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Challenges of a Clean Energy Transition and Implications for Energy Infrastructure Policy

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AUTHORS

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ABSTRACT

The United States faces the challenge of dramatically reducing carbon emissions while simultaneously ensuring the reliable supply of on-demand energy services that its residents have come to expect. Federal policy will be instrumental in driving investments in energy infrastructure that will be required to transition the U.S. energy supply to zero-emissions sources. This paper discusses the major barriers that policy will need to overcome in order to successfully execute this transition at a reasonable cost. A core problem is that wind and solar generation are intermittent. Provision of reliable zero-emission supply therefore requires combining wind and solar resources with investments in dispatchable zero-emission sources (such as nuclear, hydroelectric, geothermal, and fossil-fueled power plants with carbon capture and sequestration), long-distance transmission, demand flexibility, and storage technologies. But given uncertainties about technological progress, it is difficult to know which combination of investments will be most cost-effective. We argue that broad incentives – such as carbon pricing, clean energy standards, or clean energy subsidies – that do not discriminate across zero-emissions resources will be essential for directing capital toward cost-effective investments in clean energy infrastructure. We also argue, however, that such incentives on their own will be insufficient to meet the overall challenge. Policy must also address a suite of additional problems in energy markets that clean energy pricing incentives alone will not address. These problems include motivating global emissions reductions, overcoming regulatory barriers to long-distance

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transmission construction, addressing deficiencies in wholesale energy markets, reducing utilities' inclusion of non-marginal costs in volumetric retail rates, eliminating inequities in the distribution of clean energy's benefits and costs, and funding infrastructure decommissioning at the end of its useful life.

1. Introduction

The provision of reliable, on-demand energy services to households and businesses is a central feature of the modern U.S. economy. Americans generally take it for granted that their local gasoline stations will have fuel on-hand, that a steady supply of natural gas is available to run their furnaces in the winter, and that electricity will be there to power their lights, refrigeration, or air conditioning.

Reliable, on-demand energy supply has required substantial investments in both physical infrastructure – including wells, mines, refineries, long-distance transmission pipelines and wires, electric generators, and distribution networks – and the human capital to use it effectively. Historically, U.S. energy policy has emphasized investing in and operating this infrastructure at lowest cost, while maintaining reliability. Energy policy in the late 20th century focused on reducing regulation of energy markets in order to lower end-user costs. These market reforms – some of which were federal changes, but many of which were enacted unevenly across the states – eliminated gasoline price regulation, liberalized natural gas extraction, and broke up integrated utility monopolies, thereby permitting independent power producers to enter into electric generation markets. The core idea motivating these reforms was to lower costs by using competitive forces to drive efficiency improvements relative to the well-known inefficiencies of regulated monopolies.

The core challenge for energy policy in the 21st century is how to supply low-cost energy that is not only reliable but also does not harm the environment. This paper focuses on the problem of global climate change and the need to substantially reduce the emissions of carbon dioxide (CO_2) and other greenhouse gases that are associated with the widespread use of fossil fuels as primary energy sources. There is also, however, an increasing imperative to address long-standing local environmental damages and inequities associated with energy production and use. So climate change solutions must be paired with improvements in environmental justice.

The problem of climate change is vexing, and not one that private markets will solve on their own. The core challenge arises from the fact that fossil fuels became dominant energy sources in the first place because they can be reliably supplied at low cost. Oil, coal, and (to a lesser extent) natural gas are energy-dense and storable. Oil and gas can easily be transported in bulk over long distances by pipeline, and oil can be transported across the oceans via tanker at low cost. These resources are therefore amenable to energy infrastructure that allows end-users to consume energy when they want it and where they want it.

Unfortunately, current zero-emission technologies mostly lack fossil fuels' desirable characteristics. Compared to fossil fuels, electricity is extremely costly to store with current technology. Generation from wind and solar are also not *dispatchable*. They produce only when the wind is blowing or the sun is shining, which are not necessarily the times when end-users demand energy. Moreover, even with recent technological improvements in solar and wind generation, in many locations they remain more costly than fossil fuel–fired generation due to weak availability of the solar or wind resource. An alternative approach, fossil fuel generation with carbon capture and storage (CCS), also remains costly given current technology, as do more storable, low-carbon fuels like hydrogen.

These challenges imply that massively reducing CO_2 emissions, while simultaneously maintaining reliable supplies of energy for on-demand consumption, will not be easy. Achieving these twin goals will likely require large, policy-driven investments in new energy infrastructure for generation, transmission, storage, and distribution of zero-emission power. The policy question is then how to catalyze the necessary investments without unduly increasing costs to end-users.

One potential approach to energy infrastructure policy would follow models of public investments in transportation infrastructure, in which agencies identify particularly promising investment opportunities (say, a specific transmission line or renewable power generation facility) and then direct public funds to those investments. Alternatively, policy could take a less targeted approach of providing blanket incentives for zero-emissions energy production (either by taxing emissions or by subsidizing clean production), continuing to provide strong incentives for grid reliability, and otherwise getting out of the way to let "the market" figure out the lowest-cost solution.

Direct public investment into specific projects or technologies is fraught; when technology is evolving rapidly, governments picking winners often does not end well. The history of U.S. biofuel policy provides a cautionary tale. In the early 2000s, there was widespread hope for production of liquid fuels from plants, such as switchgrass, or from agricultural waste products. Federal legislators were sufficiently optimistic about these technologies that the Energy Policy Act of 2005 and the Energy Independence and Security Act of 2007 specified minimum blending requirements for advanced biofuels into automotive gasoline. Yet these technologies never came to fruition, and U.S. biofuels today consist almost entirely of corn-based ethanol. Despite questions over corn-based ethanol's CO_2 emissions relative to gasoline, the large implicit subsidies that sustain this industry have proven politically difficult to remove.[1]

We view a pricing policy that supports zero-emissions energy production, coupled with robust reliability incentives, as a strong foundation for U.S. energy infrastructure policy. Still, we argue that very large carbon taxes or renewable subsidies on their own would be an insufficient

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[1] See Mullins, Griffin, and Matthews (2011), Hoekman and Broch (2018), and Scully *et al.* (2021) for discussions of uncertainty in estimates of corn-based ethanol's life cycle emissions and reviews of recent literature.

response to the global task at hand. First, direct costs are not the only barrier to investments in zero-emission energy infrastructure. Most importantly, construction of long-distance, high-capacity transmission lines – which will be essential to address renewables' non-dispatchability limitation – is beset by multi-jurisdiction regulatory and hold-up problems. Regulatory reform that invests federal authorities with the power to certify interstate transmission lines will be essential to enabling needed transmission investments.

Reforms to wholesale and retail electricity markets also have a role to play in promoting efficient investment and dispatch of zero-emissions generation resources. Increased use of organized, transparent wholesale power auctions can increase the dispatch of low-cost generators while sending clearer price signals for resource investment. In retail electricity markets, the standard pricing paradigm used nearly ubiquitously in the U.S. excessively marks up end-users' electricity prices by folding recovery of fixed distribution costs into retail rates. Retail pricing reforms that reduce or eliminate these mark-ups can improve end-users' incentives to switch from natural gas to electricity for space heating, and to switch from gasoline-powered to electric vehicles. Such reforms can also improve the progressivity with which the fixed costs of electricity distribution are shared across consumers.

The transition to a net-zero emission energy system will also lead to stranded fossil fuel assets. These assets will include both physical infrastructure and human capital. Policy will need to ensure the repurposing or proper decommissioning of fossil fuel infrastructure while also helping identify – and in some cases directly provide – opportunities for displaced workers to apply their skills. The impacts of a clean energy transition on the oil, gas, and coal workforce is one of several ways in which energy market outcomes can be inequitable. Policies on stranded assets, recovery of fixed distribution costs, infrastructure siting, and addressing legacy infrastructure's impacts on disadvantaged communities all have a role to play in ensuring a just transition that equitably shares benefits and costs.

One area where we will argue for increased direct public funding is research, development, and deployment of early-stage clean energy technologies. The climate challenge is a global challenge, and emissions reductions from the U.S. alone will not allow the planet to avoid the worst effects of climate change. An important pathway for driving global emissions reductions is technological improvement. While U.S. intellectual property policy is typically concerned with preventing free access to IP by other countries, the climate problem is a situation where the optimal policy is likely to be investing in technology and then licensing it for free, at least to low-income countries. Private innovators do not have an incentive to behave in this manner.[2] Thus, there is an important role for public funds to drive the development and export of low-cost, low-carbon technologies.

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[2] Jones (2021) discusses at greater length why science and innovation are public goods that merit substantial publicly funded investment, not just in the energy sector but in a variety of settings.

The remainder of the paper is divided into three primary sections. Section 2 presents background on the energy industry in the U.S., divided into the oil and gas industry and the electricity industry. Section 3 discusses seven areas of challenges the country faces in transitioning to a low-carbon energy system while maintaining affordability, equity, and reliability. Section 4 then discusses potential solutions and the role that infrastructure investment can play in addressing these challenges. We conclude in section 5.

2. Background

The energy industry has more than the usual level of institutional and operational complexities that are important for discussing the relevant policy issues. In this section, we briefly outline those factors in order to establish a baseline understanding of the industry before examining the challenges it presents and possible solutions.

2.a. Oil and gas extraction, transportation, and distribution

We begin by discussing the current state of markets and infrastructure for the dominant source of energy in the U.S.: fossil fuels. Our discussion focuses on oil and natural gas, highlighting their energy density, storability, and transportability. These private advantages, combined with the unpriced pollution externalities of these fuels, will pose significant challenges for climate policy.

Our discussion, for the most part, omits coal. While coal remains a significant share of U.S. primary energy consumption, its importance has steadily declined over the past decade, in large part due to the shale boom that dramatically increased U.S. natural gas supplies. Even in the absence of aggressive climate policy, the trend of disinvestment from coal is likely to continue unabated.[3] We partition our discussion of the oil and gas industry into its three main activities: extraction, long-distance transportation, and local distribution.

2.a.1. Upstream extraction

Oil and gas extraction has not faced substantive economic regulation since the 1980s, when the last federal wellhead price control regulations were lifted. Despite the presence of the international OPEC cartel on the world oil market, oil and gas extraction in the U.S. can be described as competitive. There are dozens of large integrated producers and large independents, as well as thousands of small independent producers.

The most important decisions that U.S. oil and gas producers regularly make are when and where to invest in drilling new wells. These decisions weigh wells' expected production and local output prices against their drilling and completion cost. Once drilled, a well's production follows

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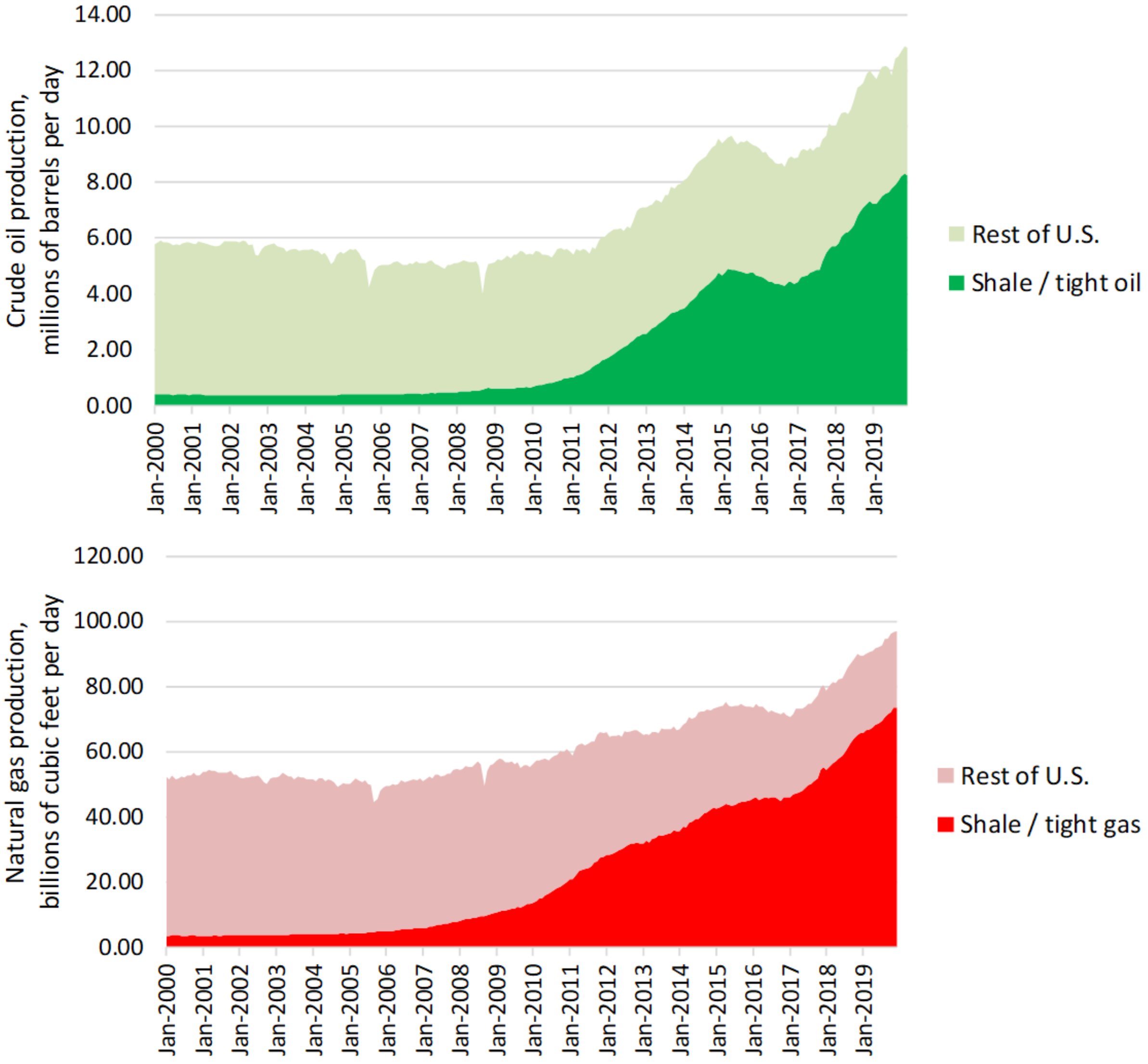
[3] Globally, however, coal remains a substantial threat to progress on reducing greenhouse gas (GHG) emissions, as highlighted in the International Energy Agency's Global Energy Review 2021. https://www.iea.org/reports/global-energy-review-2021.

a decline curve. Except in extreme situations, producers do not have an incentive to change wells' production rate in response to output prices (Anderson, Kellogg, and Salant 2018).

Beginning in the mid-2000s, U.S. production of oil and gas increased substantially due to the exploitation of shale oil and gas reserves. Profitable extraction from these deposits had previously been considered impossible, but combining horizontal drilling with high volume hydraulic fracturing (injecting large volumes of water, sand, and chemicals to fracture the shale formation itself) was a technology breakthrough that transformed the U.S. oil and gas sector in just a few years. As shown in figure 1, shale oil has led U.S. oil production to more than double since 2010, and shale gas has led U.S. natural gas production to nearly double.

Figure 1: U.S. crude oil and dry natural gas production, 2000–2019



Source: Energy Information Administration (EIA) data onhale oil production, available at [*https://www.eia.gov/energyexplained/oil-and-petroleum-products/data/US-tight-oil-production.xlsx*](https://www.eia.gov/energyexplained/oil-and-petroleum-products/data/US-tight-oil-production.xlsx)*; data on total oil* *production, available at https://www.eia.gov/dnav/pet/hist/LeafHandler.ashx?n=PET&s=MCRFPUS2&f=M; data on shale dry gas production available at https://www.eia.gov/naturalgas/weekly/img/shale_gas_202104.xlsx; data on total dry gas production, available at https://www.eia.gov/dnav/ng/hist/n9070us2m.htm.*

2.a.2. Long-distance oil and gas transmission

Oil and gas deposits are often located far from demand centers and therefore require long-distance, overland transportation. Pipelines have long been the dominant (and for natural gas, the only) technology for doing so, though significant volumes of crude oil also travel via railroad.

Because long-distance transmission pipelines are characterized by economies of scale, service between any two distant locations is often provided by just one pipeline firm, or at most a handful of firms. To prevent abuse of market power, the transmission rates that pipelines may charge are therefore regulated by the Federal Energy Regulatory Commission (FERC).

Per the Natural Gas Act of 1938, FERC not only regulates service rates but also authorizes interstate pipeline investments by issuing certificates of public convenience and necessity. These certificates can allow pipeline firms to use eminent domain to acquire rights-of-way, if necessary. To obtain a certificate, pipeline companies are typically required to demonstrate demand by signing firm shipping agreements with prospective customers.

Despite FERC's authority to regulate oil pipelines' service rates, it does not have certification authority over new oil pipeline construction. Oil pipelines must instead be approved individually by each state that the line passes through. Finally, both oil and gas pipelines must comply with environmental regulations and procedures, and in particular with those prescribed by the National Environmental Policy Act.

2.a.3. Refining, local distribution, and storage

Crude oil is converted to end-use products like gasoline and diesel fuel at refineries that are dispersed broadly throughout the U.S. Due to the ease with which oil and refined products can be transported and stored, their distribution and storage are decentralized. Gasoline and diesel are typically distributed to retail fueling stations via truck, and storage is so cheap that individual consumers store days of fuel on board their own vehicles. These distribution markets generally operate with little or no sector-specific economic regulation.

Natural gas is inherently less energy-dense than refined oil products, and it is therefore more costly to distribute and store on an energy-unit basis. Pipelines are the only cost-effective method for moving natural gas, so its distribution requires a pipeline connection to each customer. The large up-front capital expense of building a gas distribution network, along with ongoing maintenance costs, make gas distribution a classic example of a natural monopoly. Throughout the U.S., local natural gas distribution companies are therefore monopolies licensed by the state or local government. They are usually owned by private investors but sometimes owned and operated by local governments, with rates regulated under cost-of-service principles.

It is more economical to store natural gas at scale, and substantial storage is held by local distribution companies, large industrial users, and third-party storage firms. Nearly all of this storage makes use of underground geologic formations rather than above-ground vessels. This gas storage plays an essential role in managing both seasonal and short-term fluctuations in natural gas demand. At the start of the winter heating season, the quantity of natural gas in storage is typically sufficient to satisfy more than one month of average winter gas consumption.[4]

2.b. Electricity markets

For most of the last century, electricity has been the primary energy source for lighting and appliance services, including air conditioning. But it has played a smaller role in space and water heating, industrial energy, and transportation. Increasingly, however, electricity is being viewed as the most probable path to decarbonizing not just the activities that have historically used it, but also many of the activities for which energy has been supplied by direct combustion of coal, natural gas, and refined oil products. For electrification to be a credible pathway to decarbonization, however, electricity generation must become almost entirely carbon free, while still remaining extremely reliable and cost competitive.

2.b.1. Structure of the electricity industry

The electricity industry comprises four major functions: generation, transmission, distribution, and procurement/retailing.[5] In a few parts of the U.S., all four functions are provided by a single entity (as was the case in most areas thirty years ago), but in most of the country generation is now competitively supplied. In 2020, about 40% of U.S. electricity came from burning natural gas, 19% from coal, 20% from nuclear power, and about 20% from renewables (wind 8.4%, hydro 7.3%, solar 2.3%, biomass 1.4%, and geothermal 0.4%).[6] As shown in figure 2, this fuel mix is a drastic change from a decade ago, when coal provided a much larger share of generation fuel. Figure 3 shows the share of electricity generation from non-utility producers.

Transmission is generally viewed as a natural monopoly in the sense that the lowest-cost capacity along a given corridor is a single transmission facility. Interstate transmission lines, 80% of which are owned by investor-owned utilities (IOUs), are authorized and regulated by FERC. Nonetheless, siting new transmission lines requires approval from multiple state authorities as well as FERC. Local distribution is indisputably a natural monopoly, with about

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[4] U.S. storage volumes typically peak at around 4 trillion cubic feet just before winter, and January gas consumption has been roughly 3 trillion cubic feet in recent years. See EIA data on storage and consumption at https://www.eia.gov/dnav/ng/hist/nw2_epg0_swo_r48_bcfw.htm and https://www.eia.gov/dnav/ng/hist/n9140us2m.htm.

[5] Transmission refers to long-distance transport at very high voltages while distribution is done at lower voltage for local delivery to customer locations.

[6] https://www.eia.gov/energyexplained/electricity/electricity-in-the-us.php.

70% of electricity distributed by state-regulated IOUs and the remainder by nonprofit municipal utilities and co-ops.[7]

Figure 2: Fuel sources for U.S. electricity generation, 1950–2020

Figure 2a. Generation from all major energy sources

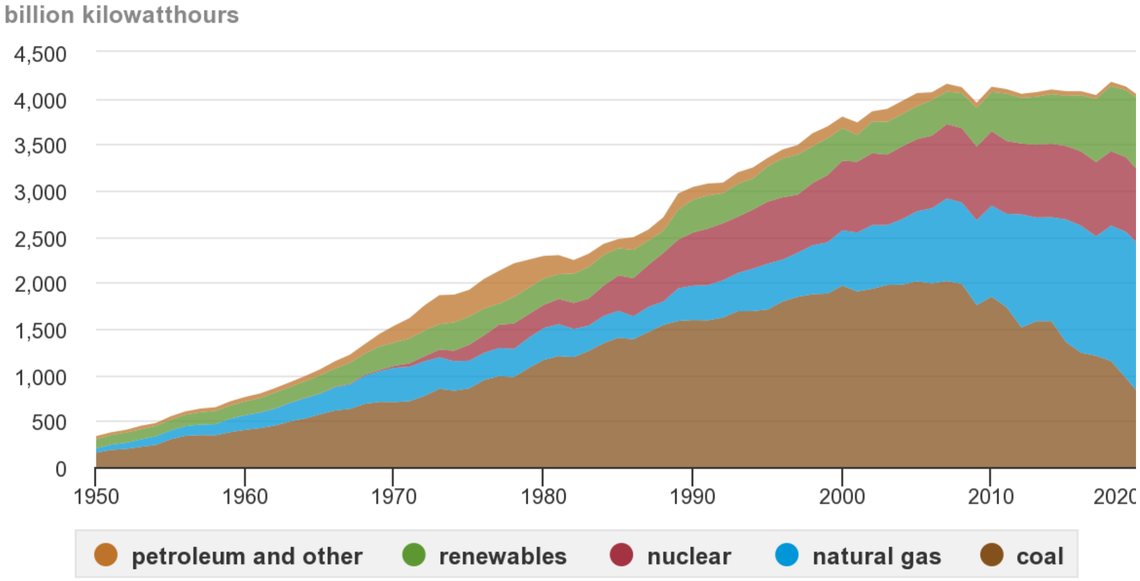
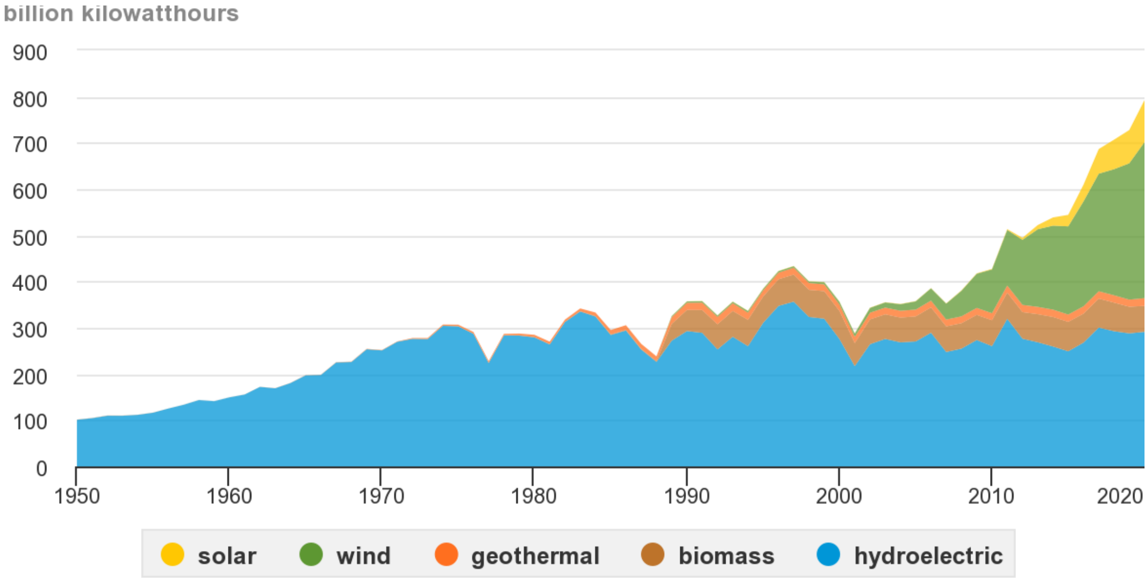


Figure 2b. Generation from renewable energy sources



Note: Electricity generation from utility-scale facilities.
Source: U.S. Energy Information Administration, Monthly Energy Review, Table 7.2a, January 2021 and Electric Power Monthly, February 2021, preliminary data for 2020.

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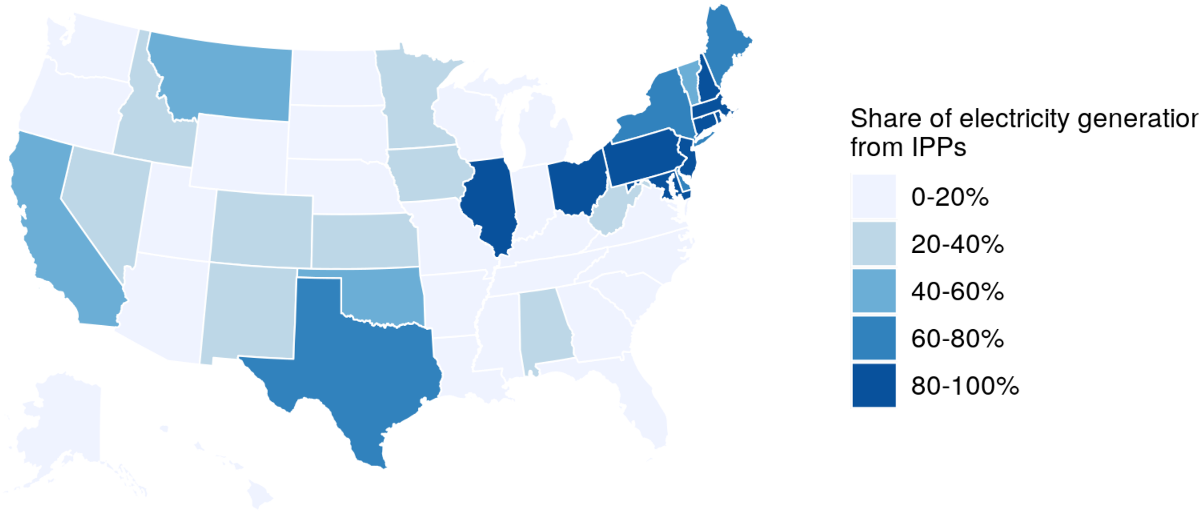
[7] Unlike in cable television, there is essentially no "overbuild," where two distribution companies serve overlapping areas.

Figure 3: Share of electricity generated by independent power producers (IPPs) in 2019, by state



Source: EIA data on "Net Generation by State by Type of Producer by Energy Source," available at https://www.eia.gov/electricity/data/state/

Procurement/retailing is a financial broker function carried out by entities that contract with (or may own) generators for electricity supply and with customers for electricity demand. In most of the country, the same regulated or municipal/co-op utility that provides distribution services also does the procurement on behalf of customers. In a few areas, "retail choice" is available to some or all customer classes, in some cases through for-profit companies (most notably in Texas) and in other cases through nonprofit local governmental organizations – known as "community choice aggregation" in California or "municipal electricity aggregation" in Illinois, two states with large numbers of customers served by such entities.[8] Figure 4 shows the share of all electricity purchased that is sold by these non-utility retailers.

Over the last twenty-five years, many electricity markets have significantly restructured, changing from mostly vertically integrated organizations that generated high proportions of the power they distributed to customers, to be much more a supply chain of separate companies that perform the four major functions and interact with one another through market transactions. There is strong evidence that the widespread move to wholesale market competition and trading has increased efficiency and reduced electricity generation costs (Fabrizio, Rose, and Wolfram 2007; Davis and Wolfram 2012; Mansur and White 2012; Cicala 2015; Cicala forthcoming). The more limited evidence on retail choice suggests it has produced fewer net benefits (Wilson and Waddams 2010; Hortaçsu, Madanizadeh, and Puller 2017; Byrne, Martin, and Nah 2019).

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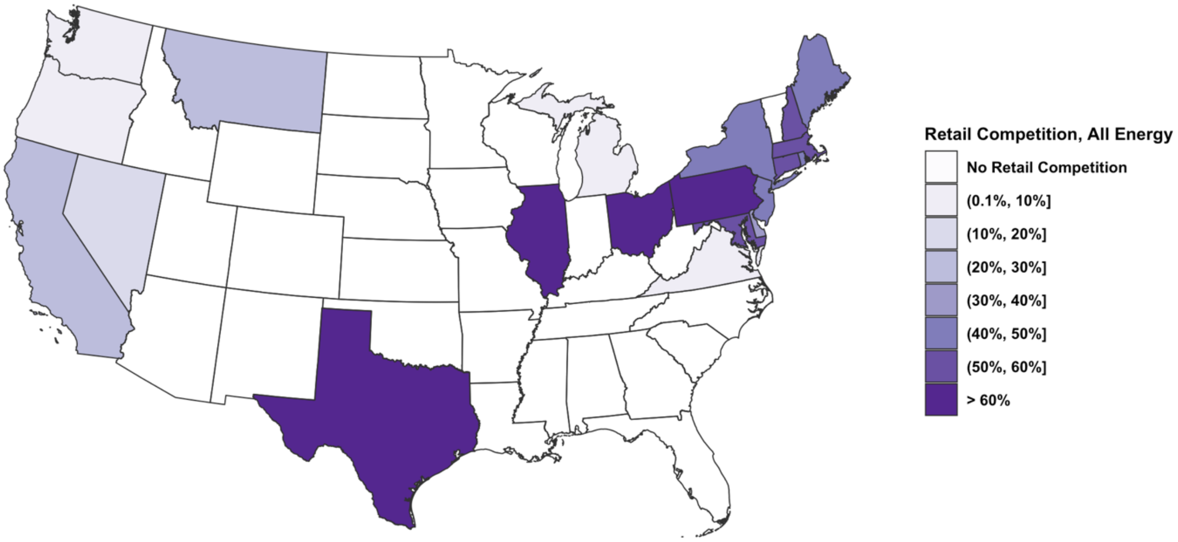
[8] More information on these government retailers is at https://www.leanenergyus.org/.

Figure 4: Share of electricity purchased under retail choice in 2019



Source: Authors' calculations based on EIA Form EIA-861.

2.b.2. What makes electricity different from other markets?

A combination of physical properties differentiates electricity markets from any other good:

1. Electricity itself is non-storable, and storage of potential energy for rapid conversion to electricity – such as through hydroelectric dams, chemical batteries, or compressed air in underground caverns – requires large capital investments and/or is subject to significant energy loss.

2. Electricity is transported through a network of common carriers – transmission wires – that are somewhat akin to pipes carrying water or gas, except the flow of electricity across connected wires is determined by laws of physics ("loop flow") and very costly to control through an equivalent of valves that can direct it along specific lines.

3. The aggregate supply of electricity injected into this grid of transmission wires must nearly exactly equal the aggregate demand for extracting power from a grid on a second-by-second basis. The same is true for supply and demand at each location if transmission capacity or loop flow constrains the flow of electricity to where it is demanded on the grid. This nearly exact balance between demand and supply must hold despite the fact that there can be substantial demand variation hour-to-hour, some of which is predictable, but some of which is not.

4. Imbalances that are more than very slight and very brief will disrupt the power quality (*e.g.,* electrical frequency) and potentially damage both generating equipment and consuming equipment. As a result, generating equipment is designed to detect frequency

deviations and disconnect from the grid if the magnitude of such deviations is too large. Thus, even a small and transitory supply shortage (or surplus) can turn into cascading outages if not managed extremely rapidly. In February 2021, frequency fluctuations brought the Texas grid to within minutes of a cascading outage situation, causing the grid operator to order disconnection of large swaths of customers in order to maintain supply/demand balance. In August 2003, an imbalance in Ohio that was not managed by the local grid operator cascaded across the upper Midwest and Northeast, as well as parts of Ontario, Canada, causing more than 500 generating units to go off-line and customers to lose power across these areas for up to four days.

5. Due to factors 1-4, in every grid there is a central balancing authority that determines at least marginal supply and demand adjustments in order to maintain balance overall and at each node of the grid. Due to the complexity of power flow on the grid and other information constraints, these balancing authorities cannot match supply that has been contracted for specific buyers with those buyers in real time. So they cannot cut off supply to specific buyers if their counter-parties fail to produce and deliver electricity to the contracted locations, resulting in insufficient supply. Thus, in real time, supply shortages are socialized across all buyers in the market.[9] After the fact, balancing authorities can impose fines on retailers whose customers withdrew more electricity than their suppliers injected into the grid for a specific time interval and location, but these fines are limited by bankruptcy constraints.

As with electricity, most service industries sell products that are non-storable and for which demand is volatile. With other non-storable services, however, a shortage from one supplier is not socialized among all suppliers in the market. Instead, one seller's supply shortage simply leads to queueing or stockouts. For the reasons discussed above, neither is an option with electricity.

These physical attributes of electricity combine with unusual financial, regulatory, and administrative attributes:

1. Due to large economies of scale in construction, it typically makes sense to build transmission and distribution system capacities beyond near-term demand, so the marginal cost of usage is well below the average total cost (inclusive of the fixed costs of construction and upkeep). In such a natural monopoly situation, recovering the full cost from volumetric rates pushes retail prices up relative to marginal cost.

2. Electricity generation from fossil fuels creates significant negative externalities, including climate change externalities, which are for the most part not priced. These unpriced

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[9] This approach is particularly problematic when there are many small retail providers buying in the wholesale market, each internalizing little of the grid risk of being short, as was the case in Texas in February.

externalities push the retail price down relative to the full social marginal cost of providing electricity.

3. In many areas, electricity rates are used to pay for public policy priorities that are not a marginal cost of providing electricity, such as assistance to low-income customers, subsidies for energy efficiency programs and rooftop solar, procurement of power from immature technologies in order to support their development (climate mitigation), and aggressive vegetation management in increasingly fire-prone areas near electrical wires (climate adaptation).

4. For nearly all customers, electricity is sold under a "requirements contract," meaning that the retailer agrees to supply whatever quantity the customer demands at a preset price. Meeting this obligation while keeping the grid in balance requires investment in substantial generation and transmission capacity that is seldom used.

5. Dynamic pricing – under which retail prices adjust at roughly the same time scale as wholesale costs – is extremely uncommon in electricity. Historically, and even today, customers have very little information or technology to respond to changes in the supply/demand balance or wholesale market prices.[10]

3. Energy challenges

The U.S. is at a critical point in the arc of the energy industry and the fight against climate change. The country must rapidly reduce greenhouse gas (GHG) emissions while maintaining energy affordability, reliability, and resilience, and address the historical socioeconomic and racial disparities in both access to energy consumption and harm from energy production. These imperatives present a series of interwoven challenges to the industry and to plans for infrastructure investment.

3.a. Low-carbon technologies

If the primary pathway for a clean energy transition is to be electrification, then the electricity industry must develop systems for delivering near zero-carbon electricity while controlling costs and maintaining grid reliability. Breakthroughs in the costs of nuclear power or carbon capture and sequestration could greatly ease the path to meeting this challenge, but neither seems imminent. The more likely strategy over at least the next decade will be widespread use of intermittent renewables: wind and solar power.

Wind and solar have become cost competitive with fossil-fired generation in many locations when deployed in large-scale developments. However, continued improvements in renewables'

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[10] In the last decade, regulators have moved toward retail prices that more accurately reflect seasonal and time-of-day average differences in costs, but these average differences capture very little of the actual variation in wholesale costs.

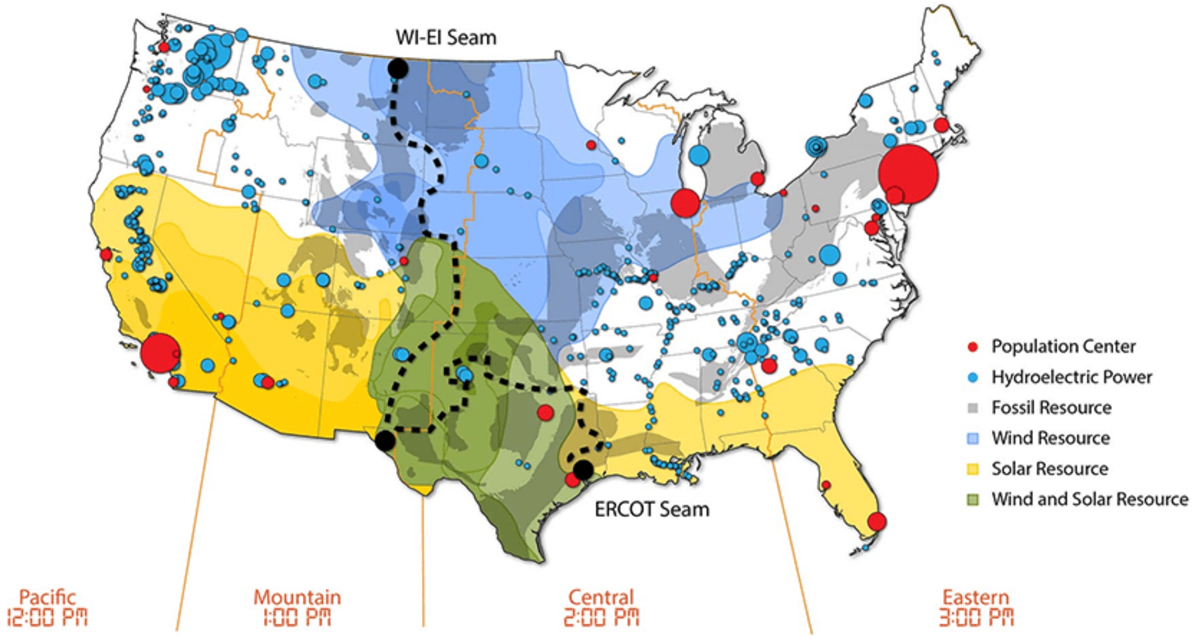
supply cost, relative to oil and gas, will require continued innovation for at least two reasons. First, the shale boom has already substantially reduced the cost of production of U.S. oil and gas, and further cost decreases cannot be ruled out. Second, as renewables displace oil and gas, the high-cost oil and gas will be displaced first, leaving lower-cost supply in the market, and lower prices. Even with current technologies, there are large quantities of oil and gas that can be produced at costs well below the current market prices (Asker, Collard-Wexler, and De Loecker 2019). Cutting even 20% or 30% from the demand for these fuels will almost certainly result in declines in their prices. Thus, absent a lucky run of technology breakthroughs in renewables – and none in oil and gas – large-scale substitution away from oil and gas toward renewables will require either substantial mandates and incentives, or direct government expenditures on renewable generation infrastructure.

Wind and solar, however, will not be able to support a stable electricity system on their own because their production pattern is determined by nature. Other resources are needed to make sure that supply and demand balance every minute. A combination of four different approaches could maintain grid stability in a system with very high levels of intermittent generation: long-distance power transmission, storage, demand flexibility, and dispatchable generation. The last of these four approaches could come from burning a storable renewable fuel such as hydrogen or biomass, fossil fuel generation (possibly with CCS), or nuclear, hydroelectric, or geothermal power. Each of these four approaches has its own challenges, however.

Transmission

Transmission is critical to taking advantage of resource-rich locations for sun and wind, many of which are far from population centers, as shown in figure 5. Transmission can also help address the problem that wind and solar are not time-shiftable energy sources by enabling a diversified portfolio of renewable generation. Such a portfolio increases supply stability by decreasing the likelihood that all of a demand center's renewable power sources are idle at the same time. At the same time, transmission also provides more market options for these intermittent resources. More market options mean less need to curtail renewable production if the output of a given facility exceeds the needs of nearby customers, which then implies higher capacity utilization and lower cost per kilowatt-hour.

Figure 5: Map of U.S. energy resources and population centers



Source: National Renewable Energy Laboratory (NREL) "Interconnection Seams Study," available at *https://www.nrel.gov/analysis/seams.html*

By connecting markets, transmission also enhances competition among generators. Because electricity demand is relatively inelastic, when an electricity market is strained, that is a particularly attractive moment for a generator to reduce output in order to drive up the wholesale price (Borenstein 2002; Borenstein, Bushnell and Wolak 2002) Transmission undermines that incentive by creating more potential competitors in every market (Borenstein, Bushnell, and Stoft 2000).

Though the direct cost of transmission is significant, by most accounts the larger barrier is siting authority, and particularly the web of authorities – including FERC and various agencies in every state through which a line passes – each of which must approve any interstate transmission proposal. These multiple veto points currently raise an extraordinarily high hurdle to interstate transmission investment, as documented in Gold's (2019) account of the failed attempts to connect wind resources in Oklahoma to population centers in the Southeast. Overall, progress on transmission is likely more dependent on reducing the regulatory barriers than on providing government funding.

Storage

Just as a battery in your basement can substitute to some extent for a reliable grid connection, large-scale battery storage can partially substitute for long-distance transmission connections by filling in when intermittent generation fades or demand surges. Battery storage has come down in cost dramatically over the last decade, and it likely has a significant role to play in balancing short-term fluctuations in supply and demand. Current battery technologies, however, are not cost competitive for long-duration storage and not likely to become so in the next decade. Challenges in long-duration storage are particularly relevant if the U.S. is to electrify space heating and depend on it for getting through cold winter periods when renewable generation is often limited.

Demand flexibility

Electricity demand is becoming less predictable and more extreme due to climate change, which has made extreme weather more common over the last 50 years.[11] This increased demand volatility amplifies the challenge of meeting demand with intermittent generation sources. Overall demand for energy services is also growing, though energy efficiency improvements – from light bulbs to refrigerators, air conditioning, and electrical heating – have reduced the growth of demand for electricity itself.

One tool for managing electricity systems with demand volatility and large shares of intermittent generation is dynamic demand adjustment. The 2009 American Recovery and Reinvestment Act funded the rollout of electric meters that can measure consumption on a sub-hourly basis and communicate data directly to the utility, but since then the pace of introducing dynamic rates, which incentivize customers to change consumption as supply availability changes, has been slow.

Dispatchable generation

Storable (and transportable) renewable fuels, such as hydrogen, are in some ways technologically ideal, but at this point they are not cost competitive at scale. Credible pathways exist for them to potentially become a significant part of the solution, but thus far they are aspirational (Meyer and Thomas 2021). The same is true for fossil fuel generation with CCS.

Existing nuclear and hydroelectric (and to a lesser extent, geothermal) generation are the front runners for low-carbon, long-duration grid balancing in the near-term as wind and solar ramp up. But the finances of these resources have been weakened by low wholesale prices, a topic we return to below, which threatens the viability of some existing plants and discourages new construction.

Uncertain technological progress

Overall, energy technologies are evolving more rapidly now than at any time in the last century. Despite the confident claims of entrepreneurs and advocates of specific technologies, there is tremendous uncertainty about the pace and direction of future technological change. For every exciting success story, like solar photovoltaics (PV) or lithium ion batteries over the last decade, there are many disappointments, like advanced biofuels or tidal power. Investments in the industry must balance the urgency of reducing carbon emissions and demonstrating new low-carbon technologies with the option value of delaying major financial commitments to obtain more information about which technologies are likely to be most successful. The challenge is not

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[11] https://www.epa.gov/climate-indicators/weather-climate.

only to balance these factors, but also to design market and policy processes that can adapt rapidly and allow the technologies that deliver the lowest costs and greatest societal benefits to succeed.

3.b. Wholesale market design

While the technological barriers to a stable, near-zero carbon grid are widely discussed, the design challenges for market mechanisms and compensation receive less attention. The resource transition imperative brought about by the climate crisis unfortunately comes at a time when there is also wide disagreement about the best way to operate electricity markets. This debate has many facets, but probably the most important among them is how to reward supply resources whose value does not fit the standard per-kilowatt-hour compensation paradigm. These resources include those that are particularly valuable for their ability to change output rapidly on demand – such as battery storage and hydroelectric generation – as well as capacity that can stand by for very long periods – months or even years – and then reliably operate when needed in a crucial situation.[12]

Market designs created over the last two decades have not settled on how these non-standard electricity market players should be paid, but their importance is growing as weather becomes more extreme and wind and solar generation become a larger share of the portfolio. Texas pioneered one market model that is premised on extremely high electricity prices during times of grid stress. These high prices are intended to incentivize generators to be available and incentivize buyers to sign long-term contracts for supply, helping to finance the construction and continued operation of those generators. Unfortunately, the Texas grid operating under this model fell far short of delivering adequate power supply during the February 2021 Texas energy crisis. On the other hand, alternative models that require energy retailers to contract for standby capacity have also had disappointing outcomes at some peak demand times. In both cases, the risk of extreme financial losses from failures to perform do not seem to have provided sufficient incentives for ensuring supply performance during critical events.

Electricity markets continue to grapple with striking the right balance between market incentives and regulatory guardrails that can lower the cost of providing power without increasing threats to reliability.[13] This problem is not caused by intermittent renewables – as was demonstrated during the February energy crisis in Texas. But it is exacerbated by large-scale deployment of intermittent generation, which adds greater uncertainty on the supply side to the growing

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[12] A centralized grid operator could, in theory, optimize use of each type of resource in order to minimize costs, though the information and computational requirements of doing so would be enormous. In a market setting, with dispersed ownership and control of supply resources, the technological complexities described in the previous section make it difficult to create compensation mechanisms that incentivize suppliers to behave as efficiently as this theoretical optimum.

[13] See, for instance, the discussion of the 2021 Texas outages at https://www.wsj.com/articles/a-failure-of-texas-size-proportionsstate-struggles-to-overhaul-its-power-market-11618565415.

uncertainty on the demand side – as was demonstrated by the (much smaller) power shortage California experienced in August 2020.

Wholesale electricity markets have also been strained by renewable electricity policies. While economists generally argue for pricing GHG emissions (as well as emissions of other pollutants), policymakers have instead preferred to mandate and subsidize renewable power. Rather than increasing wholesale prices, as a carbon price would do, these approaches have reduced wholesale prices.[14] This price reduction has squeezed the profits of nuclear, hydro, and other generation sources that are near carbon free but have not been included in states' subsidies and mandates. This problem has been especially severe for existing nuclear power plants, many of which are not earning revenue sufficient to cover their ongoing operating costs. Because wholesale prices are depressed by renewable generation policies, the standard market test doesn't convey appropriate information about whether these plants should continue to operate.

3.c. Sustainable retail pricing and distributed energy resources

Most models of a clean energy transition suggest that it can be done at a fairly modest cost to the overall economy (National Academies of Science, Engineering and Medicine 2021; Larson *et al.* 2020; Phadke *et al.* 2020), but the way that some of the leading states and countries in the low-carbon movement are financing their transitions raises concerns that it could undermine the goals of both large-scale electrification and equity. In California, New York, Germany, and other market-based economies that are aggressively pursuing decarbonization, much of the cost has been covered through increased volumetric electricity rates. As a result, rates in these areas, particularly for residential customers, are now many times higher than the social marginal cost (*i.e.*, the marginal cost inclusive of externalities) of providing incremental electricity.

High volumetric rates are used to cover many costs that do not vary with the volume of electricity delivered, such as most costs of electric infrastructure, climate mitigation (*e.g.,* contracting for new low-carbon forms of generation or storage technologies when they are still quite expensive), climate adaptation (*e.g.,* increased vegetation management), subsidies for rooftop solar and low-income customers, and energy efficiency programs. Many of these programs are worthwhile expenditures, but paying for them through high volumetric rates discourages switching from direct combustion of fossil fuels to electricity. Borenstein and Bushnell (2019) shows that in California, New England, and a few other areas of the U.S. that have made significant investments in climate change mitigation and other social programs, retail prices are two to three times higher than the social marginal cost. These high retail volumetric rates pose a problem if electrification is the preferred pathway to reducing GHG emissions.

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[14] Subsidizing renewables differs from pricing GHG emissions in other ways. Both approaches encourage renewable generation, but subsidies for renewables don't distinguish between renewable resources that crowd out coal-fired generation versus those that displace natural gas-fired generation (which emits half as much GHGs as coal), or even displace other zero-carbon generation such as hydro, nuclear, or incumbent renewables. Pricing the "bad" directly avoids this problem by appropriately changing the costs of each type of generation (Borenstein 2012).

High volumetric electricity rates are also a challenge to equity. Borenstein, Fowlie, and Sallee (2021) suggests that high volumetric rates disproportionately burden low-income households. It also shows that paying for climate mitigation and adaptation by raising retail electricity rates is a more regressive approach to funding these programs than a sales tax or gas tax. Historically, the alternative to high volumetric rates has been to impose uniform monthly connection charges for residential customers – which are even more regressive then volumetric rates – or forms of charging commercial and industrial customers based on their own peak usage (known as “demand charges"), which create another set of perverse incentives (Borenstein 2016).

The states that have taken the early steps on climate mitigation and adaptation – and have generally funded their environmental and equity programs from electricity rates – have also been leaders in promoting behind-the-meter (BTM) resources, including rooftop solar installations and batteries. These technologies hold promise for improving system efficiency, but they are also incentivized by retail pricing that exceeds the actual value of additional supply or reduced demand to the grid. Residential rooftop solar, for instance, is thriving mostly in California and other areas of the country with very high retail rates, where more than half of those rates are covering fixed costs of the system or paying for state policies that do not affect the marginal cost of consumption.

BTM resources deployed efficiently can be a valuable part of a decarbonization strategy, but if adopted in response to retail prices that far exceed social marginal cost, they will raise the total cost of achieving carbon reduction goals. In addition, when utilities rely on high volumetric rates to recover their fixed costs, BTM resources reduce utilities' revenue, thereby forcing them to raise their volumetric rates to maintain cost recovery. And because early BTM solar and battery adoption tilts strongly toward wealthier households, the resulting cost shift to other customers is highly regressive (Borenstein and Davis 2016).

Finding funding sources for the non-marginal costs of electricity, along with the related programs that are now paid for through electricity rates, is an under-appreciated challenge of the energy transition. Though this retail pricing distortion is most evident in the states that are leading on climate action, it is likely to become a concern in other areas should federal policies press them to meet a clean energy standard or other carbon reduction mandate.

3.d. Energy infrastructure and equity

Retail pricing problems are far from the only way in which energy systems can impose disproportionate costs on disadvantaged communities. Energy infrastructure has been at the heart of U.S. economic growth for more than a century, but that same infrastructure has produced negative local environmental impacts, for which there is mounting evidence of greater health effects than were recognized even a decade ago.[15] These local pollutants have disproportionately

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[15] See the U.S. Environmental Protection Agency's Integrated Science Assessment for Particulate Matter (Final Report, Dec 2019), https://cfpub.epa.gov/ncea/isa/recordisplay.cfm?deid=347534.

harmed disadvantaged communities. For years, economic analyses have often attributed that disproportionate impact to a differential willingness to pay for environmental amenities as a function of wealth. Recent work, however, shows that the cause goes beyond wealth differentials, and includes lack of political power and racial bias (Hamilton 1995; Mohai, Pellow, and Roberts 2009; Hausman and Stolper 2020).

There are a variety of ways that the transition to zero-emissions energy supply might be managed inequitably or prolong the impact of past inequities. One potential mechanism for disproportionate impact is the selection of which fossil fuel–powered installations close early versus later during the transition to zero-emission sources. Broad incentive programs for zero-carbon power, like carbon taxes or clean energy standards, may not discriminate between facilities that emit high versus low levels of local pollutants, or facilities that are near to or far from vulnerable populations. Thus, there is a risk of disproportionate impact if broad, zero-carbon incentive policies fail to reduce emissions from sources of local pollution that are concentrated in "hotspots" near disadvantaged communities. A related concern is that if CCS is a significant mechanism for achieving zero emissions, then plants that continue to burn fossil fuels might still emit local pollutants, even if the carbon is captured.

Evidence from research on emissions markets to date suggests that these markets have not increased disadvantaged communities' relative exposure to local pollution. Hernandez-Cortes and Meng (2021) studies California's CO_2 cap-and-trade program using detailed facility-level emissions data from 2008 to 2017, spanning the start of the program in 2013. The paper finds that while local pollution disparities were increasing prior to 2013, they have been decreasing since that time, in a way that appears causally attributable to the CO_2 cap-and-trade program. In related work, Shapiro and Walker (2021) studies markets for local air pollution, using data in California and Texas, and finds that these markets neither increase nor decrease disparities in pollution exposure. While recent experience with pollution markets is therefore reassuring, it remains true that the U.S. does not have experience with CO_2 emissions markets at a scale sufficient to reach (or at least draw near to) zero-carbon emissions. The possibility that such a transition may lead to unjust exposure to local pollutants therefore remains a concern.

Finally, inequities can also arise through the siting of new energy infrastructure. Even renewable generation can have adverse impacts on nearby population and property values (Jarvis 2021). History suggests that disadvantaged communities and communities of color are particularly vulnerable because they lack the resources and political influence to fight for fair compensation for these impacts. Energy infrastructure policy should not repeat the mistakes of 20th century highway policies, which displaced and divided low-income urban communities (Rose and Mohl 2012).

3.e. Stranded infrastructure, decommissioning, and human capital

Displacement of oil and gas capital with zero-emission energy infrastructure will also lead to stranded assets. Abandoned wells are already a problem in the upstream extraction industry even in the absence of large-scale climate policies. The U.S. Environmental Protection Agency (EPA) estimates that there are at least 3.6 million abandoned wells in the U.S., two-thirds of which are unplugged and potentially leaking methane (a potent GHG) and other chemicals that endanger the local environment and human health (EPA 2021; Raimi *et al.* 2021). Aggressive climate policies are likely to exacerbate these problems and spread them to the transportation, refining, and distribution sectors. Furthermore, just as with the operational infrastructure discussed in the previous subsection, this stranded infrastructure is located disproportionately near disadvantaged communities.

These stranded assets present multiple challenges. First, if the last known owner of an abandoned well is insolvent or unknown, the well is then considered to be “orphaned.” In this case, the cost of decommissioning the well must be borne by the public. Recent counts have documented 56,600 orphaned wells in the U.S., but the number of undocumented orphaned wells is likely an order of magnitude larger (IOGCC 2019; Raimi, Nerurkar, and Bordoff 2020).

Second, stranded assets include not just physical capital but also human capital. Much of the oil and gas industry workforce is heavily invested in specialized skills. Abrupt economic transitions are known to impose severe burdens on affected workers (Walker 2013), and there is no reason to believe the transition to a green economy will be different. A plan for green infrastructure investment will therefore need to include provisions for maintaining the employment of these workers' skills, both for their own sake and to blunt political opposition to zero-emission policies.

3.f. Grid and supply chain security

We recognize here two other areas of concern, though we don't delve further into them. The first, grid security, would require a paper unto itself best written by a security specialist. The grid is vulnerable to both physical and cyber attacks, much like the vulnerability of hydrocarbon transportation systems demonstrated by the May 2021 Colonial Pipeline system ransomware attack. As with grid reliability more generally, security threats to the grid pose a greater risk as society becomes more dependent on electricity and less diversified in energy delivery modes. While there are compelling arguments for “electrify everything,” it is worth recognizing that such a strategy comes with a need for greater grid security investment. Grid security risks also potentially increase the value of distributed generation paired with storage.

The second area is developing and securing the materials supply chain for grid-related hardware. Currently, this issue is discussed most in relation to critical metals and minerals for battery production, but concerns are also raised in relation to solar PV and the electronic components of wind turbines, transformers, and other grid hardware. Many of the necessary materials have only been produced in limited quantities, and there is incomplete knowledge of the available reserves for massively scaling up supply. For some materials, the known supply is mainly in countries that are insecure – such as the Democratic Republic of the Congo, where most of the world's known cobalt reserves are located – or in countries that can be described as having an adversarial relationship with the U.S. in at least some respects – such as the many rare earth minerals for which China is the primary supplier.

3.g. Decarbonizing the world

In 2018, the U.S. was responsible for 15% of worldwide CO_2 emissions, down from 24% at the turn of the 21st century.[16] The U.S. share of emissions is likely to continue falling, due in part to U.S. emission reductions but primarily to increases in emissions from other countries whose incomes are increasing rapidly. In the next few decades, much of the world's population will be coming out of extreme poverty and increasing their energy consumption for industrial production, commercial activities, homes, and transportation (Wolfram, Shelef, and Gertler 2012). If they do not have a low-carbon pathway for growth, they will almost certainly pursue high-carbon pathways that are available, just as was done by what are now the richest countries in the world. Climate change is a global challenge, so every domestic policy to address it must be also be evaluated for its global impact.

4. Implications for infrastructure policy

The challenges facing the energy industry make clear that there will be a need for substantial infrastructure investment this decade and beyond. Broad clean energy incentive policies that effectively put a price on GHGs would boost the energy sector's pivot to a more sustainable path, but as we discuss below there are multiple reasons that other tools will be needed as well in order to meet the challenges we have outlined.

4.a. Low-carbon technologies

The advantages that fossil fuels possess in their low private costs, energy density, transmissibility, and storability make it difficult for zero-emission energy sources to compete with these fuels in energy markets. Absent strong policies, energy markets on their own do not penalize fossil fuels for their emissions. Nor, conversely, do they reward clean energy sources.

A cornerstone of energy infrastructure policy then needs to include significant, broad incentives for zero-emissions infrastructure. These incentives can come from carbon pricing, clean energy standards (with tradable credits), clean energy subsidies, or some combination of these policies. To be maximally cost-effective, these policies should broadly include all zero-emission sources, including generation from sources like nuclear, hydro, and fossil-fueled power with CCS that

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[16] https://ourworldindata.org/co2-emissions.

have often been excluded from state-level renewable portfolio standards. In addition, the tradeable credits associated with a clean energy standard should be freely tradeable across state lines, in order to best direct clean energy investment to regions where renewable resources are abundant.

Yet even if the federal government were to adopt a robust clean energy standard or a carbon price equal to the full social cost of GHG emissions, standard economics, equity considerations, and institutional constraints all still suggest that other government action will be important in the pursuit of a low-carbon economy. These actions will be even more needed and valuable if a significant carbon price, clean energy standard, or low-carbon subsidy is not established.

Invest in research and development

Probably the most important reason for additional government action is that rapid innovation across many technologies will be necessary to avoid the worst impacts of climate change, and markets for innovation do not function well. This failure in innovation or knowledge markets occurs because knowledge producers are able to capture only a tiny fraction of the value they create. Thus, without government policies, the incentive to create new knowledge is suboptimal.

The inability of innovators to fully capture the value of their innovations is the fundamental justification for intellectual property protection, such as patents and copyrights. However, such mechanisms create monopolies and legal processes that inhibit use of new knowledge. In other sectors, such as medicine and basic science, knowledge creation is supported directly by the government to a much greater extent than in energy, and the norm is to make some of that knowledge freely available through academic journals.[17]

Climate change, however, creates even more of an imperative for uninhibited knowledge sharing than in other sectors, particularly sharing with the developing world. This argument follows in part from the ethical consideration that most of the GHGs in the atmosphere today were put there by what are now wealthier nations. But wealthy countries also have a self-serving incentive to share low-carbon technologies in order to avoid having nations now coming out of poverty ramp up their growth through intensified use of fossil fuels, because emissions from that pathway will create spillover damages to the wealthier countries. Sadly, the current pandemic is a close analog, creating large private benefits to wealthier nations from sharing vaccine knowledge with poorer nations in return for little or no compensation. This knowledge market failure exists quite apart from appropriate GHG pricing in the U.S. or in all advanced economies. Direct investment in research, development, and deployment of new technologies can create appropriate incentives to innovate in GHG-reducing technologies without creating barriers to worldwide diffusion of those technologies.[18]

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[17] See Table 2 in https://ncses.nsf.gov/pubs/nsf21315#data-tables.

[18] We include deployment in this discussion of knowledge market spillovers because competitors gain immense information value from the success or failure of another firm's attempt at innovation. In the recent past of the energy

Promote charging infrastructure

With transportation electrification playing a major role in virtually every strategy for deep decarbonization, there will be a need for widespread investment in electric vehicle (EV) charging infrastructure, including the electrical distribution system upgrades needed to support the service. Overcoming the network economics challenge of rapidly growing both EVs and EV charging infrastructure is important, but there is still great uncertainty about the best technologies, locations, and business models for EV charging. This uncertainty suggests the need for a flexible approach to government support – such as incorporating energy use for personal transportation into broad clean energy standards or carbon pricing – while leaving EV charger siting decisions and business model experimentation to private firms.

One important area for policy to play a hands-on role in facilitating EV adoption is in harmonizing and enforcing standards for high-speed ("level 3") charging stations. At present, there are three standards for level 3 chargers, and vehicles built to one standard cannot be charged at a station built for a different standard. Li (2019) shows that, since drivers' willingness to adopt EVs depends on the availability of charging, harmonizing standards (or at least requiring charging stations to have adapters) can substantially increase take up of EVs.

Support technology for dynamic demand response

As the country expands the range of energy services powered by electricity, it also has an opportunity to expand the array of devices that can time-shift electricity demand and help to integrate intermittent renewables on the grid. Electric hot water heaters and vehicles likely offer the greatest residential and commercial opportunities for automated demand shifting, which can be enabled with low-cost communicating technologies. Similar technologies have been shown to be effective in shifting electricity demand for space heating/cooling and refrigeration as well (Callaway 2009). Industrial demand also offers demand response potential, which tends to be more specific to the industrial process, but could be equally or more valuable. Efficient dynamic price signals will provide incentives for all customers to adjust their demand in ways that help balance a system with large quantities of intermittent supply.

Simplify regulatory pathways for long-distance interstate transmission

Finally, a massive expansion of long-distance electricity transmission is likely to be a key factor in attaining deep decarbonization at reasonable cost. Government incentives to support transmission that enhances grid access for zero-carbon generation would obviously help drive this expansion, but more important will be policies that simplify – and give investors greater clarity and certainty about – the processes for building these facilities.

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industry, examples of valuable information from failures include attempts to build new conventional nuclear power plants in Georgia and South Carolina that resulted in cancellation or massive cost overruns and a number of carbon capture and sequestration facilities that have been canceled before completion. On the positive side, solar panel manufacturers have greatly benefited from learning about process improvements of their competitors, and battery manufacturers are able to extract valuable information from the chemistry of competitors' products without violating intellectual property laws.

Currently, investors seeking to build interstate transmission lines must obtain permission from each state through which the line passes, providing multiple opportunities for incumbent interests to extract rents or exercise veto power. This tortuous regulatory pathway contrasts sharply with that for natural gas pipelines, where FERC is the central certification authority for rights-of-way and use of eminent domain. As discussed at greater length in Cicala (2021), a statute that gives FERC this same authority for interstate transmission (along with institutional capacity with which to execute that authority) would provide a much-needed clear regulatory pathway for transmission investors. In addition, conflicts with local governments and landowners can be minimized by developing a regulatory process that endeavors to use existing public infrastructure rights-of-way – such as railroads, highways, and pipelines – to the maximum extent possible.

4.b. Wholesale market design

The challenges facing wholesale electricity markets reflect the complexity of operating an electricity grid and the uncertainty about how to meet the goals of clean, safe, reliable, and affordable operations as intermittent renewable generation becomes a larger share of the total energy market. It is not possible to predict how specific generation and storage technologies will progress, so it is important to design markets and policies to reward capabilities and performance that help meet these goals.

One implication of these challenges is the need for greater awareness of the impact of subsidizing wind and solar on wholesale market outcomes, an impact that will grow as wind and solar become a larger share of the market. More broadly, these market design challenges argue for supporting research not just on the science and engineering of new electricity resources, but also on the business, economics, and engineering of designing markets that allow the resources to work together efficiently, as well as on how firms will respond, for good or bad, to the incentives created by various market designs.

For instance, Mansur and White (2012) and Cicala (forthcoming) study reforms to wholesale market design in some parts of the U.S. that transformed systems of decentralized, bilateral power trades to highly organized and centralized wholesale auctions. Both papers demonstrate that these reforms substantially increased inter-regional trade and reduced generation costs by promoting the efficient dispatch of relatively low-cost generation units. This work suggests that geographic expansion of such reforms can help promote the dispatch of renewable generation (which has nearly zero marginal generation cost once installed) while increasing the transparency of price incentives that guide investment in new generation and transmission infrastructure.

The February 2021 electricity crisis in Texas also highlights the need for wholesale market designs to address the challenges that extreme weather events pose for grid reliability. These challenges will only become more acute over time as climate change increases the frequency, duration, and severity of extreme temperatures and storms. The Texas disaster demonstrated that even very large financial incentives for energy production were insufficient to compel the electricity supply chain to deliver power during critical conditions.

The challenges that extreme weather events pose to grid reliability are in some ways similar to the challenges that systemic risk poses to financial markets. During these events – and as occurred in Texas – suppliers that fail to perform can avoid the full costs of non-performance through insolvency. This judgment-proof problem dampens incentives to take steps in advance, such as weatherization, that help ensure performance during critical events. Non-performance can cascade through the system physically as discussed in section 2. In addition, non-performance and insolvency can cascade financially via the contracts that link utilities, retailers, generators, and fuel (especially natural gas) providers. For instance, non-performance by a natural gas supplier can then lead to non-performance by generators dependent on that gas. Those generators then must, in order to fulfill their contracts with utilities and retailers, purchase large volumes of extraordinarily expensive electricity on the spot market, leading to their insolvency (and possibly the insolvency of the non-performing gas supplier as well).

The problem of ensuring reliability in the face of these challenges is daunting. And much like the problem of ensuring financial stability, the ideal solution is far from clear. One route is to increase the use of direct regulations such as weatherization standards. Such approaches can be valuable, though they run the risk of "responding to the last crisis" rather than being forward-looking, and they require dedicated enforcement by government agencies. Another approach would be to require financial assurance for performance during critical events. Such assurance could be provided by diversified financial entities, who would have the ability to demand preventative steps (such as weatherization) as a condition of underwriting performance contracts.

4.c. Sustainable retail pricing and distributed energy resources

As discussed in section 3, states (and many countries) that have pursued the most aggressive climate policies have financed them in large part by raising retail electricity prices such that those prices are now greater than social marginal cost. These high prices discourage electrification, create perverse incentives for BTM generation and storage, and disproportionately burden low-income customers. These problems have a number of implications for infrastructure policy.

First, policy evaluations and support for investment in BTM resources should be based on the true avoided social marginal cost of that BTM generation in the long-run decarbonization plan, not on retail price nor on counterfactuals premised on historical fossil fuel generation. Going forward, BTM generation and storage will be substituting primarily for grid-scale low- and zero-carbon resources, and for storage technologies that benefit from scale economies. BTM generation and storage has characteristics that still give it value – such as enhanced customer resilience, avoided land use disputes, and potential for reduced demands on transmission and distribution networks. Those factors must be weighed against the higher cost per kilowatt-hour of energy delivered. Retail pricing that reflects social marginal cost is a powerful tool with which to incorporate these tradeoffs into households' and firms' decision-making.

Second, any electricity revenues collected above social marginal cost should be seen as a distortionary tax, just as taxes on labor, capital, and consumer goods are distortionary. In the case of the states leading on climate change, the electricity tax raises the prices to two or more times the social marginal cost, a far larger gap than is seen in most other sectors of the economy. One justification for this pricing has been that electricity demand is highly inelastic, so the deadweight loss from this tax has still been small. However, as customers are now more able to substitute among fuels for many of their energy services – electricity versus gasoline for vehicles and electricity versus natural gas for space and hot water heating – and as they now have more options for BTM generation and storage, the inefficiency from these distorted prices is growing.

Third, this electricity tax should also be recognized to be highly regressive. In California, the location of about half of the country's residential BTM solar capacity, *net* electricity consumption (after adjusting for BTM generation) of residential customers in the wealthiest quintile of census block groups is now only slightly higher than for poorer areas. Nearly any other funding source, including sales taxes and gasoline taxes, would be more progressive than this electricity tax. Fixed monthly charges that are indexed to income may be part of the solution, but there isn't an equivalent charge for commercial and industrial customers, which consume 62% of all electricity.[19]

Many costs similar to those covered by the electricity tax in the energy sector are paid from state or federal budgets in other sectors. Food and healthcare subsidies for low-income families are typically government budget items, but electricity subsidies for the poor come from electricity prices. Climate adaptation, such as sea walls, road and bridge reinforcement, and forest management, are paid primarily from local, state, and federal budgets. Yet adapting transmission and distribution infrastructure, as well as greatly expanding utility vegetation management, is currently financed from electricity prices.

Covering the costs of infrastructure, climate mitigation, and climate adaptation policies through funding mechanisms that do not rely on retail electricity pricing should be a priority. Direct government support for policies that will otherwise raise volumetric electricity rates – including energy efficiency programs, early investment in new low-carbon energy technologies, and climate mitigation and adaptation programs, among others – can mitigate excessive electricity rates in areas that have invested in clean energy and encourage such investment in areas that have not.

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[19] https://www.eia.gov/electricity/monthly/epm_table_grapher.php?t=table_5_01.

4.d. Energy infrastructure and equity

Policies that incentivize zero-emission energy infrastructure must also be accompanied by policies that guard against the possibility of local pollution “hotspots” during the transition. One model for doing so might be California, which passed legislation (Assembly Bill 617) in 2017 that augmented its CO_2 market with policies to address the needs of communities affected by local pollution. Fowlie, Walker, and Wooley (2020) discusses how this legislation responded to communities' frustrations with California's carbon policies, largely by empowering community organizations with enhanced monitoring capabilities and authority to address local pollution problems. Fowlie, Walker, and Wooley (2020) concludes that, while it is still too early to definitively evaluate this program, California's community driven approach to local pollution could be a useful model for a complement to federal climate policies.

Transportation electrification, particularly if it can substitute for diesel engines in heavy trucks and rail locomotives, can also contribute to reducing local pollution in populated areas. Public funding of research and development can help lower technological hurdles to electrification of heavy transportation.

Distributive and procedural justice must also be a consideration for the siting of new, zero-emissions energy infrastructure. The federal transmission siting authority that we argue for in section 4.a. above cannot be a blank check for use of eminent domain to condemn the land of disadvantaged households. Instead, and as argued by Cicala (2021), new transmission infrastructure should primarily leverage existing rights-of-way, with judicious use of eminent domain as a last resort option.

4.e. Stranded infrastructure, decommissioning, and human capital

When energy infrastructure reaches the end of its useful life, it can present environmental hazards if not decommissioned properly. Orphaned oil and gas wells are perhaps the most prominent example of improperly decommissioned infrastructure that then becomes a burden to the public. But zero-emissions infrastructure can present environmental hazards as well. Batteries, for instance, contain toxic compounds. Investment in energy infrastructure must therefore be accompanied by policies that provide assurance that decommissioning will occur.

Liability rules alone are insufficient to assure decommissioning due to what is known as the “judgment-proof” problem (Shavell 1986, 2002). If the owner of an asset at the end of its life is highly leveraged, it will be able to avoid decommissioning liabilities via bankruptcy.

One way to address the judgment-proof problem is to require firms to post a decommissioning bond at the time of investment. Bonding policies only work, however, to the extent that the bond amounts are commensurate with decommissioning costs. For oil and gas wells, state and federal bond requirements are often well below estimated decommissioning costs, leading directly to the widespread existence of orphaned wells (Boomhower 2019; GAO 2019).

Evidence from oil and gas bonding reforms in Texas shows that increased bond amounts can reduce orphaned wells and environmental incidents, primarily by encouraging small, poorly capitalized firms to divest their assets to better-capitalized entities (Boomhower 2019). Such reforms must become more widespread in order to end the proliferation of orphaned wells in the U.S. Moreover, adequate bonding requirements need to be imposed on new energy infrastructure development in order to save public funds from being saddled with decommissioning expenses for future abandoned assets.

Improvements in bonding policy cannot, however, remedy the sins of past policy inadequacy. The environmental hazards presented by the current stock of orphaned wells can only be addressed by direct public investment in their decommissioning. The decommissioning of all of these wells – including restoration of their surroundings – is likely to cost more than $10 billion (Raimi *et al.* 2020; Raimi, Krupnick, Shah, and Thompson 2021).

A silver lining to this necessary expenditure is that it provides an opportunity to employ oil and gas workers who would otherwise be displaced by the transition to zero-emission energy infrastructure. Raimi *et al.* (2020) estimates that decommissioning the full inventory of orphaned wells would require 100,000 person-years of labor. The natural source of such labor would be displaced oil and gas workers, whose skills would naturally transfer to well decommissioning work.

Even putting aside the inherent value of eliminating the health and environmental threats posed by orphaned wells, providing opportunities to displaced oil and gas workers conveys benefits of its own. Well decommissioning would employ a valuable stock of human expertise that would otherwise depreciate away were these workers to move to another sector or drop out of the labor force. These job opportunities may also soften political opposition to the zero-emission energy transition, and from a distributive justice perspective help reduce inequitable impacts of green infrastructure policies.

Well decommissioning on its own is not going to be a long-run solution to displacement of oil and gas workers, whose workforce has numbered around 400,000 people over the past several years (Raimi *et al.* 2020). Nonetheless, it could at least serve as a temporary bridge to future employment opportunities, including opportunities in hydrogen, geothermal energy, offshore wind, and carbon sequestration, that could play a role in a zero-carbon economy.

4.f. Grid and supply chain security

We are not in a position to offer specific guidance on investments to address grid security or supply chain security. We will note, however, that both are areas with immense spillovers beyond the organizations that are directly affected by security failures. The Texas crisis of February 2021 demonstrated the cascading economic and health impacts when the grid fails to deliver extremely high reliability. If decarbonization makes electricity more dominant in energy supply, any vulnerabilities become more of a threat to society. Supply chain security presents less risk of a short-term acute crisis than does grid security. But it conveys serious risk of stalling long-term progress on energy goals, with implications beyond the firms directly involved in the supply chain.

4.g. Decarbonizing the world

Recognizing that the only GHG reduction goal that really matters is the global one has implications that are often lost in the U.S. energy and climate debate. Every proposed investment should be judged on how it could scale to reduce global emissions and on the knowledge that can be gained and applied globally. One immediate implication is that independent *ex post* evaluation is central to the value of U.S. energy infrastructure policies and investments that address climate change. To make such evaluation possible, programs should be designed at the front end in ways that maximize the reliability of evaluation at the back end.

Unfortunately, it now also seems possible that the world will not meet the challenge of reducing greenhouse gas emissions as quickly or effectively as necessary to avert extreme temperature changes and other catastrophic consequences. Though carbon dioxide removal and solar radiation modification in some ways lie outside the area of energy infrastructure, it is necessary to also note the high potential returns to investments in RD&D in these technologies (Keith and Deutch 2020).

5. Conclusion

The defining energy challenge of the 21st century is to transition the provision of energy services to zero-emissions sources, while simultaneously controlling costs and ensuring the reliability of energy supply. This transition will require historic investments in zero-emissions energy generation, transmission, storage, and distribution infrastructure. Federal policy choices will play a leading role in determining whether, where, and when these investments will occur, how costly they will be, and who will bear those costs.

The zero-emissions technologies that have thus far become cost competitive at scale are wind and solar PV. However, the intermittent nature of generation from these resources will present ever greater challenges to grid reliability as their share of generation capacity increases. Investment in technologies such as long-distance transmission, battery storage, hydrogen, nuclear, geothermal, or carbon capture and sequestration will be needed to ensure reliable, on-demand energy services.

Because the rate of future technological advances is uncertain, it is difficult to know in advance which combination of technologies will provide the lowest-cost solution. One way to avoid over-investment of public funds into technologies that ultimately fail is to employ policies – such as carbon prices, clean energy standards, or clean energy subsidies – that provide broad incentives for zero-emissions energy supply without discriminating across different technologies.

Broad incentive policies should therefore be a core component of energy infrastructure policy, but on their own they will leave unsolved a variety of challenges and market failures. Some of these challenges concern investment barriers that cannot be surmounted by investment incentives alone, and others concern ensuring that the benefits and costs of the clean energy transition are shared equitably. We therefore advocate that energy infrastructure policy include a number of features in addition to broad clean energy production incentives:

- ***Invest in research, development, and early-stage deployment of novel technologies.*** The climate challenge is a global challenge, and an essential way to encourage other nations to reduce their own emissions will be to develop low-cost zero-emissions technologies and then export those technologies around the globe.

- ***Improve the design and price transparency of wholesale power markets.*** Improvements in wholesale market design can help accommodate increased use of intermittent generation resources and ensure reliability in the face of increased climate-driven demand and supply uncertainty. Possibilities include increased use of wholesale power auctions to improve price transparency and facilitate inter-regional trade, development of mechanisms to compensate resources that can change output rapidly on demand, and implementation of more targeted reliability regulations to guard against the risk of system-wide failures.

- ***Enhance federal authority over long-distance transmission siting.*** Construction of long-distance transmission is currently hobbled by multi-jurisdictional control over approvals. Significant new investments will require centralized federal authority, like that which currently exists for natural gas pipeline construction.

- ***Reform retail electricity rates to more accurately reflect society's full marginal cost.*** In many parts of the country, the current practice of relying on volumetric charges to recover the costs of climate response, fixed infrastructure, and other public purpose programs discourages electrification, distorts end-user investment incentives, and disproportionately burdens lower-income households. Covering many of these costs through state and local budgets would be more efficient and equitable. Retail rates in these locations could also make greater use of fixed connection charges, particularly by making them income-based.

- ***Address local pollution and involve local communities.*** During the transition, policies on local pollutants must ensure that disadvantaged communities are not disproportionately affected by pollution from fossil fuel power plants, industrial facilities, and homes that are slow to switch to alternative fuels or shut down. Local communities should be empowered to play a role in local pollution monitoring and enforcement.

- ***Ensure funding for infrastructure decommissioning.***
  Infrastructure inevitably depreciates and must be decommissioned. Authorizing agencies should require that new investments be accompanied by bonds that ensure that future decommissioning costs are covered. And to address the orphaned wells problem – a consequence of insufficient bonding requirements in the past – public funds can cover the required decommissioning while simultaneously providing employment opportunities to oil and gas workers who are displaced by the clean energy transition.

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