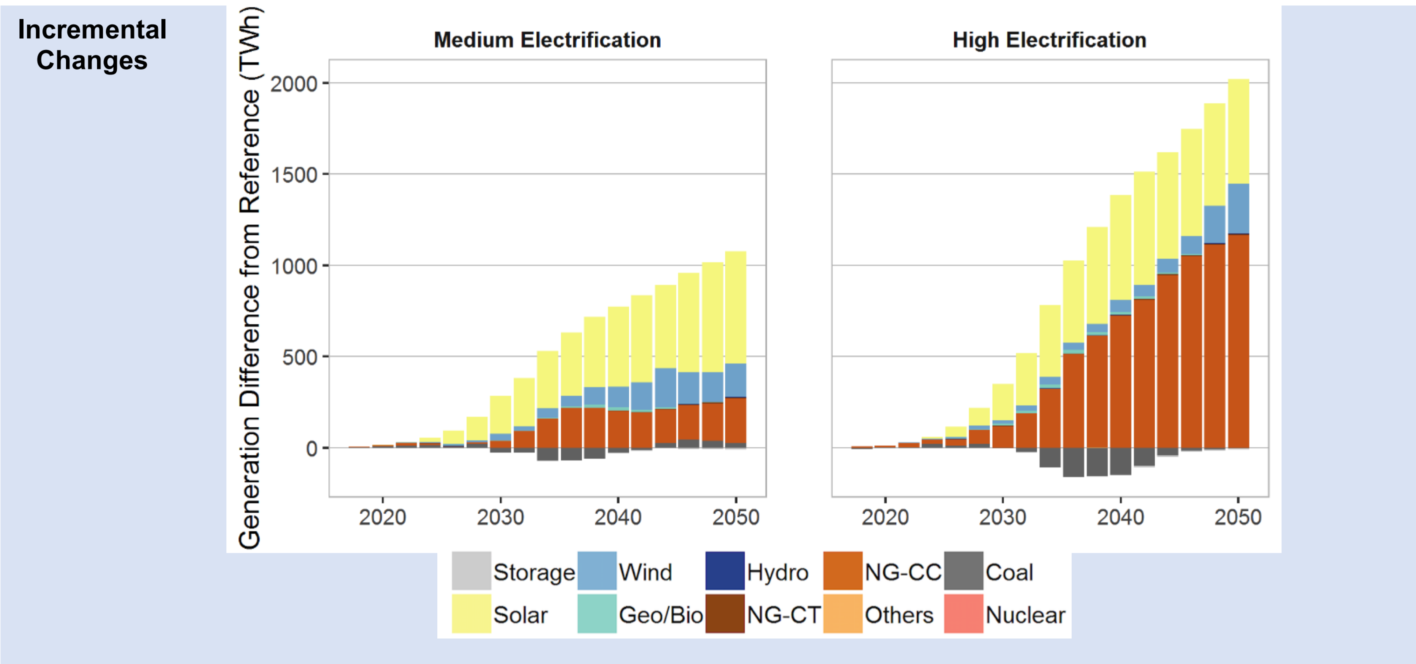

Figure 4- 27. Incremental changes to the generation mix under Medium and High electrification

Source: [90]

The VRE penetration level does not scale with electrification. Under reference renewable technology cost assumptions,[27] the VRE penetration level under three electrification levels was between 43% to 49%, with High electrification having the lowest VRE penetration. This is because VRE penetration level is influenced by multiple factors, including technology costs, fuel costs, transmission network, and load. Lower renewable energy cost assumptions led to about 66% of VRE penetration in the High electrification scenario. In the operational analysis of the EFS power systems, we found that electrification can contribute to sizable increase in VRE curtailment—from around 3% in Reference scenario to around 9% in the High electrification scenario [100].

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[27] The EFS used technology cost and performance data from NREL's 2018 Annual Technology Baseline [59]. Both the Reference and High electrification scenarios discussed here used the reference renewable technology cost and fuel price data.

4.3.8.5 Electrification Increases the Total Power System Costs, but not Marginal Cost. Total Power System Cost Increases are Largely Offset by Fuel and Operational Savings in the Other Sectors.

With the expansion of the generation and transmission infrastructure under electrification, the total bulk power system costs increased by 12%–17% under Medium electrification, relative to Reference electrification, and by 21%–29% under High electrification (representing an approximately $600–900 billion increase).[28] Dividing this by the present value of incremental electrification consumption, however, the EFS study found the levelized marginal costs to be $40–$46/MWh under both Medium and High electrification. This suggests that even under the High electrification scenario, there are abundant low-cost generation resources available in the continental United States to meet electrified demand.

Combining the electric sector with the buildings, transportation, and industry demand sectors, the EFS found that the impact of electrification on total energy system costs depended strongly on the extent of electrification and the future cost and performance of electric end-use technologies. Electrification can achieve net energy system savings when it occurs together with rapid advancements in the cost and efficiency of end-use electric technology or when it primarily electrifies cost-effective technologies and end uses (Figure 4- 28).

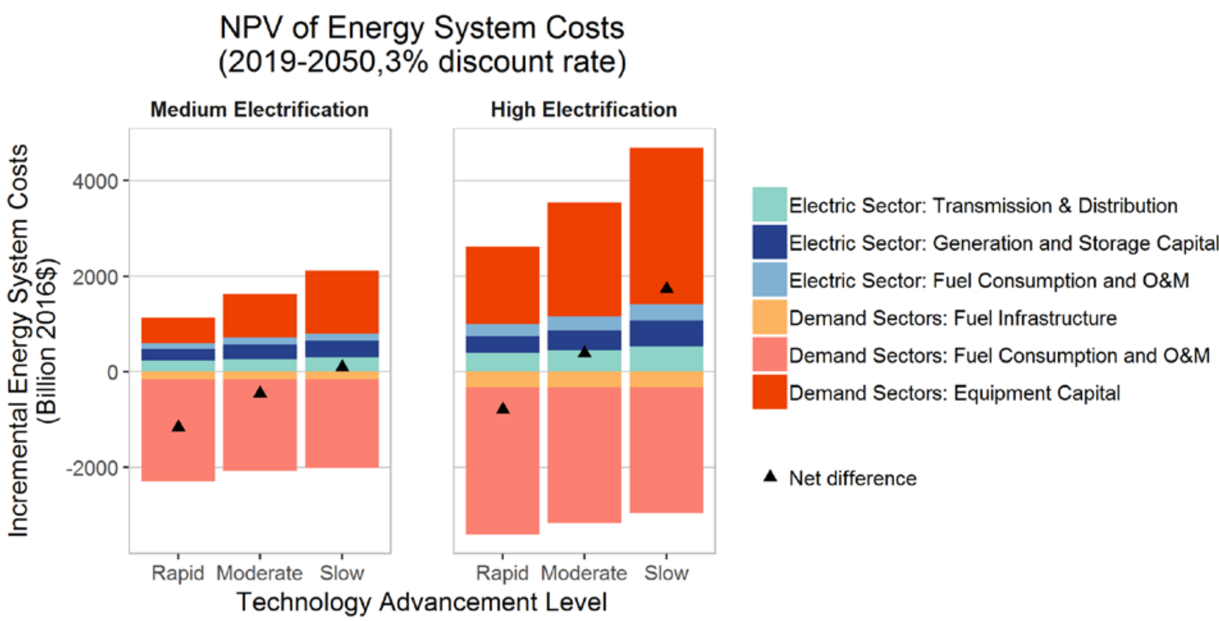

Figure 4- 28. Incremental energy system costs by the level of electrification, technology advancement, and by sector

This section described the range of impacts electrification could have on the power system, including on capacity, transmission, generation, and system cost. Electrification could also present opportunities for demand-side flexibility (as discussed in Section 4.2) that can help avoid significant power system

[28] This result is based on the present value of total bulk electric system costs from 2019 to 2050 and a 3% real discount rate. The use of a social discount rate (3%) is consistent with discount rates used by the U.S. Energy Information Administration and the IEA to estimate long-term costs and benefits, and it is in line with guidance from the White House Office of Management and Budget for "cost-effectiveness" analysis that spans multiple decades. Note that a higher discount rate (5.3% real, WACC) is used in most cases for the ReEDS investment and dispatch decision-making. For comparison, applying a 7% discount rate instead yields incremental bulk electric system costs that range from 11% to 15% under Medium electrification, and from 16% to 24% under High electrification.

investments by reducing peak demand and shifting load, facilitate the integration of VRE by reducing curtailment and net load ramps, and enhance power system operational efficiency despite challenges from the additional demand and demand variability.

References

[1] IEA (International Energy Agency). 2020. "Energy Efficiency 2019 – Analysis." Accessed May 18, 2020. https://www.iea.org/reports/energy-efficiency-2019.

[2] IRENA (International Renewable Energy Agency). 2019. *Global energy transformation: A roadmap to 2050 (2019 edition)*. https://www.irena.org/publications/2019/Apr/Global-energy-transformation-A-roadmap-to-2050-2019Edition.

[3] Doris, E., J. Cochran, and M. Vorum. 2009. *Energy Efficiency Policy in the United States: Overview of Trends at Different Levels of Government.* Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A2-46532. https://www.nrel.gov/docs/fy10osti/46532.pdf.

[4] Mims, N., M. Bell and S. Doig. 2009. *Assessing the Electric Productivity Gap and the U.S. Efficiency Potential.* Basalt, CO: Rocky Mountain Institute. https://rmi.org/wp-content/uploads/2017/05/RMI_Document_Repository_Public-Reprts_CGU.RMI_.pdf

[5] Metcalf, G. 2006. *Energy Conservation in the United States: Understanding its Role in Climate Policy.* National Bureau of Economic Research and Tufts University. 2006. https://ase.tufts.edu/economics/papers/200609.pdf.

[6] Ang, B., A Mu., and P. Zhou. 2010. "Accounting Frameworks for Tracking Energy Efficiency Trends." *Energy Economics* 32 (5): 1209-1219. https://reader.elsevier.com/reader/sd/pii/S0140988310000563?token=8B1143410DD23D02277957139FD3DB7FA1512699EC1AD8E05A241D57BEF0A4B899F6E4682BA243B454A05713E8A5B761.

[7] Baatz, B. 2015. *Everyone Benefits: Practices and Recommendations for Utility System Benefits of Energy Efficiency*. Washington, D.C.: American Council for an Energy-Efficient Economy (ACEEE). https://www.aceee.org/sites/default/files/publications/researchreports/u1505.pdf.

[8] Golove, W., and J. Eto. 1996. *Market Barriers to Energy Efficiency: A Critical Reappraisal of the Rationale for Public Policies to Promote Energy Efficiency*. Berkeley, CA: Lawrence Berkeley National Laboratory. https://emp.lbl.gov/sites/all/files/lbnl-38059.pdf.

[9] Vaidyanathan, S., S. Nadel, J. Amann, C. Bell, A. Chittum, K. Farley, S. Hayes, M. Vigen, and R. Young. 2013. *Overcoming Market Barriers and Using Market Forces to Advance Energy Efficiency.* Washington, D.C.: ACEEE. Report #E136. https://www.aceee.org/sites/default/files/publications/researchreports/e136.pdf.

[10] IEA. 2007. *Mind the Gap: Quantifying Principal-Agent Problems in Energy Efficiency*. Paris: International Energy Agency. https://www.oecd-ilibrary.org/energy/mind-the-gap_9789264038950-en.

[11] Levine, M., J. Koomey, J. McMahon, A. Sanstead, and E. Hirst. 1995. "Energy Efficiency Policy and Market Failures." *Annual Review of Energy and the Environment* 20: 535–555. https://www.annualreviews.org/doi/pdf/10.1146/annurev.eg.20.110195.002535.

[12] Jaffe, A., and R. Stavins. 1994. "The Energy-efficiency Gap: What Does it Mean?" *Energy Policy*, 22(10): 804-810. https://scholar.harvard.edu/stavins/publications/energy-efficiency-gap-what-does-it-mean.

[13] Gillingham, K., and K. Palmer. 2013. "Bridging the Energy Efficiency Gap: Insights for Policy from Economic Theory and Empirical Analysis." Washington, D.C.: Resources for the Future. https://www.rff.org/publications/working-papers/bridging-the-energy-efficiency-gap-policy-insights-from-economic-theory-and-empirical-evidence/.

[14] Lacey, S. 2014. "This Graphic Illustrates the Energy Efficiency Problem Created by Split Incentives." *Greentech Media*. August 5, 2014. https://www.greentechmedia.com/articles/read/a-graphic-that-illustrates-the-problem-with-split-incentives.

[15] ASE (Alliance to Save Energy). 2013a. "Energy Efficiency Resource Standard (EERS)." https://www.ase.org/resources/energy-efficiency-resource-standard-eers.

[16] ACEEE. 2020. "The Utility Energy Efficiency Scorecard." Washington, D.C.: ACEEE. Last modified 2020. https://www.aceee.org/utility-scorecard.

[17] Aznar, A., J. Logan, D. Gagne, and E. Chen. 2019. *Advancing Energy Efficiency in Developing Countries: Lessons Learned from Low-Income Residential Experiences in Industrialized Countries.* Golden, CO: NREL. NREL/TP-7A40-71915. https://www.nrel.gov/docs/fy19osti/71915.pdf.

[18] Taylor, R., C. Govindarajalu, J. Levine, A. Meyer, and W. Ward. 2008. *Financing Energy Efficiency: Lessons from Brazil, China, India and Beyond*. Washington, D.C.: World Bank. https://www.esmap.org/sites/default/files/esmap-files/financing_energy_efficiency.pdf.

[19] Bernstein, H. 2019. "Looking to Finance Money-Saving Energy Efficiency Projects? Here's a Tool for That." *ensia.* July 24, 2019. https://ensia.com/notable/financing-energy-efficiency/.

[20] Langner, R., B. Hendron, and E. Bonnema. 2014. *Reducing Transaction Costs for Energy Efficiency Investments and Analysis of Economic Risk Associated with Building Performance Uncertainties: Small Buildings and Small Portfolios Program.* Golden, CO: National Renewable Energy Laboratory. NREL/TP-5500-60976. https://www.nrel.gov/docs/fy14osti/60976.pdf.

[21] C2ES (Center for Climate and Energy Solutions). 2017. "Strengthening Energy Efficiency Programs for Low Income Communities."

https://www.c2es.org/site/assets/uploads/2017/07/strengthening-energy-efficiency-programs-low-income-communities.pdf.

[22] Kane, R., and N. Srinivas. 2014. "Unlocking the Potential of Behavioral Energy Efficiency: Methodology for Calculating Technical, Economic, and Achievable Savings Potential." *ACEEE Summer Study on Energy Efficiency in Buildings.* https://www.aceee.org/files/proceedings/2014/data/papers/5-284.pdf.

[23] Yang, M. 2013. *Closing the Gap: GEF Experiences in Global Energy Efficiency.* Berlin, Germany: Springer.

[24] SLEEAN (State and Local Energy Efficiency Action Network). 2012. *Energy Efficiency Program Impact Evaluation Guide: Evaluation, Measurement, and Verification Working Group.* Washington, D.C.: DOE. https://www4.eere.energy.gov/seeaction/system/files/documents/emv_ee_program_impact_guide _0.pdf.

[25] Castro-Alvarez, F., S. Vaidyanathan, H. Bastian, and J. King. 2020. *The International Energy Efficiency Scorecard.* Washington, D.C.: ACEEE. https://www.aceee.org/portal/national-policy/international-scorecard.

[26] ASE. 2013b. *The History Of Energy Efficiency.* Washington, D.C.: ASE. https://www.ase.org/sites/ase.org/files/resources/Media%20browser/ee_commission_history_report_2-1-13.pdf.

[27] Mai, T., Paige Jadun, Jeffrey Logan, Colin McMillan, Matteo Muratori, Daniel Steinberg, Laura Vimmerstedt, Ryan Jones, Benjamin Haley, and Brent Nelson. 2018. *Electrification Futures Study: Scenarios of Electric Technology Adoption and Power Consumption for the United States.* Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A20-71500. www.nrel.gov/docs/fy18osti/71500.pdf.

[28] Roberts, D. 2018. "After Rising For 100 Years, Electricity Demand is Flat. Utilities are Freaking Out." *Vox*. February 27, 2018. https://www.vox.com/energy-and-environment/2018/2/27/17052488/electricity-demand-utilities.

[29] Nadel, S, and R. Young. 2014. *Why is U.S. Electricity Use no Longer Growing?* Washington, D.C.: ACEEE. https://www.naesco.org/data/news/documents/ACEEE%20White%20Paper,%20Electricty%20Use%20Declining,%202-25-14.pdf.

[30] Clemente, J. 2018. "Why U.S. Electricity Demand Will Increase." *Forbes*. August 26, 2018. https://www.forbes.com/sites/judeclemente/2018/08/26/why-u-s-electricity-demand-will-increase/#5cdaaf0f6dfb.

[31] EPRI (Electric Power Research Institute). 2018. *U.S. National Electrification Assessment*. Palo Alto, CA: EPRI. http://mydocs.epri.com/docs/PublicMeetingMaterials/ee/USNEA_FinalReport_Executive_Summary_3002013582.pdf.

[32] IRENA. 2018b. *Power System Flexibility for the Energy Transition, Part 1: Overview for policy makers*. Abu Dhabi: International Renewable Energy Agency. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2018/Nov/IRENA_Power_system_flexibility_1_2018.pdf.

[33] Grubler, A., C. Wilson, N. Bento et al. 2018. "A Low Energy Demand Scenario for Meeting the 1.5 °C Target and Sustainable Development Goals without Negative Emission Technologies." *Nature Energy* 3 (2018): 515–527.

[34] van Soest, H., D. McCollum, C. Bertram. 2018. "Opportunities for Enhanced Action to Keep Paris Goals in Reach." *COMMITT and CD Links*. https://unfccc.int/sites/default/files/resource/437_Enhanced%20Action%20to%20Keep%20Paris%20Goals%20in%20Reach.pdf.

[35] Nurunnabi, M., J. Esquer, N. Munguia, D. Zepeda, R. Perez, and L. Velazquez. 2020. "Reaching the sustainable development goals 2030: energy efficiency as an approach to corporate social responsibility (CSR)." *GeoJournal* 85 (2): 363–374. doi: 10.1007/s10708-018-09965-x.

[36] Satre-Meloy, A., and J. Langevin. 2019. "Assessing the Time-sensitive Impacts of Energy Efficiency and Flexibility in the US Building Sector." *Environmental Research Letters* 14 (12). https://iopscience.iop.org/article/10.1088/1748-9326/ab512e.

[37] Ghambir, A., J. Rogelj, G. Luderer, S.Few, and T. Napp. 2019. "Energy System Changes in 1.5 °C, Well Below 2 °C, and 2 °C Scenarios." *Energy Strategy Reviews* 13 (2019). https://www.sciencedirect.com/science/article/pii/S2211467X18301184.

[38] Hale, E., B. Stoll, and J. Novacheck. 2018. "Integrating Solar into Florida's Power System: Potential Roles for Flexibility." *Solar Energy* 170 (August): 741–51. https://doi.org/10.1016/j.solener.2018.05.045.

[39] Nichols, J., and K. Haag. 2018. "Demand Response Auditing." Webinar Training, March 27, 2018. https://www.iso-ne.com/static-assets/documents/2018/03/20180327-dr-auditing.pdf.

[40] Neukomm, M., V. Nubbe, and R. Fares. 2019. *Grid-Interactive Efficient Buildings Technical Report Series: Overview of Research Challenges and Gaps.* Washington, D.C.: DOE Office of Energy Efficiency and Renewable Energy. https://www1.eere.energy.gov/buildings/pdfs/75470.pdf.

[41] Cole, Wesley J., Kody M. Powell, Elaine T. Hale, and Thomas F. Edgar. 2014. "Reduced-Order Residential Home Modeling for Model Predictive Control." *Energy and Buildings* 74 (2014): 69–77.

[42] Denholm, P., Y. Sun, and T. Mai. 2019. *Introduction to Grid Services: Concepts, Technical Requirements, and Provisions from Wind*. NREL/TP-6A20-72578. Golden,

CO: National Renewable Energy Laboratory. January 2019. https://www.nrel.gov/docs/fy19osti/72578.pdf.

[43] Afshari, S., J. Wolfe, Md Salman Nazir, I. Hiskens, J. Johnson, J. Mathieu, Y. Lin, A. Barnes, D. Geller, and S. Backhaus. 2017. "An Experimental Study of Energy Consumption in Buildings Providing Ancillary Services." In *Power & Energy Society Innovative Smart Grid Technologies Conference (ISGT), 2017 IEEE*, 1–5. IEEE.

[44] Beil, I., I. Hiskens, and S. Backhaus. 2015. "Round-Trip Efficiency of Fast Demand Response in a Large Commercial Air Conditioner." *Energy and Buildings* 97 (2015): 47–55.

[45] Vrettos, E., E. Kara, J. MacDonald, G. Andersson, and D. S. Callaway. 2018a. "Experimental Demonstration of Frequency Regulation by Commercial Buildings—Part I: Modeling and Hierarchical Control Design." *IEEE Transactions on Smart Grid* 9 (4): 3213–23.

[46] ———. 2018b. "Experimental Demonstration of Frequency Regulation by Commercial Buildings—Part II: Results and Performance Evaluation." *IEEE Transactions on Smart Grid* 9 (4): 3224–34. https://doi.org/10.1109/TSG.2016.2628893.

[47] Todd, D., M. Caufield, B. Helms, M. Starke, B. Kirby, and J. Kueck. 2009. *Providing Reliability Services through Demand Response: A Preliminary Evaluation of the Demand Response Capabilities of Alcoa Inc.* ORNL/TM-2008/233. Oak Ridge, TN: Oak Ridge National Laboratory. https://www.energy.gov/sites/prod/files/2015/04/f21/Alcoa%20%26%20ORNL%20Demand%20Response%20White%20Paper%20-%20Jan.%202009.pdf.

[48] McAnany, J. 2016. *2016 Demand Response Operations Markets Activity Report: January 2017.* PJM Demand Side Response Operations. https://www.pjm.com/~/media/markets-ops/dsr/2015-demand-response-activity-report.ashx.

[49] Bell, F., A. Nguyen, M. McCarty, K. Atef, and T. Bialek. 2016. "Secondary voltage and reactive power support via smart inverters on a high-penetration distributed photovoltaic circuit." In *2016 IEEE Power Energy Society Innovative Smart Grid Technologies Conference (ISGT)*, Sep. 2016, pp. 1–6, doi: 10.1109/ISGT.2016.7781272.

[50] F. Ding et al. 2016. "Voltage support study of smart PV inverters on a high-photovoltaic penetration utility distribution feeder." In *2016 IEEE 43rd Photovoltaic Specialists Conference (PVSC)*, Jun. 2016, pp. 1375–1380, doi: 10.1109/PVSC.2016.7749840.

[51] Cohen, M.A., P.A. Kauzmann, and D.S. Callaway. 2016. "Effects of Distributed PV Generation on California's Distribution System, Part 2: Economic Analysis." *Solar Energy* 128 (April): 139–52. https://doi.org/10.1016/j.solener.2016.01.004.

[52] R. Walton. 2017."Straight Outta BQDM: Consolidated Edison looks to expand its non-wires approach." *Utility Dive*. Accessed July 19, 2017. https://www.utilitydive.com/news/straight-outta-bqdm-consolidated-edison-looks-to-

expand-its-non-wires-appr/447433/#:~:text=Deep%20Dive-,Straight%20Outta%20BQDM%3A%20Consolidated%20Edison%20looks,expand%20its%20non%2Dwires%20approach&text=Just%20don't%20call%20it,MW%20of%20distributed%20resource%20investments.

[53] K. Anderson et al. 2018. "Quantifying and Monetizing Renewable Energy Resiliency," *Sustainability* 10 (4): 933. doi: 10.3390/su10040933.

[54] J. Peppanen et al. 2019. "Impact and Value of Energy Storage on a High-DER Penetration Distribution Feeder in Southern California." In *25th International Conference on Electricity Distribution*, Madrid, Spain, Jun. 2019, p. Paper No. 1413, doi: http://dx.doi.org/10.34890/631.

[55] Hummon, M., D. Palchak, P. Denholm, and J. Jorgenson. 2013. *Grid Integration of Aggregated Demand Response, Part 2: Modeling Demand Response in a Production Cost Model*. NREL/TP-6A20-58492. Golden, CO: NREL. http://www.nrel.gov/docs/fy14osti/58492.pdf.

[56] Stoll, B., E. Buechler, and E. Hale. 2017. "The Value of Demand Response in Florida." *The Electricity Journal*, Energy Policy Institute's Seventh Annual Energy Policy Research Conference, 30 (9): 57–64. https://doi.org/10.1016/j.tej.2017.10.004.

[57] Denholm, P., J. Novacheck, J. Jorgenson, and M. O'Connell. 2016. *Impact of Flexibility Options on Grid Economic Carrying Capacity of Solar and Wind: Three Case Studies.* NREL/TP-6A20-66854. Golden, CO: NREL. http://www.nrel.gov/docs/fy17osti/66854.pdf.

[58] Madaeni, S.H., P. Denholm, and R. Sioshansi. 2012. *Comparison of Capacity Value Methods for Photovoltaics in the Western United States*. NREL/TP-6A20-54704. Golden, CO: NREL. http://www.nrel.gov/docs/fy12osti/54704.pdf.

[59] NREL. 2020. *Annual Technology Baseline*. Accessed September 13, 2020. https://atb.nrel.gov/.

[60] Smil, V. *Energy in World History*. 1994. Boulder, CO: Westview.

[61] Smil, V. *Energy and Civilization: A History*. 2017. Cambridge, MA: The MIT Press.

[62] Weissman, S., S. Constantine, P. Hernandez, C. Gallagher. 2016. *Natural Gas as a Bridge Fuel – Measuring the Bridge.* Center for Sustainable Energy. 2016. https://energycenter.org/sites/default/files/docs/nav/policy/research-and-reports/Natural_Gas_Bridge_Fuel.pdf.

[63] Kusnetz, N. 2020. "Is Natural Gas Really Helping the U.S. Cut Emissions?" *Inside Climate News*, January 30, 2020. https://insideclimatenews.org/news/30012020/natural-gas-methane-carbon-emissions.

[64] Heiligtag, S., J. Kleine, and A. Schlosser. 2019. *Fueling the Energy Transition: Opportunities for Financial Institutions.* McKinsey & Company. https://www.mckinsey.com/industries/electric-power-and-natural-gas/our-insights/fueling-the-energy-transition-opportunities-for-financial-institutions.

[65] EY. 2019. "Decarbonization, digitization, and decentralization are accelerating the countdown to a new energy world faster than expected." Press release. June 4, 2019. https://www.ey.com/en_gl/news/2019/07/decarbonization-digitization-and-decentralization-are-accelerating-the-countdown-to-a-new-energy-world-faster-than-expected.

[66] IRENA. 2018a. "A Digitized, Decentralized Future is Around the Corner." Press Release. September 23, 2018. https://irena.org/newsroom/articles/2018/Sep/A-Digitalised-Decentralised-Future-is-Around-the-Corner.

[67] Klein, Murray. 2010. *The Power Makers: Steam, Electricity, and the Men who Invented Modern America*. London: Bloomsbury Publishing.

[68] Jonnas, Jill. 2003. *Empires of Light: Edison, Tesla, Westinghouse and the Race to Electrify the World*. New York City: Random House Publishing Group.

[69] McNichol, Tom. *AC/DC: The Savage Tale of the First Standards War*. 2006. Hoboken, NJ: Wiley.

[70] Albert, Dan. 2019. "We Could Have Had Electric Cars from the Very Beginning." An excerpt adapted from *Are We There Yet? : The American Automobile Past, Present, and* Driverless. W. Norton & Co. https://longreads.com/2019/06/13/we-could-have-had-electric-cars-from-the-very-beginning/.

[71] Wigley, T., R. Richels, J.A. Edmonds. 1996. "Economic and Environmental Choices in the Stabilization of Atmospheric CO2 Concentrations." *Nature* 379 (1996) 240–243.

[72] Johansson, T., R. Williams, H. Ishitani, J. Edmonds. 1996. "Options for Reducing CO2 Emissions from the Energy Supply Sector." *Energy Policy* 24 (10-11): pp 985-1003.

[73] van der Zwaan, B. 2002. "Nuclear Energy: Tenfold Expansion or Phase Out?" *Technological Forecasting and Social Change* 69 (2002) 287-307.

[74] Williams, J., A. DeBenedictis, R. Ghanadan, A. Mahone, J. Moore, W. Morrow III, S. Price, and M. Torn. 2012. "The technology path to deep greenhouse gas emissions cuts by 2050: The pivotal role of electricity," *Science (80-)* 335 (6064): 53–59. https://science.sciencemag.org/content/335/6064/53.

[75] Williams, J., B. Haley, F. Kahrl, J. Moore, A. Jones, M. Torn, H. McJeon. 2014. *Pathways to Deep Decarbonization in the United States.* Deep Decarbonization Pathways Project of the Sustainable Development Solutions Network and the Institute for Sustainable Development and International Relations. http://unsdsn.org/wp-content/uploads/2014/09/US-Deep-Decarbonization-Report.pdf.

[76] Nadel, S., and L. Ungar. 2020. *Halfway There: Energy Efficiency Can Cut Energy Use and Greenhouse Gas Emissions in Half by 2050*. Washington, D.C.: ACEEE. Report U1907. https://www.aceee.org/sites/default/files/publications/researchreports/u1907.pdf.

[77] Billimoria, S., L. Guccione, M. Henchen, and L. Louis-Prescott. 2018. "The Economics of Electrifying Buildings." Rocky Mountain Institute. https://rmi.org/insight/the-economics-of-electrifying-buildings/.

[78] Gowrishankar, V. and A. Levin. 2017. *America's Clean Energy Frontier: The Pathway to a Safer Climate Future*. New York, NY: Natural Resources Defense Council. www.nrdc.org/resources/americas-clean-energy-frontier-pathway-safer-climate-future.

[79] Goldie-Scot, L. 2019. "A Behind the Scenes Take on Lithium-ion Battery Prices." Bloomberg New Energy Finance (BNEF). https://about.bnef.com/blog/behind-scenes-take-lithium-ion-battery-prices/.

[80] Mohlin, K., A. Bi, S. Brooks, J. Camuzeaux, and T. Stoerk. 2019. "Turning the corner on US power sector CO_2 emissions—a 1990–2015 state level analysis." *Environmental Research Letters* 14 (8).

[81] Houser, T., J. Bordoff, and P. Marsters. 2017. *Can Coal Make a Comeback?* Columbia University Center on Global Energy Policy. https://energypolicy.columbia.edu/sites/default/files/Center%20on%20Global%20Energy%20Policy%20Can%20Coal%20Make%20a%20Comeback%20April%202017.pdf.

[82] Johnson, S., and K. Chau. 2019. "More U.S. coal-fired power plants are decommissioning as retirements continue." *Today in Energy*. https://www.eia.gov/todayinenergy/detail.php?id=40212.

[83] EIA. 2019. "U.S. energy-related CO2 emissions rose in 2018 for the first year since 2014 - Today in Energy - U.S. Energy Information Administration (EIA)." *Today in Energy*. https://www.eia.gov/todayinenergy/detail.php?id=42115.

[84] EIA. 2020. "Total Energy Monthly Data - U.S. Energy Information Administration (EIA)." *Monthly Energy Review*. https://www.eia.gov/totalenergy/data/monthly/index.php.

[85] DOE. 2020. "All-Electric Vehicles." Accessed May 26, 2020. http://www.fueleconomy.gov/feg/evtech.shtml.

[86] Dincer, I., and M. Rosen. 2013. "Exergy Analysis of Heat Pump Systems." https://www.sciencedirect.com/topics/engineering/coefficient-of-performance.

[87] Shaffer, L. 2016. "Electric Vehicles will soon be cheaper than regular cars because maintenance costs are lower, says Tony Seba." *CNBC*. June 14, 2016. https://www.cnbc.com/2016/06/14/electric-vehicles-will-soon-be-cheaper-than-regular-cars-because-maintenance-costs-are-lower-says-tony-seba.html.

[88] Olivetti, E., G. Ceder, G. Gaustad, and X. Fu. 2017. “Lithium-Ion Battery Supply Chain Considerations: Analysis of Potential Bottlenecks in Critical Metals.” *Joule* 1 (2).

[89] Henchen, M. 2019. “To Wean Off Natural Gas, Cities Push for All-Electric New Buildings,” *Axios*. October 2019. https://www.axios.com/wean-off-natural-gas-cities-push-all-electric-new-buildings-191eb136-1e8c-4f8c-995e-1797157ddf62.html.

[90] C. Murphy et al. 2021. *Electrification Futures Study: Scenarios of Power System Evolution and Infrastructure Development for the United States.* Golden, CO: NREL. NREL/TP-6A20-72330. https://www.nrel.gov/docs/fy21osti/72330.pdf.

[91] Jadun, P., C. McMillan, D. Steinberg, M. Muratori, L. Vimmerstedt, and T. Mai. 2017. *Electrification Futures Study: End-Use Electric Technology Cost and Performance Projections through 2050.* Golden, CO: NREL. NREL/TP-6A20-70485. https://www.nrel.gov/docs/fy18osti/70485.pdf.

[92] Reichmuth, D. 2018. “New Data Show Electric Vehicles Continue to Get Cleaner,” *Union of Concerned Scientists*. March 8, 2018. https://blog.ucsusa.org/dave-reichmuth/new-data-show-electric-vehicles-continue-to-get-cleaner.

[93] Macknick, J. 2011. “Energy and CO2 emission data uncertainties.” *Carbon Manag.* 2 (2): 189–205.

[94] Donohoo-Vallett, P. 2016. *Accounting Methodology for Source Energy of Non-Combustible Renewable Electricity Generation.* Washington, D.C.: DOE. DOE/EE-1488.

[95] Newell, R., S. Iler, and D. Raimi. 2018. “Global Energy Outlooks Comparison Methods: 2018 Update.” *Resources for the Future*. Washington, D.C. https://www.rff.org/publications/reports/global-energy-outlooks-comparison-methods-2018-update/.

[96] Weiss, J., R. Hledik, M. Hagerty, and W. Gorman. 2017. *Electrification: Emerging Opportunities for Utility Growth.* The Brattle Group. https://brattlefiles.blob.core.windows.net/files/7298_electrification_emerging_opportunities_for_utility_growth.pdf.

[97] Steinberg, D., D. Bielen, J. Eichman, K. Eurek, J. Logan, T. Mai, C. McMillan, A. Parker, L. Vimmerstedt, and E. Wilson. 2017. *Electrification and Decarbonization: Exploring U.S. Energy Use and Greenhouse Gas Emissions in Scenarios with Widespread Electrification and Power Sector Decarbonization.* Golden, CO: NREL. NREL/TP-6A20-68214. https://www.nrel.gov/docs/fy17osti/68214.pdf.

[98] Iyer, G. L. Clarke, J. Edmonds, P. Kyle, C. Ledna, H. McJeon, and M. Wise. 2017. *GCAM-USA Analysis of U.S. Electric Power Sector Transitions.* Richland, WA: Pacific Northwest National Laboratory. PNNL-26174. https://www.pnnl.gov/main/publications/external/technical_reports/PNNL-26174.pdf.

[99] Quiggin, D. and R. Buswell. 2016. "The Implications of Heat Electrification On National Electrical Supply-Demand Balance Under Published 2050 Energy Scenarios." *Energy* 98 (March): 253–270.

[100] Zhou, Ella, and Trieu Mai. 2021. *Electrification Futures Study: Operational Analysis of U.S. Power Systems with Increased Electrification and Demand-Side Flexibility*. Golden, CO: NREL. https://www.nrel.gov/docs/fy21osti/79094.pdf.

[101] Kutscher, Chuck, Jeffrey Logan, and Timothy Coburn. 2020. *Accelerating the US Clean Energy Transformation: Challenges and Solutions by Sector.* Renewable and Sustainable Energy Institute (RASEI), University of Colorado Boulder. https://www.colorado.edu/rasei/sites/default/files/attached-files/accelerating_the_us_clean_energy_transformation_final.2.pdf

[102] Roberts, David. 2019. "How California Became Far More Energy Efficient Than the Rest of the Country." *Vox*. May 2019. https://www.vox.com/energy-and-environment/2019/5/31/18646906/climate-change-california-energy-efficiency.

[103] EIA. 2021. "U.S. Energy-Related CO2 Emissions Declined by 11% in 2020." *Today in Energy*. April 2021. https://www.eia.gov/todayinenergy/detail.php?id=47496

[104] EIA. 2021. "Monthly Energy Review; Carbon Dioxide Emissions from Energy Consumption: Electric Power." March 2021. https://www.eia.gov/totalenergy/data/monthly/pdf/sec11_9.pdf

[105] Kaplan, Stan. 2020. "Coal-fired Power in 2021: A Recovery or a Reckoning?" *Power Magazine*. October 2020. https://www.powermag.com/coal-fired-power-in-2021-a-recovery-or-a-reckoning/

[106] Bradford, Andrew. 2020. *Coal Retirement Outlook 2020*. BTU Analytics. September 2020. https://btuanalytics.com/power-and-renewables/coal-retirement-outlook-2020/

[107] BNEF. 2020. "New Energy Outlook 2020." *Bloomberg New Energy Finance*. October 2020. https://about.bnef.com/new-energy-outlook/

[108] Brinkman, G., J. Jorgenson, A. Ehlen, and J. Caldwell. 2016. *Low Carbon Grid Study: Analysis of a 50% Emission Reduction in California.* Golden, CO: NREL. NREL/TP-6A20-64884. https://www.nrel.gov/docs/fy16osti/64884.pdf.

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