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Building the Energy Infrastructure Necessary for Deep Decarbonization throughout the United States

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Building the energy infrastructure necessary for deep decarbonization throughout the United States

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Abstract

The world must rapidly shift to clean energy sources in order to avoid causing additional, catastrophic damage to the climate. While there are many fierce debates about the nature, speed, and cost of the necessary energy transition, there is also fairly good agreement about *what* needs to be built to enable deep decarbonization throughout the United States. Based on this agreement, this paper therefore focuses on *how* and *where* the energy infrastructure necessary for deep decarbonization should be built. This paper first examines interactions between the private and public sectors in the building of past energy infrastructure systems, such as fossil fuel resources, large-scale hydropower, and the electric grid. This paper then examines past and present infrastructure policies in order to consider how local and regional capacity to build, operate, and maintain infrastructure can be better aligned with national-level goals. Finally, in order to analyze where this new infrastructure should be built, this paper identifies distinct regions for further proposals and study using a mapping layer analysis of existing fossil fuel infrastructure, renewable energy potential, and present and future climate risks. The paper concludes with a summary and synthesis of key findings.

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1 Introduction

The effects of a changing climate are already apparent and accelerating all over the United States.[1] Rising average temperatures, shifts in climate and species, along with intensifying extreme weather events are now readily apparent in all regions and to the general public. For example, in the past year alone, there has been flooding in the Midwest, hurricanes in Texas and Florida, drought and wildfires in the West, and extreme cold in the Northeast. The increased frequency and severity of these events is now directly attributable to human-caused climate change. Public opinion about climate change in the United States and other countries is also rapidly changing, with concern reaching all-time highs.[2] Despite rapid growth in wind and solar energy sources, however, many forecasts predict that clean energy is not yet growing rapidly enough to keep up with growing global energy demand and to replace existing fossil fuels.[3] In order to avoid causing additional, catastrophic damage to the climate, the U.S. and other countries must embark on a rapid and comprehensive effort to reduce or eliminate almost all, if not all of their net carbon emissions by mid-century, a goal generally referred to as "deep decarbonization".

Many researchers are engaged in a number of fierce debates over different pathways to deep decarbonization, including which policies, priorities, speed, targets, and costs might be required to meet this goal.[4] However, on a broad scale, there is also broad agreement that deep decarbonization will require both (1) continued, rapid growth in clean energy sources to several times larger than our current clean energy sources, and (2) reductions in total primary energy consumption through more efficient energy use and processes.[5] Let us repeat this point for emphasis because it provides the motivation for this paper: deep decarbonization can only occur if we reduce our energy consumption roughly by half through more efficient use, and if we replace the remaining half with new clean energy sources. Action to reduce consumption and increase renewable energy sources are both necessary.

Based on this general agreement, this paper then addresses two interconnected and geographic issues raised by deep decarbonization: *how* and *where* should we build the necessary infrastructure throughout the U.S.? Improvement of infrastructure has long been understood to be fundamental to the project of American nation-building, and despite a remarkably heterogeneous population, physical environment, social attitudes, and economic activity spread over a large land area, the U.S. was able to build large, visionary infrastructure projects both domestically and abroad in the 19th and 20th centuries, such as the Erie Canal, transcontinental railroads, land grant colleges, the Panama Canal, the electric grid, and the interstate highway system.[6] But so far in the 21st century, the U.S. has not been able to build new infrastructure or even adequately maintain its existing infrastructure.

The key questions of *how* and *where* must be answered together, because a recurring theme in U.S. infrastructure – as well as politics and history – is that different regions

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[1] United States Global Climate Research Program {USGCRP} (2018).

[2] Fagan and Huang (2019); Funk and Kennedy (2019); Saad (2019); Aton (2019).

[3] {International Energy Agency} (2019).

[4] Bataille et al. (2016); Maize (2017); Williams et al. (2015).

[5] In terms of technology, nuclear power, agricultural sequestration, carbon capture and storage, and geoengineering are areas of disagreement. Policies, costs, and political strategy are much more contentious.

[6] Rohatyn (2009); Clarke and Pears (2019).

can act together towards common goals but will often participate differently. For example, like other countries with a federal system of government, the U.S. delegates significant responsibility to local and state governments to build, operate, and maintain much of its infrastructure, which shapes how policies are implemented. Furthermore, for a deep decarbonization pathway comprised one-half of new renewables and one-half of changes in energy use, each half will have very different geographic implications because resources and uses follow different drivers: renewable resources will follow resource potential, which is geologically determined; changes in uses and processes tend to follow population and industry, respectively; and energy transmission and carrying systems are needed to connect them.

Therefore, in order to address the *how* question, this paper examines our existing infrastructure systems in three steps. First, we simply describe the development of large energy infrastructure systems, including fossil fuel resources, large-scale hydropower, and the electric grid. Second, we then examine specific policies and mechanisms that were used to align local investments in infrastructure in the past with national goals and emergencies. The third and last step is to use these historical descriptions of infrastructure systems and policies in order to evaluate prospective new policy mechanisms towards deep decarbonization.

Then, in order to address the *where* question, this paper uses maps to analyze how three key drivers for existing and future infrastructure are distributed across the U.S., including:

1. existing fossil fuel infrastructure, that must either be replaced or upgraded;
2. renewable and clean resource potential; and
3. future climate adaptation risks.

Section 2 describes what kind of infrastructure changes will be needed to achieve deep decarbonization. Section 3 describes the historical development of key energy infrastructure systems, Section 4 examines the policies that resulted in these systems, Section 5 analyzes prospective mechanisms and policies for deep decarbonization, and Section 6 presents a mapping analysis for existing and future infrastructure. The paper concludes in Section 7 with a summary and synthesis of the findings.

2 Needs for deep decarbonization

The U.S.'s existing infrastructure locks in future fossil fuel use, which will lead to higher temperatures and more severe climate change effects. In order to avoid further catastrophe, drastic changes in infrastructure are necessary in many sectors, including but not limited to electric power, industry, transportation, and buildings.[7] Researchers have therefore proposed and debated multiple possible pathways for each of these sectors to achieve deep decarbonization. This section synthesizes across these studies to identify common infrastructures and technologies among these proposals in order to consider how and where they should be built.

We limited our examination of deep decarbonization scenarios to four comprehensive reports that were economy-wide and focused on the U.S.: {White House} (2016), Williams et al. (2015), {IHS Markit} et al. (2019), and Lempert et al. (2019). All four of these studies on deep decarbonization agree on the four key areas of needed changes, including:

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[7] Tong et al. (2019).

1. New renewable resources: a many-multiple growth in renewable resources is needed, including solar technologies (both photovoltaic and thermal) as well as wind (both on- and off-shore). The location of new renewable resources is often geologically determined by existing resource potential, the proximity of users, or infrastructure systems that can connect the two.
2. Decarbonized fuels: fuels enable energy to be stored and transported, but existing fossil fuel infrastructure will only be viable if the fuels come from low- or zero-carbon sources, either through carbon-free fuels that can be used in existing systems (so-called 'drop-in' fuels); or if greenhouse gas emissions can be captured, used, and stored at the point of combustion; or if greenhouse gases can be captured directly from the air.
3. Transmission and carriers: electricity and hydrogen are expected to serve as carrying media for clean energy, but need much more development of transmission and storage networks at national, regional, and local scales. In order to enable the use of intermittent renewable resources across seasons, new and expanded means of storing energy as mechanical, thermal, chemical and potential energy also need to be developed.
4. Use changes: fundamental changes are needed in key use sectors such as buildings, industry, and transportation. Changes in these sectors all require increased end-use efficiency, switching to electricity or other decarbonized fuels, and fundamental process or system changes to eliminate upstream carbon emissions. The location of energy uses are likely to follow existing patterns of population and economic activity.

3 Development of existing energy systems

This section attempts to summarize succinctly the sprawling history of the major existing infrastructure systems in the United States, in order to illustrate how the geography of resources affected their future use and development, in order to understand how deep decarbonization might unfold. We consider infrastructure systems generally in three categories: fossil fuels; large-scale hydropower; and energy transmission and distribution. In each category, the development of existing systems are presented in historical order, but after inception, each of these infrastructure systems clearly co-evolved over time by developing interdependencies, competing with, and/or succeeding one another. Within each category, we analyze and emphasize four key themes:

- the geographic dispersion or concentration of key resources and systems within the U.S.;
- the development of U.S. firms, technology, and infrastructure compared to other countries;
- the role of the public and private sectors and how they interacted; and
- laws and authority developed by states and governments to govern infrastructure systems.

3.1 Fossil fuel resources

The development of past and current energy resources such as coal, oil, and natural gas were all led by the private sector. In this section we examine how geological concentration of particular energy resources affected the subsequent geographic development of infrastructure systems in the U.S.

The U.S. coal industry was first concentrated in Pennsylvania in the late 19th century, initially for pig iron and later for steel manufacture.[8] Coal rapidly became the U.S.'s primary fuel source for heating, industrial uses, and electricity generation for much of the 20th century. Most coal was produced east of the Mississippi until the 1950's in four states (West Virginia, Kentucky, Illinois, and Pennsylvania) and three major basins (Illinois, Central Appalachia, and Northern Appalachia).[9] In recent years, the Powder River basin in Wyoming has produced more than 40% of all U.S. coal, though production there is now declining even faster than all U.S. coal production, which in sum is at its lowest level in 39 years.[10]

Coal is still quite plentiful globally, so the U.S. competes in a global market for coal, though there are many different types and grades. Coal reserves are subject to U.S. mining laws, and is typically transported by train. Coal was used for much of the 20th century for industry and electricity generation, although it has rapidly been displaced in recent years by cheaper and cleaner natural gas, and many coal companies have gone bankrupt.[11]

Oil production also began in the 19th century, and was globally dominated by commercial firms in the U.S., Russia, and Romania. The first commercial oil operation began in Pennsylvania in 1859, with many independent oil producers quickly springing up in western Pennsylvania which became known as 'the Oil Regions'.[12] Only five years after the first commercial operation, however, John D. Rockefeller bought sole ownership of an oil refinery, built and acquired more critical assets, and began a process of vertical integration and industry consolidation to create one of the most dominant monopolies of all time, Standard Oil. By 1879, within three decades of the beginning of the industry, Standard Oil owned 90% of U.S. refining capacity, along with key pipelines and transportation systems that were needed to move oil products from the Oil Regions to the rest of the country and world, resulting in Standard Oil also having 90% of U.S. kerosene exports.[13] To put Standard Oil's dominance in perspective, ExxonMobil, Marathon Petroleum, Amoco, and Chevron – still all among the largest oil companies in the world – are merely parts of the original Standard Oil empire.

Global demand for American oil and kerosene products played a critical role in the growth of the U.S. oil industry. Rapid industrialization, economic growth, and urbanization in Europe all led to rapidly growing demands for kerosene, an oil derivative used principally for lighting. Yergin (2012) writes:

> "Consider what the global demand meant. The substance for the most popular form of lighting worldwide was provided not merely by one country, but, for

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[8] Smil (2017).
[9] Wikipedia (2019a,b).
[10] {U.S. Energy Information Administration} (2019b).
[11] Stewart (2015); Krauss (2019).
[12] Smil (2003).
[13] Yergin (2012).

> the most part, by one state, Pennsylvania ... In the 1870s and 1880s, kerosene exports accounted for half of total American oil output. Kerosene was the fourth-largest U.S. export in value; the first among manufactured goods."[14]

By the end of the 19th century, global supply and demand for kerosene led to a worldwide rise in the oil industry, led by four main rivals: Standard Oil of the U.S., competing with companies in Europe led by the Rothschilds, Nobels, and other Russian producers. Despite efforts to divide up the world's production and export markets through corporate agreements, the rivals never were able to form a global cartel. The eventual rise of other companies such as Royal Dutch Shell in Asia, the Anglo-Persian Oil Company in the Middle East, and the Gulf Oil Company in Texas, led to the eventual development of a global oil market. Plentiful supply from the Middle East led to the U.S. importing oil for much of the 20th century, until shocked by the Arab oil embargo and the Organization of Petroleum Exporting Countries (OPEC) cartel in the 1970s.

For the last half of the 20th century, OPEC members and other major nationally-owned oil companies have been dominant oil producers, until the recent growth of independent shale oil producers in the U.S. over the past ten years. At present, production in the global oil industry is now dominated by countries with large nationally-owned oil companies and proven reserves such as Saudi Arabia (13.0%), Russia (12.1%), Iran (5.0%), and Iraq (4.9%), while multinational companies such as ExxonMobil, Shell, BP, and Chevron still retain considerable technical resources and expertise. As the result of independent oil producers and drilling for shale oil, by 2018 the U.S. had the largest proven oil reserves (16.2%).[15]

Until the 1950s, natural gas was little used compared to other hydrocarbons. Often found as a byproduct of oil drilling, it was often burned off ('flared') or pumped back into the ground to maintain pressure to extract more oil. Natural gas was initially so cheap that it was not worth building pipelines to move it around, but eventually became more useful as an industrial feedstock and primary energy source for petrochemical plants concentrated along the Gulf Coast of Texas. By 1969, natural gas was used to heat a substantial percentage of U.S. homes.[16]

Natural gas from fracking is a relatively new development in the U.S. Fracking techniques were developed by the oil industry in the mid-1950s and 1960s to recover more oil from existing wells that had stopped yielding. During the energy crisis in the 1970s, the federal government funded a program that sought to use atomic explosions to release gas from known shale formations called "Project Plowshares". More successfully, the federal government funded the Unconventional Gas Research Program in Morgantown, West Virginia – never for more than $30 million dollars a year – that developed the scientific basis of successful fracking for natural gas. After reading some of the resulting research, George Mitchell, founder of Mitchell Energy & Development, began fracking the Barnett Shale in Houston using water in the early 1980s.[17]

Since then, fracking for natural gas (and shale oil as described above) has become a disruptive technology that has spread across North America and the world, resulting in proven

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[14] Yergin (2012), page 56.

[15] {BP} (2019).

[16] McLean and Elkind (2003), page 1-2.

[17] Gold (2014).

natural gas and oil reserves steadily increasing in the U.S. at a rapid rate.[18] Major gas deposits are located throughout North America, notably in the Marcellus Shale in Pennsylvania; the Fayetteville Shale in Arkansas; the Niobrara Shale in Colorado and Wyoming; the Bakken Shale in North Dakota; and the Permian Basin, the Barnett Shale, and the Eagle Ford Shale in Texas.[19]

3.2 Large-scale hydropower

Many of the first hydropower plants generated electricity for cities and transmitted this power over relatively short distances. The first such plant was in Appleton, Wisconsin in 1882, followed by Portland, Oregon in 1889, and Pomona in 1892 and Sacramento in 1895, both in California. Hydroelectric projects rapidly grew larger in scope, such as in the installation of a hydropower facility at Niagara Falls in 1895, and by the City of Seattle on the Skagit River in 1904.[20]

The development of hydropower was largely initiated by the federal government, affecting subsequent development of both investor-owned utilities and publicly-owned power across the U.S. The Constitution gives the federal government jurisdiction over the navigable waters of the U.S. Subsequent legislation such as the 1902 Reclamation Act clarified the federal government's role in the production of hydroelectric power for irrigation in the arid West, and the 1909 Rivers and Harbors Act directed the Army Corps of Engineers to plan hydropower as part of waterway improvements.

The federal government experimented with hydroelectric power to produce munitions at Muscle Shoals on the Tennessee River in World War I, but rapidly accelerated progress in the 1920s and 1930s. Passage of the Federal Water Power Act in 1920, now Part I of the Federal Power Act, had the following results:

> "Among other things [the Act] created the Federal Power Commission and established as national policy the principle of federal regulation of non-federal water power projects to assist with the orderly development of the nation's water resources … Federal government entry into hydroelectric development accelerated with the 1928 Boulder Canyon Development Act, which authorized construction of the multipurpose Hoover Dam on the Colorado River … This was followed by the large multipurpose river developments initiated by various federal laws during the Depression. These included projects such as Grand Coulee and Bonneville dams on the Columbia, Shasta Dam in California, Fort Peck Dam on the Missouri, and the Tennessee Valley Authority developments."[21]

Many historians trace President Franklin Delano Roosevelt's interest in electric power to his time as governor of New York, when he dealt with private utilities that consistently charged more than public alternatives. FDR campaigned for president in 1932 with public power as one of his main issues, and when voted into office, authorized the Grand Coulee

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[18] {U.S. Energy Information Administration} (2019a).

[19] Gold (2014).

[20] Armstrong (1976), p. 346.

[21] Armstrong (1976), page 348-9.

Dam as part of the National Industrial Recovery Act in 1933.[22] The Tennessee Valley Authority (TVA) Act was subsequently passed in May 1933 to promote economic and social development through the provision of low-cost power, leading to much lower electric rates for cities that voted to buy and distribute TVA power, and stimulating rapid growth in demand for electricity and electrical appliances throughout the region.[23] TVA also helped in the organization of rural and farm cooperatives, and eventual buy-out of the private Tennessee Electric Power Company by TVA, twenty-two municipalities, and eleven rural cooperatives.

Historian Richard White views the New Deal era of hydropower development as a result of the social and ideological turmoil of the Great Depression, rather than a technological transformation; for example, as White notes of the Columbia River basin:

> "Faced with no actual demand for all that power, advocates of the dams rediscovered electricity as a means for transforming society. The Depression provided a society desperately seeking transformation ... The ultimate point of this work was a new society. In describing it, politicians and journalists reverted to frontier metaphors that summoned up nature and conquest, old values and new opportunities: a new world for the taking and remaking."[24]

The beginning of World War II rapidly stimulated the development of electric power. The War Production Board, a federal agency in charge of coordinating industries in the production of war material, initiated the development of new regional transmission systems and dams to provide electricity for ship, munitions, and aircraft production, and later in the war, plutonium for atomic bombs.[25] The city of Oak Ridge was located near TVA, and Hanford was located near the Columbia River, in both cases because of the large amounts of electricity required to produce uranium and plutonium for the Manhattan Project.[26] In addition to the harnessing of Muscle Shoals by TVA and the Columbia River basin by the Bonneville Power Authority, other major hydropower developments in the U.S. have been the Missouri River, the Colorado River Basin, and the St. Lawrence River.

Large-scale hydropower today faces many new challenges, including water scarcity, ecosystem degradation, and climate change, all which in turn lead to decreased power production.[27] Many large-scale hydropower projects were built before (or despite) these current environmental concerns. In addition, most of the large-scale hydropower potential in North America has already been exploited. For example, by the end of World War II, TVA had already developed much of its hydropower resources, and turned to building thermal plants. Today, less than 10% of TVA's power is from hydropower, with the rest from coal, natural gas, and nuclear plants that it has built, but many of their resources are no longer competitive with the cost of new renewable resources.

Finally, while large-scale hydropower is currently one of the largest sources of renewable energy, just maintaining the existing resources remains a serious challenge. Today the

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[22] Roosevelt (1932); Armstrong (1976), page 356; Smith (2007).

[23] Armstrong (1976), page 350.

[24] White (1995), page 55-56.

[25] Armstrong (1976), pages 355-360.

[26] Armstrong (1976), page 352.

[27] Reisner (1993); Worster (1992); Markoff and Cullen (2008).

Bonneville Power Administration owes $15 billion dollars in debt, due to the uncompetitive cost of its hydropower with new solar and wind resources; environmental, treaty, and maintenance obligations; and expiration of its existing utility contracts.[28] The Army Corps of Engineers face renewed criticism over their management of the Missouri and Mississippi Rivers due to extensive flooding throughout the Midwest in 2019. Similarly, as shown in the recent collapse of two Michigan dams in May of 2020, many dams in the U.S. are in a poor state of repair and now require extensive maintenance, upgrading, and/or relicensing with new hydropower technologies.[29]

3.3 Energy transmission and distribution networks

Infrastructure exists to connect resources with people and uses across time and space. This section details the development of key infrastructure systems to connect energy resources such as fossil fuels and hydropower with users in cities, rural areas, and industries. Key systems include pipelines for oil and natural gas, as well as the development of the electric grid, which resulted from the interconnection of many regional grids across the entire North American continent.

Energy infrastructure also determines the subsequent development of political institutions and economic development. Historian Christopher F. Jones describes how the development of transportation networks for coal, oil, and electricity 'unlocked' industrial and economic development throughout the eastern U.S. and shaped the development of concentrated political and economic power between 1820 and 1930.[30] A key factor in the early dominance of the Standard Oil Company was its relative stranglehold on pipelines transmitting oil out of the 'Oil Regions'. Rockefeller used control of this key infrastructure to exert market power over competing producers and refiners, often resulting in them selling their assets to him, allowing him to create a vertically-integrated monopoly that would dominate the beginning of the 20th century until its split in 1911 by the trust-busting of President Theodore Roosevelt.[31]

As discussed above, natural gas was not a valuable resource until it began to be used as a primary fuel source and feedstock for industrial plants and a heating source for homes in the 1970s. Natural gas pipelines are also one of the few infrastructure sectors in which the federal government has complete regulatory authority because they constitute interstate commerce. The Natural Gas Act of 1938 gives FERC exclusive authority over companies engaged in sale and resale, transport, and siting of export facilities, but exempts production and gathering facilities.[32] As a result, before the 1970s and 1980s:

> "Few industries were as sleepy as the gas-pipeline business . . . mostly the pipeliners bought gas from oil plants and smaller independent exploration companies, then moved it across the country through their networks of underground pipes . . . It was all very simple and straightforward – especially since every step of the process was under government control. The federal government regulated

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[28] Jacobs (2019).

[29] **?**.

[30] Jones (2016)

[31] Yergin (2012)

[32] {Federal Energy Regulatory Commission} (2015).

> interstate pipelines, dictating the price they paid for gas and what they could charge their customers. (State agencies regulated intrastate pipelines in much the same fashion.)"[33]

The market for natural gas changed with a FERC order in 1985 requiring natural gas pipeline owners to open their systems to other producers. This order also de-regulated natural gas prices and replaced long-term contracts between producers, pipelines, and utilities with competitive markets. But this led to volatile and uncertain spot markets that traded 75 precent of all capacity in the last few days at the end of each month. In response, Enron, at the time a relatively small gas company, re-introduced long-term contracts, but this time including futures and derivative contracts that could be traded, banked and hedged in order to reduce uncertainty and volatility, essentially becoming a quasi-financial institution with all of the attendant risks.[34] By 2000, Enron was dominant in the oil and gas trading business, conducting an estimated quarter to half of all natural gas trades, shortly before going bankrupt as a result of accounting fraud.[35]

Today interstate and intrastate natural gas pipelines account for 63% and 37% of pipelines, respectively. One-sixth of all pipelines remain concentrated in Texas, and more than half are located in nine states: Texas, Louisiana, Kansas, Oklahoma, California, Illinois, Michigan, Mississippi, and Pennsylvania.[36] Facilities are spread along the pipeline system to allow natural gas to be stored for peak periods such as winter. Natural gas companies, known as marketers, may include producers, pipeline marketing, financial institutions, and large-volume users.

The fact that the development of fossil fuel sectors has been affected by control of pipelines is rather surprising, considering that in contrast to electricity which cannot be stored, oil and natural gas can be stored in reserves, making coordination of production and consumption less important. Nonetheless, owning scarce connections between resources and users remains a key source of market power. Before its dramatic bankruptcy, Enron's trading activities had an intrinsic advantage over its competitors in that they were based on its knowledge of transaction prices, buyers, and sellers.[37] In recent years, Koch Energy has absorbed many traders and techniques from Enron, allowing the Koch conglomerate to dominate entire geographic regions and industries that require fossil fuels, such as oil refining in the upper Midwest, fertilizer production throughout U.S., and the export of natural gas from the Texas Panhandle to the rest of the country.[38]

The electricity industry often uses the history of individual inventors as part of its public relations, beginning with Thomas Edison's "invention" of the incandescent light bulb in 1879, quickly followed by his invention of the electric grid in 1882. In reality Edison's experiments were often preceded and paralleled by others, including Europeans such as Werner Siemens and other Americans such as Charles Brush in Cleveland.[39]

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[33] McLean and Elkind (2003), page 2.

[34] McLean and Elkind (2003), page 33-39.

[35] McLean and Elkind (2003), page 223.

[36] {Federal Energy Regulatory Commission} (2015), page 22.

[37] McLean and Elkind (2003)

[38] Leonard (2019)

[39] Rudolph and Ridley (1986); Righter (1996)

Electrification first began in cities with large commercial and industrial uses, and public uses such as electric streetcars and lighting. The first streetcar ran in Berlin in 1879, the same year as Thomas Edison first demonstrated the incandescent light bulb at Menlo Park, and just two years later Boston and Kansas City both had their first demonstration of electrical lighting in 1881, with Boston contracting to provide electric light in public spaces one year later.[40] The use of electricity in public spaces grew rapidly:

> "The first electric tram was put into operation by Werner Siemens in Berlin in 1879; the first one in America ran between Baltimore and Hampden in 1885 ... the electrified London underground was completed in 1890, and in the following decade there was a proliferation of electric rails everywhere. In the United States the 1,261 miles in 1890 increased to 21,290 miles by 1902."[41]

What we now consider to be the 'electric grid' – loosely defined as interconnected generation, transmission, and use of electricity – emerged quickly after 1879. Despite the earlier efforts by others, much of the academic literature and industry narrative focuses on three figures, who certainly deserve some but not all of the credit for the idea of the electric grid. Thomas Edison is usually identified as building the first grid utility business in Lower Manhattan in 1882, mainly serving restaurants and shops. George Westinghouse developed the use of alternating current, which allowed electricity to be transmitted over longer distances with lower losses than Edison's direct current systems. Finally, Samuel Insull is credited with building the first viable utility, eventually building a small utility, Chicago Edison, into a much larger conglomerate, Commonwealth Edison. Insull simultaneously innovated in three areas: first, in terms of the utility business model, by balancing different groups of users throughout the day; second, in terms of technology, by adopting alternating current and developing increasingly larger dynamos; and third, in developing a legal and regulatory model for utilities, obtaining exclusive franchises within cities and then advocating for regulation at the state-level by public utility commissions, which were safely out of the reach of competing municipal interests.[42]

By the 1930's, the electric industry was well-established in American cities. After the experience of cities with railroad monopolies, one of the principal struggles of the era became the effort by cities and towns to gain control of their electricity supplies either by buying private systems or starting their own to compete. Many cities developed and operated municipally-owned systems, many which still exist today.[43]

As central electric systems grew, public and private companies frequently interacted and competed. Private companies bought municipally-owned utilities as their systems grew rapidly. Cities dissatisfied with the service of private companies often sought to take over or 'municipalize' their systems, with a mixed record of success.[44] However, electricity generation grew much more rapidly in the private sector than from federal and municipal sources between 1917 to 1937, a period that saw rapid growth in electricity use.[45] Investor-owned

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[40] Jacobson (2000); Rose (1995).

[41] Kern (2003), page 114.

[42] McDonald (1962); Rudolph and Ridley (1986).

[43] Schap (1986); Jacobson (2000).

[44] Jacobson (2000).

[45] Cohn (2017), page 47

utilities today dominate the provision of electricity, although their power has been eroded by a number of factors since the 1980s.[46]

In comparison, rural electrification is understood to have occurred much more slowly because of the unwillingness of utility companies to provide service to lower population densities, leaving rural dwellers without access to energy and a harsh life.[47] Utility companies did not provide rural electric service because it was not profitable – previous studies showed that rural lines could be run profitably – but because it wasn't *as* profitable as urban service.[48] The Rural Electrification Act of 1936, as part of the New Deal, therefore offered federal subsidies to reduce the cost of rural electric distribution in areas that electric companies would not otherwise serve.

Historian Richard Hirsh highlights three sets of actors previously neglected in the history of rural electrification, because he argues, they do not necessarily fit into this prevailing narrative of market failure and subsequent government success through the New Deal. Contrary to the generally accepted history, Hirsh finds evidence that utility managers and utilities were engaged in electrification efforts before the federal government. Hirsh also finds that professors at land grant universities sought to develop an understanding of the problem, because many of the problems of rural electrification were simply unknown, rather than deliberate omissions. Finally and perhaps most intriguingly, like a few other scholars before him, Hirsh also finds that farmers experimented with distributed energy resources such as windchargers and lead-acid storage systems to bring electricity to rural farms and areas.[49]

Many of the same struggles between private and public ownership of electricity generation also occurred over long-distance transmission lines. After experiences during World War I of planning and coordinating energy resources, many groups including the utility industry, the Army Corps of Engineers, and the Smithsonian Institution all began to consider how to coordinate electricity over large areas. The 'Superpower' plan was promoted by private industry as a grid connecting power plants and trunk lines up the eastern seaboard.[50] In contrast, Governor Gifford Pinchot of Pennsylvania proposed a 'Giant Power' plan, which would establish "common carrier" status for transmission lines along with heavy oversight and regulation.[51] However, neither transmission plan made any progress, because at the beginning of the twentieth century, in an era of strong partisanship similar to our own, both plans were viewed as too extreme: "Progressive politicians opposed excessive private sector control. Private utilities opposed a central government planning agency."[52]

The private sector rapidly gained control throughout the 1920s. Holding companies – essentially utility conglomerates – began to acquire multiple utilities across large areas. At its height in 1929, Insull's Commonwealth Edison was supplying one-eighth of the U.S.'s electricity and gas power, in 32 states, as much as the entire national power supply of any

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[46] Hirsh (1989, 1999).

[47] Caro (1982). Many of these challenges exist in the present in the developing world today, particularly for women who do much of the household labor.

[48] Caro (1982); Fountain (2018).

[49] Hirsh (2018); Righter (1996).

[50] Gold (2019).

[51] Cohn (2017); Rudolph and Ridley (1986).

[52] Cohn (2017), page 47.

European country".[53] An argument in favor of holding companies was that this led to greater interconnection between utilities, but "neither fans nor critics managed to resolve whether holding companies in the aggregate benefited consumers and investors in the 1920s or merely increased the wealth of those at the top of the pyramid."[54] The holding company structure would ultimately be discredited by broad public concern over industry concentration into "a power trust", leading to investigations by the Federal Trade Commission in 1928. In the next year, implosion of Insull's highly-leveraged utility empire in the stock market crash of 1929 further discredited the structure and deepened the effects of the Great Depression.[55]

As a result of the dramatic collapse of Insull's company and much of the industry, both Republican President Herbert Hoover and Democratic candidate Franklin Delano Roosevelt campaigned on the issue of control of electric power in 1932. FDR's victory and Congress' subsequent passage of the Public Utility Holding Company Act (PUHCA) in 1935 essentially allowed regulators to unwind multi-state utility empires into individual companies that were financially conservative, pure-play, and relatively less complicated and risky. The regulation of investor-owned utilities at the state level would remain relatively stable for the next fifty years.

At the national level, however, World War II renewed government and industry efforts to interconnect existing utilities. In preparing for war, the federal government began to study and plan national transmission efforts. During the war, "between 1941 and 1944, the Federal Power Commission ordered forty-five interconnections, the majority during the first two years."[56] Government intervention and planning, along with the rapid development of pooling schemes between operators, led to the first effective transmission efforts that transcended local and regional constraints:

> "The interconnections built through federal and private sector cooperation proved critical to meeting defense power demands. All told, through interconnections and careful planning of operations, the government and private utilities together assured that hundreds of billions of kilowatt-hours of electricity traveled across roughly two hundred thousand miles of power lines to both defense and domestic users. With only a 25 percent increase of installed capacity from 1940 to 1945, the nation's power system generated nearly 60 percent more electricity during the war years."[57]

Notably, different regions pursued different strategies towards interconnection and pooling. Operating techniques in each power pool or region varied considerably, a historical consequence that continues through today.

Integration of electrical networks continued in the postwar period towards a national, or coast-to-coast interconnected electrical transmission network, in order to meet the rapid growth of industrial and consumer demand. However, the Northeast blackout of 1965 affected thirty million Americans and highlighted many remaining problems with a national grid built out of local and regional networks. Systematic application of advanced power control

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[53] Evans et al. (2004), page 330.

[54] Cohn (2017), page 49-50.

[55] Holland and Neufeld (2009); Lambert (2015), page 41; Rudolph and Ridley (1986).

[56] Cohn (2017), page 111.

[57] Cohn (2017), page 111-112.

technologies began throughout the 1970s and 1980s in order to solve increasingly complex grid control problems of reliability, robustness, and efficiency.[58]

Recent changes in electricity transmission have been stimulated by efforts to restructure the electric power sector. The 1978 Public Utilities Regulatory Policies Act (PURPA) allowed non-utility and independent power producers to sell into transmission grids. The 1992 Energy Policy Act enabled the Federal Energy Regulatory Commission (FERC) to require transmission operators to accept power from any generator and to establish competitive markets. FERC issued Order Number 2000 in 1999 to initiate the voluntary formation of regional transmission organizations (RTOs) and independent system operators (ISOs). These non-profit organizations have taken over some of the management of the electricity transmission system from power pools and individual utilities.

Furthermore, twenty-two states in the 1990s and early 2000s sought to establish competitive electricity markets, though many of these efforts stopped or reversed with the California energy crisis in 2001. Today, only eighteen states have deregulated electricity markets, all to varying degrees. In many of these states, transmission lines remain privately-owned but are run by the RTOs or ISOs.

The 2005 Energy Policy Act also gave the federal government through FERC, for the first time, the powers and authority to maintain reliable grid operations in transmission. This act also effectively repealed PUHCA from 1935, which for seventy years had limited utilities largely to single-state utility operations that were conservatively-run and -financed. Since the repeal of PUHCA, multi-state holding companies or utility conglomerates have emerged again. Although the degree of their market power is hard to establish, these firms often have have firm-, conglomerate-level, or vertical market power incentives to use transmission networks at the expense of consumers.[59]

4 Past and current infrastructure policies

This section examines past and current infrastructure policies in the U.S. As in other countries with a federal system of government, the majority of all kinds of infrastructure in the U.S. is built by state and local governments. This makes consideration of infrastructure policies from similar countries like Canada and Australia more relevant, rather than comparing countries with more unitary and centralized forms of government like France, New Zealand, or the United Kingdom.[60]

While most infrastructure in the U.S. is generally not categorized as energy infrastructure, we examine the role of state and local governments because this provides the template by which the U.S. has built all of its infrastructure. The basic fact is that local and state governments build the majority of infrastructure in the U.S. The Bureau of Economic Analysis classifies most infrastructure as fixed assets, and the national accounts show that of the $22 trillion of fixed assets in the U.S., the majority of fixed assets in the U.S. is owned by the public sector (68%) rather than the private sector (32%). Privately-owned utilities,

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[58] Cohn (2017).

[59] Marks et al. (2017).

[60] Chan et al. (2009).

presumably some of the main owners of energy infrastructure, comprise a relatively small portion of infrastructure, just 3%.[61]

The federal government intervened during financial crises such as the Great Depression and the Great Recession with packages of legislation known as the New Deal and ARRA stimulus spending plans, respectively. This section then goes onto examine how those stimulus plans differed (if at all) from the normal state of infrastructure spending in the U.S. which occurs through state and local governments.

4.1 Role of state and local governments

State and local governments play a critical role in building, owning, operating, and maintaining infrastructure in the United States. Table 1 below shows the breakdown of the total fixed assets of the U.S. ($22.1 trillion in 2018) as comprised of 68% owned by the public sector, and 32% owned by the private sector. Drilling down further, state and local governments own 52% of all fixed assets, and the overwhelming majority these assets (50 of 52%) are comprised of publicly-owned structures such as buildings. Put another way, state and local governments own "over 90 percent of all non-defense public infrastructure assets."[62]

The composition of these existing assets follows the responsibilities of the public sector in state and local government. A study by the Center for Budget Priorities finds that "states and localities spend the vast majority of their capital dollars – 85 percent – on key building blocks of a state's economy: schools, transportation, and drinking water treatment and distribution."[63]

Total	$22,128	billion of fixed assets						
Public	$15,058	68%	Federal defense	$1,796	8%			
			Federal nondef.	1,708	8%	Structures	$819	4%
						Equipment	138	1%
			State & local	$11,554	52%	Structures	$11,150	50%
						Equipment	264	1%
Private	$7,070	32%				Manufacturing	$1,449	7%
						Utilities	654	3%
						Transport.	597	3%
						Information	551	2%
						Health & soc.	551	2%
						Mining	177	1%

Table 1: Breakdown of total fixed assets in the U.S. by ownership sector and type. Dollar figures all in billions of 2018 USD, all percentages as percentage of the total $22,128 billion fixed assets. Sources: {Bureau of Economic Analysis (BEA)} (2019b,a).

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[61] {Bureau of Economic Analysis (BEA)} (2019a,b).

[62] Tomer (2019); McNichol (2019).

[63] McNichol (2019).

Key infrastructure		Public Sector			Private sector
Category	Sector	Fed.	State, tribal	Local	
Uses	Buildings	GSA	State govt.	Schools	Residential
				Hospitals	Commercial
	Transport	Highways	Roads	Roads	Private vehicles
			Bridges	Bridges	Railroads
	Industry		Critical infrastructure		Industrial facilities
Land	Agriculture				
	Afforestation	Public lands (40%)			Private lands (60%)
	Bioenergy				
Extraction	Coal				
	Natural gas				
	Oil				
Renewable	Wind, onshore		Public lands		Private lands
	Wind, offshore	BOEM	PUCs, legislatures		Private lands
	Solar PV		Public lands		Private lands
	Solar CSP		Public lands		Private lands
	Hydropower	TVA, BPA	Some	Some	Some
	Wave, tidal	BOEM	State shore law		
	Nuclear	NERC	PUCs, legislatures		Utilities, non-utility gens.
	Waste				
Carriers	Electric transmission	FERC, RTO	PUCs, legislatures	Munis	Utilities, coops

Table 2: Jurisdiction over, ownership of, and responsibility for infrastructure.

Table 2 generally shows how infrastructure assets are governed and managed both in the public and private sectors. In general, the federal government sets broad goals and policies at the national level, assists states and local governments, and invests in major interstate projects. But state and local governments do most of the work of owning, funding, operating and maintaining most of the infrastructure in the U.S. Figure 1 shows that the state and local governments have always spent more than the federal government, and that this gap has grown wider over time. As Table 3 shows, state and local governments invest the majority of funds in building, operations, and maintenance of infrastructure. In 2017, state and local governments spent more than the federal government in all major infrastructure categories.[64] The federal government in 2017 spent about 38% of all funds on transportation and water infrastructure, with this proportion ranging from a low in 1955 of 10% to a high in 1977 of 57%.[65] As a result of this prior role, most national-level infrastructure building programs have largely channeled funds through state and local governments.

The role of state and local governments in providing infrastructure in the U.S. is reinforced by its active municipal bond and capital markets, which allow state and local governments to access financial markets for capital directly. Countries with a federal system of government, such as the U.S., Australia, and Canada, tend to have the most developed municipal or

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[64] Congressional Budget Office (2018).

[65] Congressional Budget Office (2018).

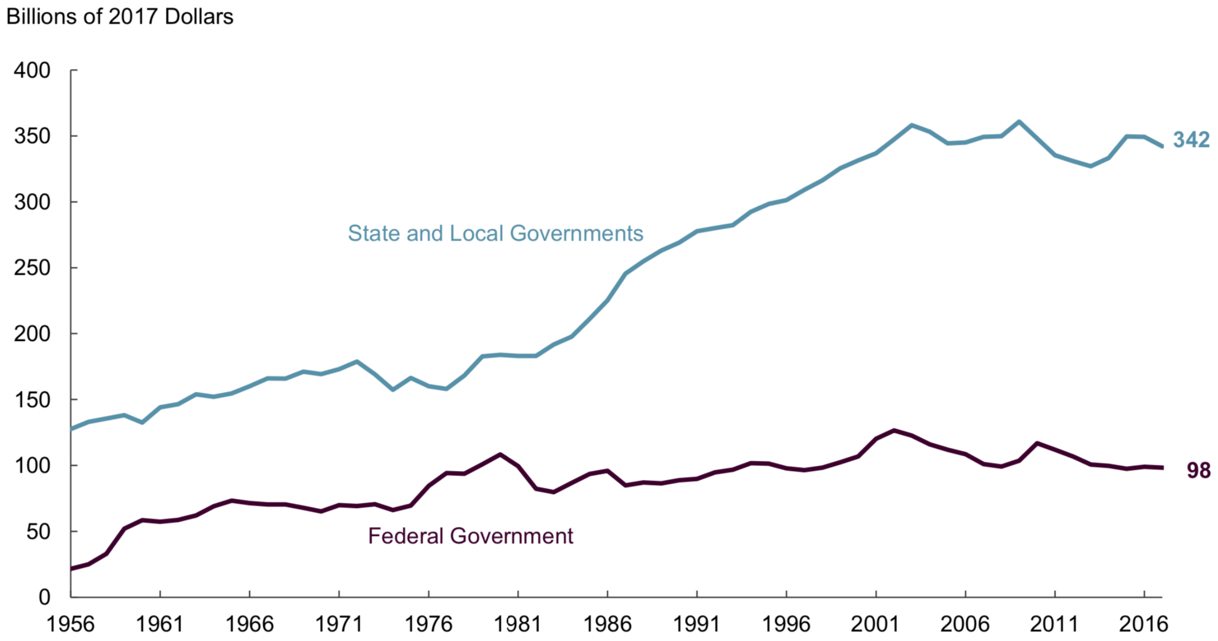

Figure 1: Public Spending on Transportation and Water Infrastructure by Level of Government from 1956 to 2017. Figured copied from Congressional Budget Office (2018).

	Federal		State & local	
Capital	$72	(41%)	$102	(59%)
Operations & maintenance	$27	(10%)	$240	(90%)
Total	$98	(22%)	$342	(78%)

Table 3: Spending on capital versus operations and maintenance for the federal and state and local governments, measured in billions of dollars in 2017. Data from Congressional Budget Office (2018).

sub-sovereign capital markets.[66] Public finance for infrastructure is a longstanding tradition for U.S. cities. For example, the spread of clean water systems in U.S. cities in the 19th century – and the reduction of diseases associated with dirty water – has been linked to the spread of reforms in municipal finance that resulted in the large share of public ownership in the drinking water sector that persists to the present day.[67]

The market for local and state government bonds is also greatly assisted by the exclusion of municipal bond interest from federal income tax, since a federal income tax was introduced in 1913. This exclusion effectively subsidizes infrastructure investment for municipal borrowers by lowering the interest rates needed to sell their bonds to U.S. investors. This exemption is statutory and not Constitutional – that is, it can be revoked – but over the past century, Congress has not shown any desire to do this.[68] Bonds can be issued for general obligations or designated for a specific purpose, such as revenue bonds, in which the interest is paid by pledged project revenues.

In the U.S. federal system, state and local governments also have other powers to finance infrastructure such as general purpose taxation, governmental appropriations, and intergovernmental transfers from the federal government. Other financing techniques are used in particular sectors in the U.S., such as:

- tax-exempt private activity bonds: such as Fannie Mae for home mortgages, Freddie Mac for multifamily housing, or Sallie Mae for student loans.
- authorities: also known as government trading enterprises, mostly used for railroads, ports, electricity, and water supply.
- development contributions: also known as impact fees, especially in California and the West.

Finally, despite frequent proposals and discussion, the financing of infrastructure through public-private partnerships (P3) in the U.S. has waxed and waned throughout history.[69] Chan et al. (2009) define P3 as an "arrangement [where] the private sector is typically contracted to design, build, operate, manage and finance new infrastructure and meet government obligations for a set period of time." By this definition, projects that are completely delivered by P3 are currently rare and have been mostly limited to the procurement of transportation and building projects, again by state and local governments. In the U.S., many steps in the building of new infrastructure are already met by the private sector in parts, but advocates of P3 insist that there are further synergies to be gained by having a single firm provide all of these steps in an integrated fashion. Many critics point out that high transaction costs, natural monopoly, and the ability of firms to exit from their commitments through joint ventures and strategic bankruptcy make them a poor fit for infrastructure projects.[70] The use of P3 for financing will be addressed further below when considering the advantages of a national infrastructure bank.

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[66] Chan et al. (2009).

[67] Cutler and Miller (2006); Jacobson (2000).

[68] Chan et al. (2009), box 5.6, page 81.

[69] Likosky (2010).

[70] Gomez-Ibanez (2006); PricewaterhouseCoopers (2016); Capps (2017).

4.2 Keynesian stimulus spending

This section considers two national-level infrastructure programs, the New Deal between 1933 and 1939, and the American Recovery and Reinvestment Act (ARRA) of 2009, both of which were Keynesian investment programs designed to stimulate the national economy through large-scale infrastructure investments. A recurring and important debate in both programs was whether these stimulus programs should invest in “people,” i.e. labor-intensive job creation in the short term, or in “projects,” i.e. capital-intensive infrastructure projects with long-term benefits.

4.2.1 The New Deal, 1933-1939

Initiated by President Franklin Delano Roosevelt in response to the Great Depression in 1933, the New Deal package of programs fundamentally changed the role of government in planning and financing infrastructure, while also seeking to put millions of unemployed workers back to work. Smith (2006) wrote: “If the overall purpose of the New Deal was to bring about relief, recovery, and reform, the public works programs were understood to focus on these first two tasks.”[71]

Smith emphasizes that the combined size of the physical and financial transformation wrought by the New Deal was unprecedented before or since: “on average, between 1933 and 1939 over two-thirds of federal emergency expenditures went towards funding public works programs.”[72] Two major building programs, the Public Works Administration (PWA) and the Works Progress Administration (WPA), accounted for the majority of the public works expenditures and buildings (infrastructure was generally referred to in the New Deal era as “public works”):

> “The PWA, created in 1933, received an initial appropriation of $3.3 billion [$66.0 billion in 2019 dollars], which it mainly applied to heavy construction and large-scale building. To put this figure in context, this amount was just over 165 percent of the federal government’s revenues in 1933, or 5.9 percent of the 1933 U.S. gross domestic product (GDP). Relying on private contractors, the PWA deployed funds in 3,068 of the nation’s 3,071 counties, while helping to pay for projects like the Tennessee Valley Authority and Boulder Dam. Created in 1935, the WPA did lighter construction work and avoided private contracting. Its initial appropriation of $4.88 billion [$92.3 billion in 2019 dollars] was about 135 percent of the federal government’s revenues in 1935, or about 6.7 percent of GDP in that year.”[73]

To put these figures in perspective, the current yearly GDP of the U.S. is approximately $21 trillion dollars a year, or the same value as all of the existing fixed assets of the U.S. If we were to implement an equivalent size infrastructure program at 6% of current GDP, this

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[71] Smith (2006), page 8.

[72] Smith (2006), p. 1.

[73] Smith (2006), page 2. Current day equivalent dollar figures inflated from the original text (2002 dollars) to the current year (2019) using the Consumer Price Index for all items from the St. Louis Federal Reserve, an increase of 44.2% between 2002 and 2019.

would amount to \$1.26 trillion dollars – and the New Deal authorized two such programs in the space of three years. In comparison, the Troubled Asset Relief Program (TARP) of 2008 was authorized for \$700 billion (about \$831 billion in 2019 dollars) and only purchased troubled assets rather than trying to build new infrastructure.

Given differing historical interpretations of the New Deal, however, we should also note that the New Deal did not fundamentally seek to change the terms of ownership, labor, and work:

> "The federal government worked with labor and industry to use public works spending – what we today call 'public investment' – to revive the construction sector, and through it, to try to pull the economy out of the Depression. New Dealers, though, never attempted or seriously contemplated the use of public works projects to effect radical structural reform of American capitalism. New Dealers did not propose that the federal government nationalize the investment functions of the economy, for example."[74]

The unprecedented size and speed of New Deal, however, did raise a number of logistical, geographical, and political issues, particularly around the role of the federal government in building infrastructure.

The first problem was how to deploy these considerable funds into large-scale public works projects quickly. One debate in the New Deal era, that may be familiar to observers of contemporary debates over infrastructure spending and investment, was whether government investment in infrastructure should pay for itself by directly generating revenues, or instead by stimulating the broader economy by putting people and institutions to work. The first approach, referred to as "self-liquidation", was the one that the Hoover administration started the Reconstruction Finance Corporation with in 1932, but as Smith writes:

> "Self-liquidation produced valuable public works in a financially prudent manner, but during the Depression, this strategy had its limitations: It did not seem to put the public to work. Despite this drawback, Hoover's programs represented an important shift in public works policy. For the first time, the federal government was undertaking large-scale national planning and coordination of public construction."[75]

This approach, expanded under subsequent acts, "merits attention not because it was a rousing success – indeed, it was not – but rather because it provided the legislative blueprint for the New Deal's Public Works Administration (PWA)."[76]

As a new government agency empowered to spend more than twice the amount under Hoover's previous approaches, the original administrators of the PWA were initially concerned with the speed of the projects while taking special care to avoid any appearance of graft or waste of public funds. "To Ickes and most of the Special Board, though, it seemed only logical that the established departments of the federal government would be able to get projects underway in a timely fashion."[77] The PWA rapidly organized itself using existing

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[74] Smith (2006), page 87-88.

[75] Smith (2006), p. 85-86.

[76] Smith (2006), p. 28.

[77] Smith (2006), p. 34.

federal departments and an existing system used by the Treasury Department that divided the country into seven zones.[78]

Local and state governments, and organized labor unions, however, feared that the federal government would replace their role as conduits of public work funds going to their citizens and members, respectively. This led to considerable debate within the federal administration over how local governments and labor unions would be consulted. At the same time, the process of choosing projects, advisors, and experts was extensively debated to avoid any appearance of favoritism or corruption.[79]

Similarly for Harry Hopkins, the administrator for the WPA, the other main agency for New Deal public works spending, working with state and local governments was a logistical and administrative priority. As quoted in Smith:

> "Hopkins stressed to his staff the importance of working with mayors and governors. 'We would have been awful damned fools,' he bluntly said, 'if we thought for a minute that we have either the power or the ability to go out and set up 100,000 work projects as we are going to have to do, probably 200,000 before the year is over, without the complete cooperation of local and state officials. We couldn't do it if we wanted to.' Indeed, Hopkins argued, the work the WPA does 'in the main is work not on Federal property but on city and county and state property, it is work that is going to be of interest to the local taxpayers and local people, and we couldn't if we wanted to develop these projects, organize them or prosecute them for that matter, without bringing the cities and the counties and the states into a complete partnership with us."' [80]

Table 4 shows the percentage of all PWA funds spent that can be clearly identified for local use, compared with large projects that could presumed for interstate, regional, or national uses. For local uses, building structures such as educational buildings, hospitals, public buildings, sewer and water systems, and streets and roads, received the largest share of funds (43.6%). Electric power projects (1.0%) were probably still used largely for local uses given the state of technology at that time. Interstate projects such as highways, engineering structures, flood control and reclamation, and railroads made up a much smaller number of the projects, but receiving a clearly smaller share of funds out of the total amount (37.7%). The remainder (18.6%) was devoted to naval vessels and other unspecified uses.

The distribution of projects and funds also varied across the seven previously-defined regions. The eastern and midwestern states received the most projects, because that was where the majority of the existing construction, manufacturing, and building trades were already located, but most states received a proportion of projects and funds similar to the percentage of the building industry already in each state. Southern states, with less people in the building trades, for the most part received shares larger than the percentage of the building trades in their state.[81]

After two years of public works programs under the PWA, however, both FDR and the business community began to critique the PWA as ineffective at putting people directly

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[78] Smith (2006), p. 35.

[79] Smith (2006), p. 37-42

[80] Smith (2006), p. 105.

[81] Smith (2006), page 91

Scale of Use	Category	% of PWA Projects	% of PWA Funds ($)
Local	Educational buildings	22.0	14.0
	Public buildings	12.4	9.1
	Sewer systems	5.4	7.1
	Water systems	7.5	4.1
	Hospitals	2.0	4.1
	Housing (Federal and non-fed.)	0.17	3.4
Local/interstate	Electric power	1.0	1.8
	Streets and highways	33.0	15.7
	Flood-control, reclamation	1.4	10.4
	Engineering structures	1.9	6.9
	Railroads	0.09	4.7
National	Vessels	0.75	6.4
Unspecified	All others	12.0	12.2
Total		99.6	99.9

Table 4: Projects sponsored by the PWA, 1933-1939. Reorganized from Smith (2006), page 90, and {Public Works Administration (PWA)} (1939), page 291, table 21. Ordered by scale of use and then percentage of funds.

back to work either quickly or consistently enough. Neither group was receptive to the argument that public works projects stimulated off-site employment in the manufacturing or materials sectors through indirect employment effects, as advocated by economist John Kenneth Galbraith at the time.[82] Many of these objections would occur again seventy years later when the federal government again sought to stimulate the economy through infrastructure spending.

4.2.2 ARRA stimulus, 2009-2019

The most severe global recession since the Great Depression began in the United States in 2007 with the collapse of the U.S. real estate market and the subsequent spread of financial risk through the world financial system by subprime mortgages. The Great Recession, as it is called, resulted in many governments quickly implementing Keynesian-style infrastructure programs in order to stimulate their economies back to growth.

The U.S. passed the American Recovery and Reinvestment Act (ARRA) in 2009, which will be referred to as the ARRA stimulus going forward. The Congressional Budget Office estimates that more than half of the financial impact of the ARRA stimulus occurred in 2010, and that 95% of the financial impact was realized by the end of 2014. At its high point in 2010, the ARRA stimulus is estimated to have reduced unemployment by 0.4 to 1.8 percentage points, or increased the number of jobs by between 0.9 and 4.7 million full-time employment years in that year alone.[83] A review of nine academic studies, contrasting ex-

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[82] Smith (2006), page 96.

[83] {Congressional Budget Office (CBO)} (2015).

perimental and macroeconomic modeling approaches, states that "six find that the stimulus had a significant, positive effect on employment and growth, and three find that the effect was either quite small or impossible to detect."[84]

The ARRA stimulus increased spending on infrastructure through the following key departments and agencies:[85]

- Department of Education: $87.2 billion, including qualified school construction bonds.
- Department of Energy: $19.4 billion, including energy efficiency and renewable energy, innovative technology loan guarantees, and a federal buildings fund.
- Environmental Protection Agency (EPA): $6.4 billion.
- Department of Transportation: $31.9 billion, including highway construction.

Estimates of the output multiplier of this spending (the cumulative impact on gross domestic product) ranges from 0.5 to 2.5.[86]

Another view however is that the 2009 spending did relatively little to add to critical infrastructure such as bridges and highways. Dupor (2017) finds that a relatively small portion was set aside for infrastructure – $27.5 billion – out of the total $840 billion package. Drafters of the stimulus intentionally did not require that states provide matching funds, in the usual fashion for federal highway-spending programs, in order to provide states with more flexible aid. This, however, had the effect of adding relatively little to state spending for bridges and highways because states then reduced their own spending on highways and used the federal aid, resulting in no net gain. Or, as Dupor (2017) put it succinctly, based on the statistics, "for each grant dollar [from the ARRA stimulus], the [typical] state government [cut] its own contribution to highway infrastructure by 81 cents."

5 Policies to coordinate energy infrastructure

This section describes how particular mechanisms and policies, especially financial mechanisms and legislative, regulatory, and legal changes, can be used to build energy infrastructure coordinated with a national goal like deep decarbonization.

5.1 Financial mechanisms

Specific financing mechanisms that have been much discussed and used in other countries, respectively, are infrastructure banking, competitive grants, and regional development funds. This section will discuss each of these mechanisms briefly.

5.1.1 Infrastructure banking

Many financial institutions or banks have been set up to finance projects for economic development with a special emphasis on large infrastructure projects. These banks usually focus on a particular region of the world or investment theme, with different shareholders and partner structures. Table 5 shows some examples of development banks around the world.

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[84] Matthews (2011).

[85] {Congressional Budget Office (CBO)} (2012a).

[86] {Congressional Budget Office (CBO)} (2015).

Institution	Founded	Focus	Member states (#)
World Bank Group	1944	Poverty, prosperity	All UN members (193)
European Investment Bank	1958	Regional integration, social cohesion	All EU members (28)
Inter-American Dev. Bank	1959	Development, regional integration	Latin Am. & Caribb. (26), most of OECD* (22)
Asian Development Bank	1966	Regional development	Asia & Pacific (49), other regions (19)
Eur. Bank for Recon. & Dev.	1991	Development of market economies	Former Eastern Bloc (30), partners (69, 2 EU instit.)

Table 5: International development & infrastructure banking examples. OECD stands for the Organization of Economic Co-operation and Development. Source: Wikipedia.

Infrastructure banking has been proposed multiple times in the United States in the past decade. A bipartisan National Infrastructure Bank bill was submitted in the Senate and companion legislation in the House in 2007, but hearings were held without any further progress.[87] President Obama also proposed an infrastructure bank while on his first presidential campaign in 2008. Many similar proposals have since been introduced by bipartisan groups in the Senate: Senators Kerry and Hutchinson proposed the creation of an American Infrastructure Financing Authority in 2011 to use public money as equity to raise private capital for infrastructure investment,[88] and Senators Warner and Blunt again proposed this with a wide range of co-sponsors in 2013.[89]

These proposals for infrastructure banks are very similar to the existing international infrastructure banks:

> "The Obama Infrastructure Bank idea and the Clean Energy Bank proposals now on the table are essential for devising effective-partnership-based growth. They base themselves explicitly on the international infrastructure banks. The idea is to turn this foreign policy model inward to reinvest in the American economy."[90]

How would it work? A national infrastructure bank for the U.S., through a combination of expert technical, engineering, and finance staff, would select specific local construction projects to finance. Rohatyn (2009) provides the most specific description of the structure and financing for such a bank:

> "Funded with an initial capital base of $60 billion, this bank would be empowered to insure the bonds of state and local governments, provide targeted and precise subsidies, and would issue its own thirty- to fifty-year bonds to finance itself with conservative 3:1 gearing. Such an institution could easily provide $250 billion of new capital over the next five years to invest in construction and maintenance

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[87] S.1926 — 110th Congress (2007-2008)

[88] Likosky (2011).

[89] Laing (2013).

[90] Likosky (2010), page 5.

> projects across the nation – money that would create several million new jobs as a recession deepens. With additional reasonable gearing, significantly higher levels of capital – as much as $1 trillion – could be generated over a five- to seven-year period . . . How would the nation pay for this new infrastructure policy? The first source of funding should come from the funds now dedicated to existing programs: approximately $60 billion annually could be taken from these programs and there would still be a balance remaining. Additionally, taxes and fees that are currently imposed on infrastructure users –for example, port fees, fuel taxes, airline ticket surcharges – would continue to generate revenue."[91]

The idea of a national infrastructure bank has various strengths and weaknesses. Likosky (2010) describes two advantages of the infrastructure banking model as the abilities first to leverage sizable amounts of private capital for socially beneficial uses, and second to designate a particular agency or institution with the decision-making power to select the best projects. The strengths of a national infrastructure bank, as assessed by the Congressional Budget Office, include new abilities to: select new projects; handle a large number of new projects; repay loans directly from user fees, leading to higher and more efficient use of new infrastructure; and partner with the private sector in new ways. Additional prospective advantages of a national infrastructure bank include: focusing on national-level infrastructure goals; coordinating large, complex, and long-term public investments; creating a stable environment for private investments; and assisting local and state governments with technical expertise, coordination, and execution.[92] Since it would presumably be owned and run by the federal government, it would be included in the federal budget and subject to federal accounting rules and oversight.[93] These advantages point to the fact that individual states are not able to execute large and coordinated projects because of their limited size, and that the federal government is not pursuing large-scale projects because of departmental fragmentation or political paralysis.

But Likosky (2010) also concedes that the track record of international infrastructure banks has been decidedly mixed.[94] The main prospective weakness of a national infrastructure bank for the U.S. is the fact that states and local governments already borrow at lower rates than the federal government because of their exemption from federal income tax, as was described above in section 4.1 on existing municipal finance markets.

5.1.2 Competitive grants

Federal governments face the challenge of coordinating national policy in other areas as well. An interesting example similar to infrastructure coordination in the United States is educational policy, which is also largely implemented at the subnational level by state and local governments.

A novel mechanism tried in the ARRA stimulus spending (other aspects described in Section 4.2.2) was to reserve competitive educational grants to states, generally known as

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[91] Rohatyn (2009), page 224.

[92] Puentes (2012).

[93] {Congressional Budget Office (CBO)} (2012b).

[94] Likosky (2010), page 323

the Race to the Top (RTTT). RTTT aimed to change educational policies in many states by reserving $4.35 billion dollars for the federal Secretary of Education to spark educational reforms at the state level through competitive grant making. Specific priorities included adopting educational benchmarks and curricula, building data systems for comparative evaluation, increasing teacher effectiveness and equity in teacher distribution, and turning around low-performing schools.[95] While we cannot find any causal studies of the effect of the RTTT program on educational outcomes, criticisms of the RTTT program, much like the much-maligned federal No Child Left Behind legislation before it, focus on its establishment of unpopular curriculum standards, standardized testing, and charter schools.[96]

The most relevant aspect of RTTT to infrastructure was its success in getting subnational governments to adopt key policy priorities in alignment with the federal government. Howell (2015) argues that the RTTT program was effective in getting many states to adopt RTTT policies with relatively little money: “The president managed to stimulate reforms that had stalled in state legislatures, stood no chance of enactment in Congress, and could not be accomplished via unilateral action.”[97] Statistical evidence shows that states that applied for the grants did enact significant policy reforms regardless of whether they eventually won or lost. After the competition, both statistics and interviews show that *all* states engaged in policy reforms, whether or not they applied, and that the RTTT competition affected policy discussions in every state.[98]

Unlike spending formulas which distribute funds to all states, and unlike large political appropriations which may not occur because of multiple, competing interests, the competitive grant process may be an interesting mechanism to incentivize the alignment of local and state governments with federal priorities for national-level infrastructure.

5.1.3 EU regional integration funds

One example from the European Union (EU), which is a federal system in some ways, is that it sets aside dedicated funds for structural and regional investments with specific themes, increasingly with a focus on climate change. An overall objective for EU spending over the past six years in the period from 2014 to 2020 has been to spend 20% of the overall EU budget on climate change-related actions such as mitigation and adaptation projects.[99] Of the total sum of EUR 114 billion spent between 2014 and 2020, approximately half, EUR 56 billion, is administered through the European Agricultural Fund for Rural Development, and roughly the other half is administered through the European Regional Development Fund (ERDF) and the Cohesion Fund, which are intended to “strengthen economic and social cohesion in the EU by correcting imbalances between its regions”.[100]

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[95] Manna and Ryan (2011).

[96] Tanner (2013).

[97] (Howell, 2015, page 58).

[98] Howell (2015).

[99] EU climate change spending page.

[100] European Regional Development Fund webpage.

5.2 Legislative, regulatory, and legal changes

Gerrard and Dernbach (2019) recently edited a hefty volume titled *Legal Pathways to Deep Decarbonization*, weighing in at 1,116 pages, that addresses many of the key legal issues that need to be solved to achieve deep decarbonization. This section simply summarizes the legislation and legal authorities suggested in this volume at the national, regional, state, and local levels, organized around the main four categories of necessary infrastructure for deep decarbonization described in Section 2.

5.2.1 Renewable siting

Utility-scale renewable energy will require large amounts of land due to lower energy densities.[101] In the western United States, the federal government and tribal governments hold large amounts of land that coincide with high solar and wind potential. In coastal areas, offshore wind has a great deal of potential, but state governments control resources up to three nautical miles from shore and from there, the federal government controls resources out to two hundred nautical miles from shore. Disturbed lands such as contaminated sites, mining areas, and closed landfills also have considerable potential for re-use. All of these could be opened up with the better design of expedited approval and permitting processes at all levels of government, leasing, incentives, and liability exemptions to reduce regulatory barriers. Other difficult issues that require addressing are impact assessment under the National Environmental Protection Act (NEPA) and its state equivalents ('the little NEPAs'), and federal species protection laws.[102] The Trump administration has recently introduced updated rules for NEPA, which have been met with opposition from environmental and renewable energy groups.

Distributed energy resources such as solar PV, solar thermal, and storage will all depend heavily on incentives and mandates, acceptance by public utility commissions, and governmental and industry action, in particular standardization of permitting and regulations.[103]

5.2.2 Decarbonized electricity and fuels

Decarbonizing the electric power sector will require social, political, economic, and legal policies all to: prohibit or discourage the use of fossil fuels, limit and/or change the price of greenhouse gas emissions, and to address currently stranded generating assets.[104]

Achieving decarbonized fuels will require the development of multiple pathways. Bioenergy feedstocks require changes in land use law; mandates, incentives, and/or subsidies to enable the creation of cultivation value; and direct regulation of cultivation processes.[105] Low-carbon or renewable gaseous fuels like biogas, hydrogen, and synthetic methane require creation of state laws to regulate renewable gas production, changes in regulation to allow existing natural gas pipelines to carry renewable gases, and policies to promote the use and

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[101] Smil (2015).

[102] Gerrard (2019).

[103] DuVivier (2019).

[104] Weissman and Kakon (2019).

[105] Hudson and Outka (2019).

delivery of renewable gases.[106] Biofuels for high-value end uses such as aviation and industry will require further mandates, incentives, and/or subsidies such as low-carbon fuel standards, measures to promote emissions reductions, and carbon capture and storage at biorefineries.[107]

5.2.3 Transmission siting

Widespread use of electricity and hydrogen from renewable or low-carbon sources will require both the building of new infrastructure as well as the repurposing of existing infrastructure. Existing electrical transmission and distribution lines will need to be upgraded with higher capacity, better control, and more robust safety measures for new threats such as wildfires. New lines will be needed to make available solar and wind resources to other regions, since the most potential for these resources is concentrated in the Southwest and Midwest, respectively.

Some infrastructure could also be re-used or repurposed. It may be possible to repurpose natural gas and oil pipelines for hydrogen, but given their very different physical characteristics, new storage and pumping capacity will likely be necessary. The most valuable aspect of existing infrastructure may be its existing land use permitting and rights-of-way, which may allow additional pipelines for liquid and gas fuels, and electrical transmission lines could perhaps be run on the same right-of-ways as well. This is similar to how in the past, existing railroad right-of-ways enabled the rapid development of first telegraph and later telephone lines, and now in the present, where existing power lines are being used to provide rural broadband.

Siting new transmission infrastructure has been and continues to be a difficult challenge, due to political interests and regulatory authorities that are fragmented between the federal government and individual states. There has been considerable debate about how to achieve the appropriate federal balance of responsibilities between national and state goals, such as through voluntary regional planning processes.[108] The failure of Clean Line, a merchant transmission developer of transmission lines, points to the urgent need for new mechanisms, policies, and/or agreements to site the necessary transmission infrastructure.[109]

5.2.4 Energy efficiency in buildings, industry, and transportation

Buildings comprise more than 40% of primary energy demand and 30% of greenhouse gas emissions in the U.S.[110] Policies to reduce energy end uses such as through appliances and lighting include but are not limited to: standards; model local and state building codes; voluntary labelling and incentive programs; and state- and utility-level efficiency programs.[111] The development of energy-efficient new buildings can be stimulated at the federal, state, and local levels by many possible policies such as: mandated performance standards; tax incentives, credits, and subsidies; government buildings programs; funding of additional research; the development of better energy codes and lifecycle cost assessments; grants for

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[106] Webb and Taylor (2019).

[107] Nostrand (2019).

[108] Benedetti (2010); Decker (2013).

[109] Gold (2019); Hurley (2018).

[110] Paddock and McCoy (2019)

[111] Kennedy (2019).

construction; professional and workforce training; and better integration of efforts between buildings and utilities.[112] Existing buildings, which will continue to represent the majority of carbon emissions into the future, can be affected with incentives, credits, and/or subsidies for retrofitting, as well as benchmarking, audit, retrocommissioning, performance standards, certification, and financing programs.[113]

Reducing energy use in industry continues to pose a difficult challenge in deep decarbonization. A carbon price is considered to be the most effective policy in stimulating technological and process innovation in hard-to-decarbonize sectors such as industry. Other possible policies include tradable permits, mandated emissions reductions, and air pollution source review for specific industrial sectors.[114]

Many possible legal and regulatory changes could be enacted to decarbonize transport. A comprehensive assessment of transportation options to reduce greenhouse gas emissions conducted a decade ago may not have changed appreciably.[115] Transportation demand itself could be reduced by sending better price signals; removing fuel and capacity subsidies; removing barriers to low- and zero-carbon alternatives such as transit, walking, and bicycling; and promoting compact development.[116] For personal mobility, a recent MIT Energy Initiative report finds energy-efficient vehicles and public transportation to be the most efficient alternatives.[117] Vehicles throughout the light-duty and heavy-duty fleets could be transformed to use low-carbon fuels such as electricity and hydrogen; fuel economy and emissions standards; and fiscal incentives. Key barriers such as infrastructure, and public preferences and perceptions will need to be addressed.[118] Freight, aviation, and shipping will all require shifting from current operational patterns that are both more flexible and more fuel-intensive, to planned operational patterns that are likely to be both less flexible but also less fuel-intensive.[119]

6 Locating new energy infrastructure

Deep decarbonization requires three simultaneous and interrelated moves. First, the U.S.'s existing fossil fuel assets span the entire country and must be either retired or repurposed. Second, new renewable energy sources and systems must be built in order to replace retired fossil fuel systems. Third, any systems that will be used in the future must be built keeping in mind emerging climate risks, that range from sea level rise to heat stress to extreme weather events. The interplay between these three factors – existing fossil fuel infrastructure, renewable energy potential, and climate change risk – vary significantly by community and will require place-based policies and programs that respond to local conditions. This

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[112] Paddock and McCoy (2019).

[113] Smith (2019).

[114] Macey (2019).

[115] {Cambridge Systematics} (2009). The only significant technology change in this ten-year old report might be the introduction of automated vehicles (AVs) or shared or network transportation companies such as Uber, which may actually be increasing emissions.

[116] Pollard (2019).

[117] Field et al. (2019).

[118] Stein and Fershee (2019); Campbell et al. (2019).

[119] Campbell et al. (2019); O'Leary (2019a,b).

paper therefore uses the following conceptual formula to determine suitable sites for new infrastructure across the country, and therefore for further study by the Roosevelt project team:

− past fossil fuel infrastructure
+ existing renewable resources
− future climate risks
= resulting suitable sites

The sequence of maps throughout this section analyzes the U.S.'s existing energy system, dominated by fossil fuels, along with the geographies of current wind and solar energy potential and future climate risks. Taken together, these maps offer a starting point for how policymakers and planners can start to think about where to locate the necessary energy infrastructure for deep decarbonization. The following paragraphs explain the source of data for, and representation within, each map.

6.1 Existing energy infrastructure

Figure 2 below shows that the U.S. energy system is a complex systems-of-systems, comprised of:

- generation, transmission, and distribution infrastructure,
- webs of institutional and regulatory bodies, private entities, and
- upstream and downstream networks of technologies, resources and markets.

Figure 3 below shows the geography of the electric power transmission network, including: over 9,700 operating power plants that rely on a range of fuel types to supply power to residential, commercial, and industrial customers throughout the country; over 300,000 miles of transmission lines; and the tens of thousands of substations currently in operation.[120] Much has been written about the growing challenges of the U.S. power grid, especially its aging and deteriorating infrastructure as a result of poor coordination and underinvestment. In 2016, for example, the American Society of Civil Engineers (ASCE) forecasted the total investment gap in the electric power system as rising to $565 billion by 2040.[121] This represents an opportunity to align investment and policy decisions with decarbonization priorities, including developing grid-scale storage and upgrading the bulk power transmission network.

Figure 4 shows the large physical footprint of the U.S.'s oil, gas, and coal infrastructure. These resources are highly concentrated in Appalachia, the Texas Gulf, and the Midwest.

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[120] U.S. Energy Information Administration (2019a).

[121] ASCE (2016).

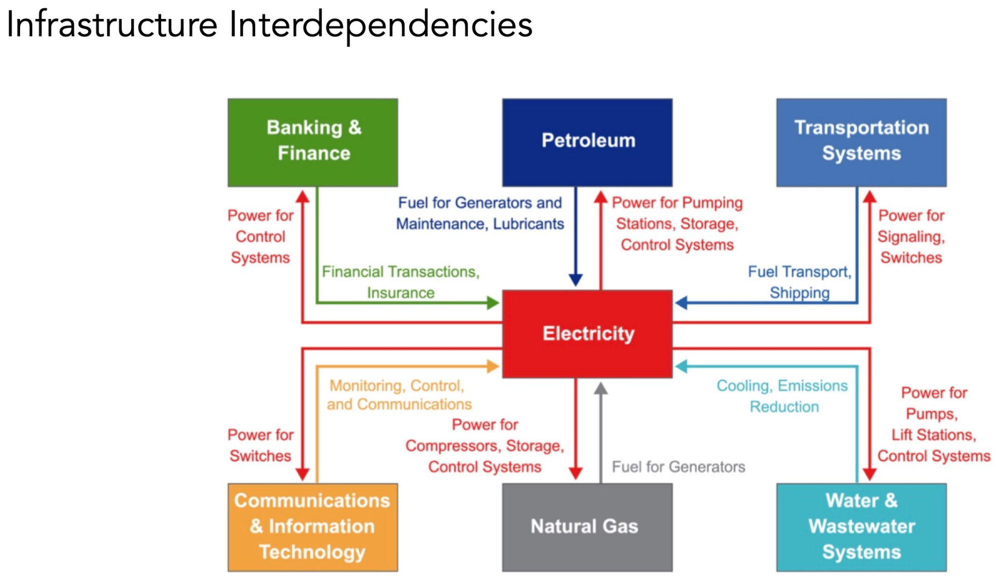

Figure 2: Infrastructure interdependencies. Source: **?**.

According to the latest figures from the U.S. Energy Information Administration (EIA), there are nearly 3,000 power plants in the U.S. that rely primarily on fossil fuel. Despite record coal plant retirements in recent years, coal power plants dominate the energy system of large portions of the Midwest and the Southeast. Meanwhile, natural gas power plants now account for more than half of all fossil fuel-based power plants in the U.S.

Natural gas production has transformed the American energy sector over the past two decades. Production has shifted from conventional natural gas to shale gas production, driven by the fracking activity in regions like the Marcellus Formation in Ohio and Pennsylvania and Eagle Ford in Texas. Figure 5 shows how natural gas is moved nationally by a network of interstate and intrastate pipelines, totaling about three million miles in length, as well as over 500 processing plants, 400 storage facilities, and over 480,000 producing wells.[122] The natural gas industry is an important economic sector in states like Texas, Pennsylvania, Louisiana, and Oklahoma. At the time of writing, the EIA is tracking over 130 active natural gas pipeline projects to expand capacity, increase delivery to Mexico, and bring liquefied natural gas (LNG) to export terminals in the Gulf Coast region.[123]

Oil and petroleum are used primarily for transportation, now the largest carbon emitting sector in the U.S. Crude oil from the United States is refined along with imported crude oil

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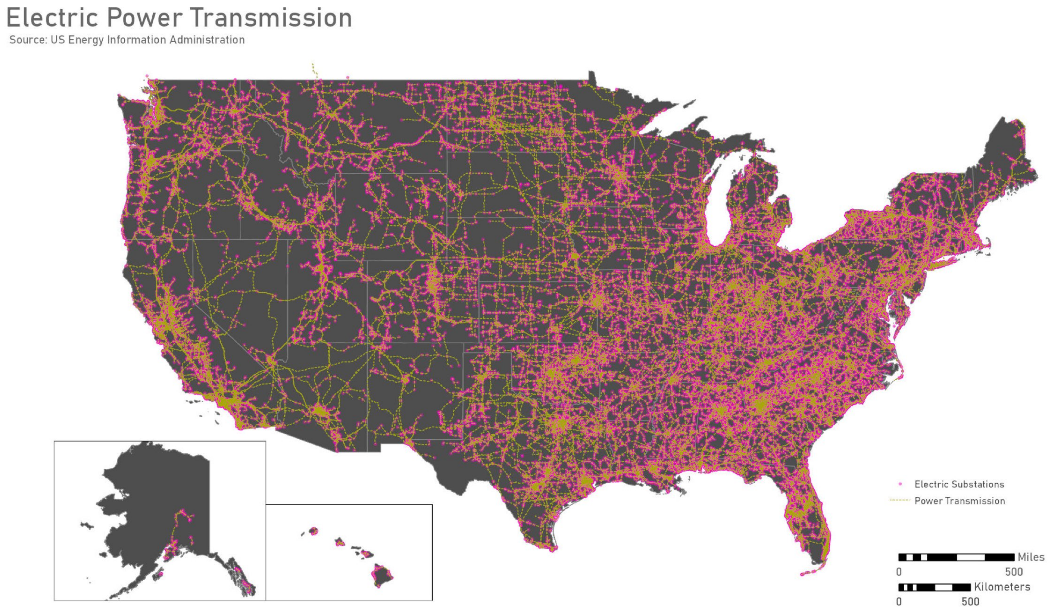
[122] **?**.

[123] U.S. Energy Information Administration (2019b).


Electric Power Transmission

Source: US Energy Information Administration

Figure 3: Electric power transmission network. Source: Energy Information Administration.

in domestic refineries to produce petroleum products such as gasoline, jet fuel, and heating oil. Similar to natural gas, oil industry activity is heavily concentrated in states like Texas, Louisiana, and Oklahoma. The EIA reports that U.S. crude oil production doubled between 2010 and 2018, and the Gulf Coast region is responsible for 70% of that growth.[124] Figure 6 shows over 120,000 miles of oil product pipelines, hundreds of ports and rail terminals, over 130 oil refineries, and thousands of storage terminals that make up the U.S.'s oil and liquid fuels infrastructure.[125]

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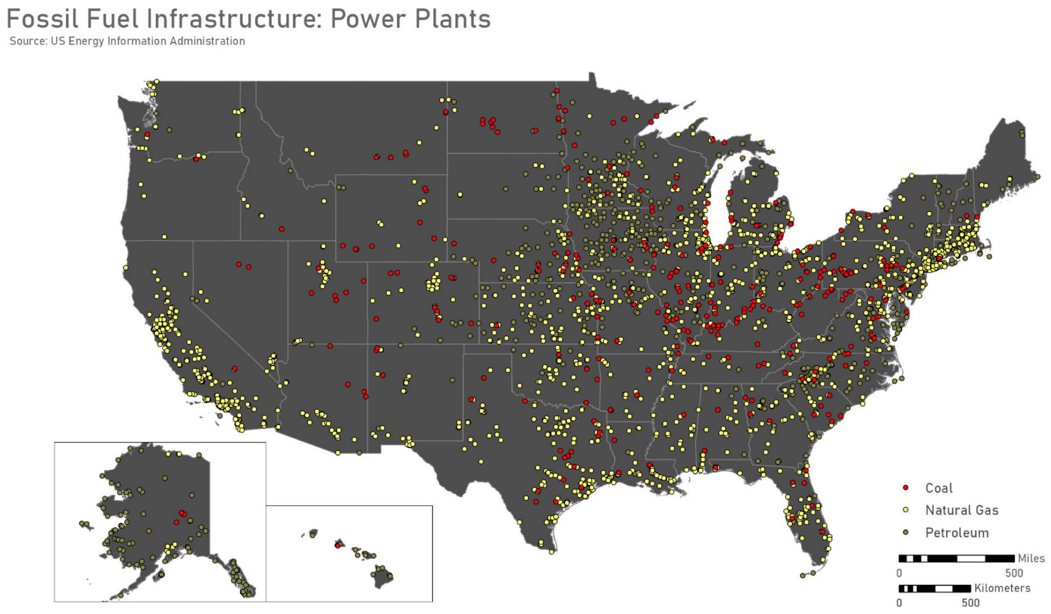
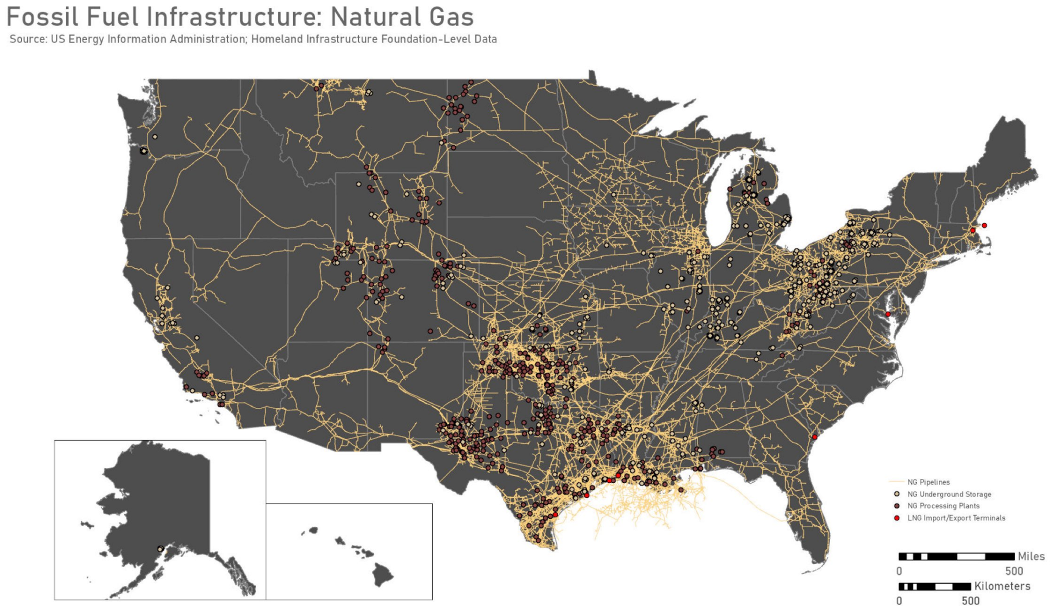
[124] U.S. Energy Information Administration (2018).

[125] **?**.


Fossil Fuel Infrastructure: Power Plants

Source: US Energy Information Administration

Figure 4: Existing fossil fuel power plants. Source: Energy Information Administration.


Fossil Fuel Infrastructure: Natural Gas

Source: US Energy Information Administration; Homeland Infrastructure Foundation-Level Data

Figure 5: Existing natural gas pipelines, which could be used for low-carbon fuels from renewable resources. Source: Energy Information Administration, Department of Homeland Security.

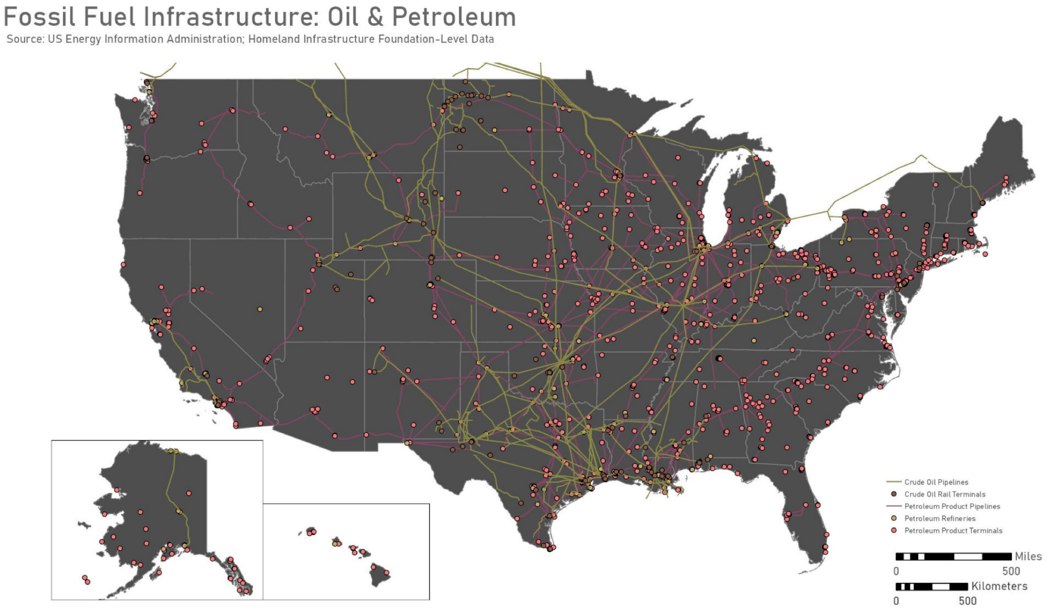
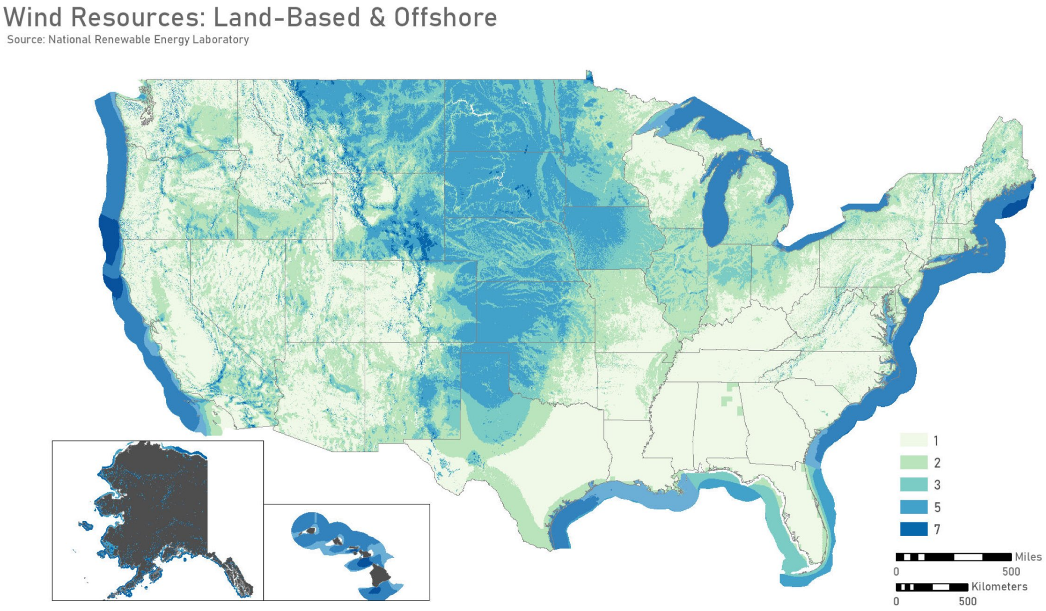


Figure 6: Existing oil and petroleum pipelines, which could be used for low-carbon fuels from renewable resources. Source: Energy Information Administration, Department of Homeland Security.

6.2 Renewable resource potential

As discussed above in the beginning, deep decarbonization of the U.S. energy system will require a dramatic expansion in the use of renewable energy sources such as wind and solar. In the last decade, a combination of federal and state policies with drastically lower prices for solar and wind have made renewables cost-competitive with all other energy sources for electricity generation. Renewable energy sources, however, still only account for just over one-tenth of all U.S. energy consumption.

The following two maps illustrate the geography of renewable energy potential. Figure 7 shows that for wind energy, there is high potential in the areas just east of the Rocky Mountains and north of Texas, where wind power reaches Class 5 and above. There is also significant potential for offshore wind development in portions of the Pacific Northwest, Eastern seaboard, and in the Great Lakes. Figure 8 shows that solar potential is highest in states like New Mexico, Arizona, Nevada, and the lower half of California.



Wind Resources: Land-Based & Offshore

Source: National Renewable Energy Laboratory

Figure 7: Wind resource potential, on- and off-shore, as measured in wind power classes. Source: National Renewable Energy Laboratory.

6.3 Climate adaptation risks

The effects of extreme weather and hazards related to climate change vary by region, but system-wide impacts expected for the energy system include overall reduction in grid effi-

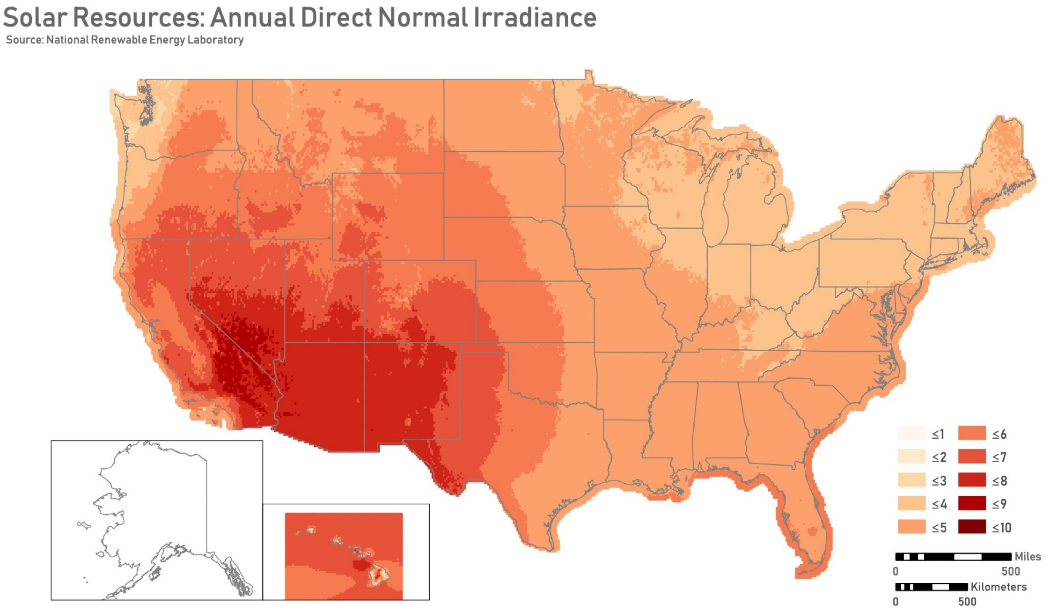


Figure 8: Total areas of renewable resource potential, measured in kWH / m2 per year. Source: National Renewable Energy Laboratory.

ciency and higher demand for electricity.[126] Because power is essential to the core functions of much of society and the economy, vulnerabilities in the energy system represent a critical policy and planning challenge across all levels of government. Future climate adaptation risks must be considered in any future energy transition.

In order to communicate the risks of climate change and associated extreme weather events, Four Twenty Seven, an analysis firm that recently became part of Moody's Analytics, has produced indices to measure the exposure of U.S. municipalities to five different climate risks: cyclones, sea level rise, extreme rainfall, heat stress, and water stress. The dataset evaluates several precipitation- and temperature-based indices together in order to measure relative and absolute change in frequency and severity of extreme conditions between historical baselines and a forecast period between 2030-2040. All 3,142 counties in the U.S. are scored from zero to 100 for each of the five climate risks listed above, identifying vulnerable jurisdictions.

Sea level rise and flooding threaten coastal infrastructure, including roads, bridges, power plants, and transmission lines. Periodic and then permanent flooding will cost jurisdictions billions of dollars for repair, maintenance, and relocation of existing infrastructure. Entire communities and ecosystems along coastal zones are at risk and there is growing evidence that global vulnerability may be underestimated. Sea level rise risk captures (1) the frequency of inundation due to a combination of sea level rise, storm surge, and high tides and (2) changes in the frequency of inundation between historical baselines and 2040.[127]

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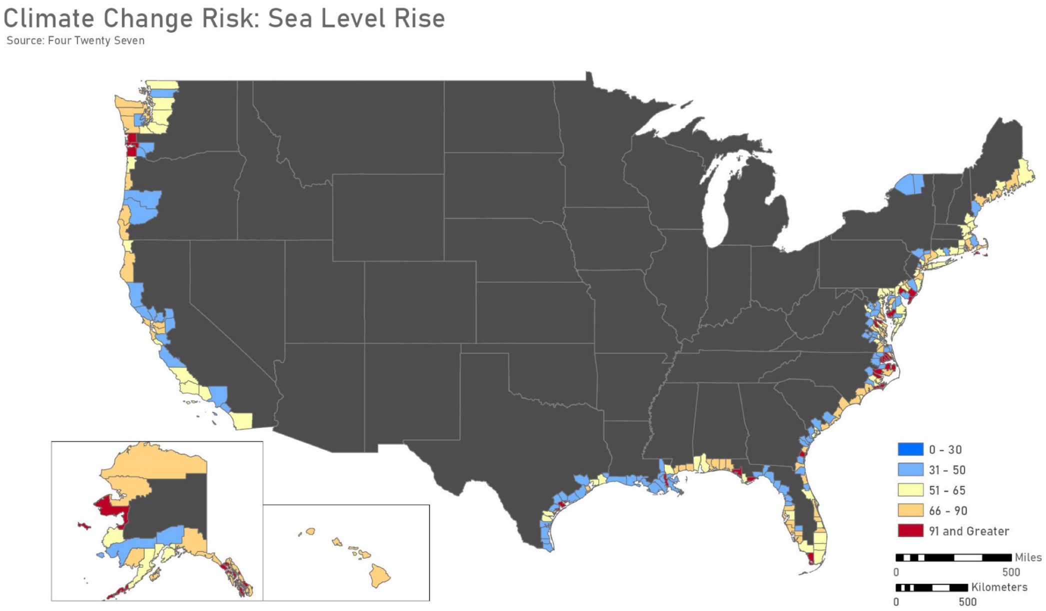
[126] Zamuda et al. (2018).

[127] Four Twenty Seven (2018).

The index mapped in Figure 9 relies on projections and relative change from historical values of extreme water levels, global high-resolution digital elevation models, and population data to measure each county's exposure to sea level rise. The dataset also assumes local median sea level rise projections under carbon emissions scenario RCP 8.5, the lowest mitigation effort scenario. Counties in New Jersey, North Carolina, Florida, and Virginia are most at risk for sea level rise and storm surges. Beyond the mid-Atlantic, jurisdictions in California's Bay Area, the Pacific Northwest, and Alaska are also vulnerable to coastal flooding. The three counties that are most at risk for sea level rise are Monroe County in Florida (which is also in highest risk class for cyclones), Cape May County in New Jersey, and Nome County in Alaska.


Climate Change Risk: Sea Level Rise

Source: Four Twenty Seven

Figure 9: Sea level rise risk. Source: 427mt.

Cyclonic risk measures the exposure to tropical hurricanes and typhoons, which cause destructive damage to communities and built structures. The index mapped in Figure 10 reflects the cumulative wind velocity from recorded cyclones over the 1980-2016 period and includes the severity of storms with the highest maximum winds and the frequency with which an area is hit by severe storms. Tropical cyclone track data is taken from IBTrACS version 3, which creates wind field radii estimates for tropical storms and hurricanes. U.S. county boundaries are intersected with estimated local wind maxima for each storm experienced at that location and aggregated to measure cyclonic frequency and severity. Projections of higher heat content in the world's oceans are expected to energize more intense hurricanes in the coming decades.

Unlike exposure to sea level rise, hurricane risk is much more geographically concentrated. Communities in the Southeast region and parts of coastal Mid-Atlantic and the Northeast are at greatest risk for cyclones. This is partially due to the proximity to large bodies of warm water that contribute to tropical storms. Notably, much of Florida is at high risk for hurricanes, as well a significant number of counties in North Carolina. In fact, thirty-two North Carolina counties rank in the highest risk class for cyclones. Large sections of oil and gas infrastructure along the Gulf of Mexico are also threatened by hurricanes.

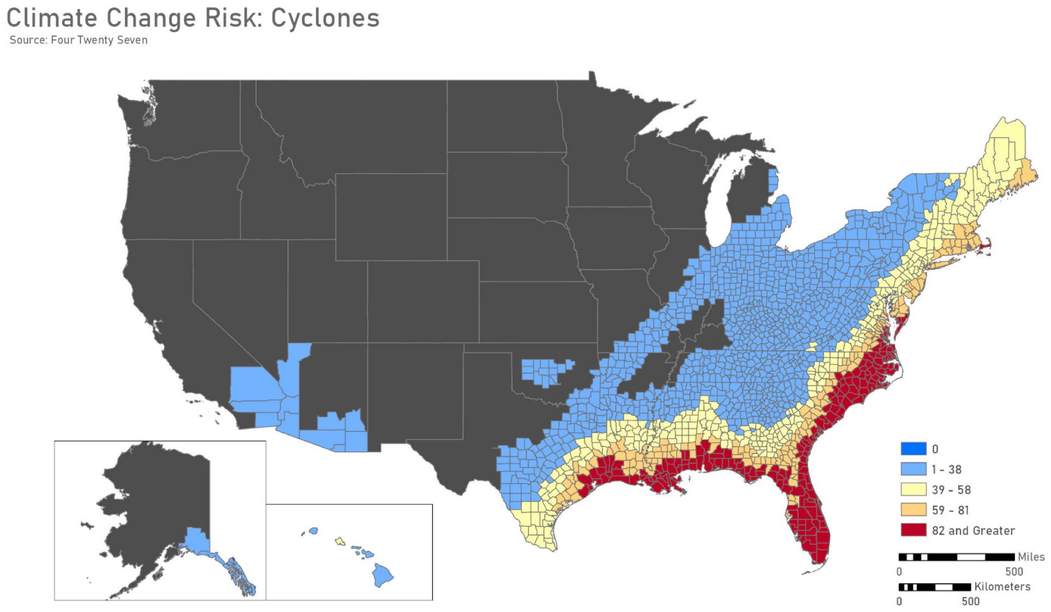

Climate Change Risk: Cyclones
Source: Four Twenty Seven

Figure 10: Cyclonic wind risks. Source: 427mt.

Higher temperatures are expected to have far-reaching impacts on communities, from lower labor productivity to higher demand for electric power and reduced power production efficiencies. Heat stress is particularly risky in cities due to the urban heat island effect, a phenomenon in which metro areas experience warmer temperatures than its surrounding rural areas due to modification of land surfaces and the intensity of human activities. The heat stress index mapped in Figure 11 includes the percent change in annual maximum temperature compared to the baseline period (extreme temperature), the additional number of extreme heat days, and changes in energy demand. Western Illinois and Missouri bear the greatest risk to heat stress, as well as counties in the Great Plains and the Mississippi River Basin. The southern parts of Florida and all of Hawaii are also among the highest risk of heat stress.

Water stress measures the expected changes in drought-like patterns, based on a range of variables including absolute and percent changes in water supply and water demand; the

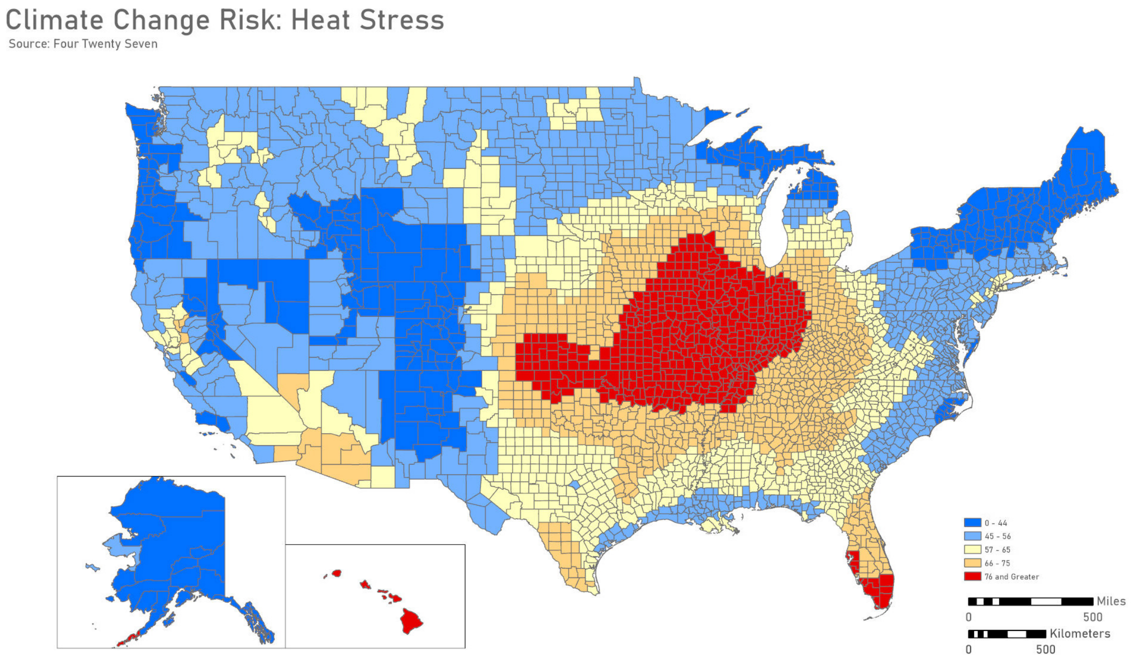


Figure 11: Heat stress. Source: 427mt.

ratio of total annual water withdrawals to total available renewable supply; and variation in water supply. Data is sourced from the Aqueduct Climate Projections provided by the World Resources Institute. Reduced water availability will place pressure on water-intensive industries such as agriculture, pose serious public health risk to vulnerable communities, and create conditions conducive to more frequent wildfires. In the energy sector, water stress is expected to lower available generation capacity, impact oil and gas production, and could disrupt fuel transport.[128]

Figure 12 shows that Western and southern states such as Nebraska, Kansas, Utah, Texas, and California rank high in vulnerability to water stress. Imperial County, an agricultural community in southern California, is the most vulnerable jurisdiction to future water stress. In addition to agricultural communities, urban areas will also face the burden of water scarcity. Consumption in fast-growing metro areas such as Las Vegas, Phoenix, and Greater Los Angeles will all challenge existing water supplies, and could require additional and significant capital investments or changes in pricing in the future.[129]

Protracted periods of heavy rainfall, which lead to destructive flooding, is part of a broader increase in climate change-induced extreme events. The extreme rainfall index mapped in Figure 13 includes changes in five-day rain volumes, defined as the percent change

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[128] U.S. Department of Energy (2013).

[129] Four Twenty Seven (2018).

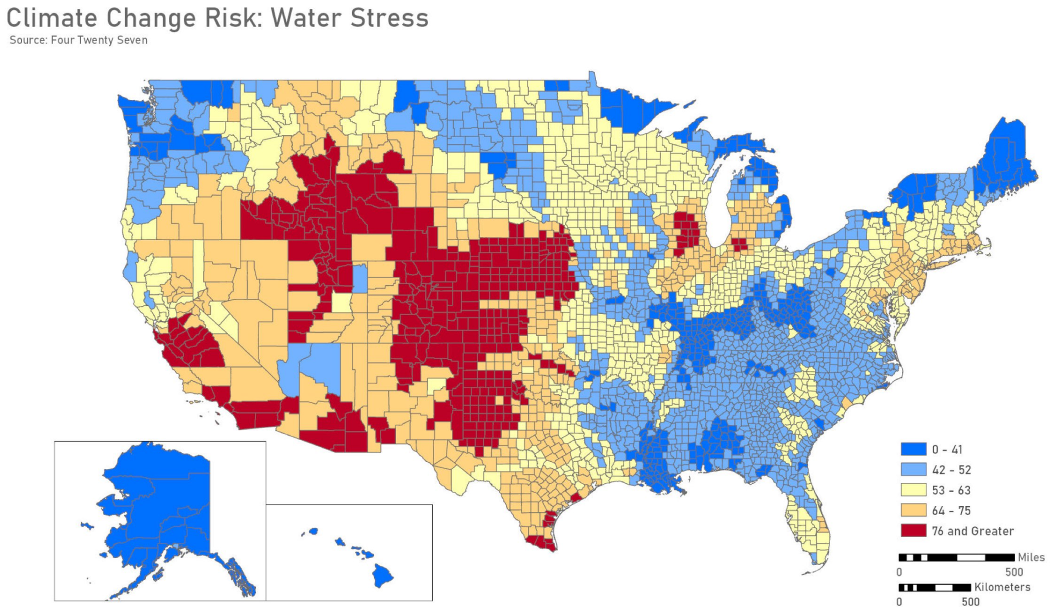


Figure 12: Water stress. Source: 427mt.

in the total maximum volume of rainfall in a five-day period in 2030; additional wet days, the additional number of days when daily precipitation exceeds 10 mm; and additional number of very wet days, the extra number of days when daily precipitation exceeds the local 95th percentile rainfall history.

The Midwest and Appalachia are particularly exposed to flood risk from extreme rainfall. Summers County in West Virginia, Hocking County in Ohio, Radford County in Virginia, and Vinton County in Ohio are among the riskiest areas for rain-induced flooding. Jurisdictions in northern California and the Pacific Northwest are also vulnerable to extreme rainfall.

Figure 14 illustrates the composite scores of cumulative exposure to sea level rise, cyclones, heat stress, water stress, and extreme rainfall at the county level. Any infrastructure program or policy adopted in these communities will need to assess carefully the physical and social risks of emerging climate threats to individual communities. Some climate impacts may be hyper localized, affecting a neighborhood district or a specific infrastructure asset, while others may cross jurisdictional lines and cascade into regional systems. The convergence of multiple climate change hazards also poses a serious challenge to policymakers, engineers, and planners.

6.4 Population growth forecasts

In addition, shifts in population concentration will determine where next generation infrastructure will be placed, as this will influence demand for energy. To highlight this, Figure 15

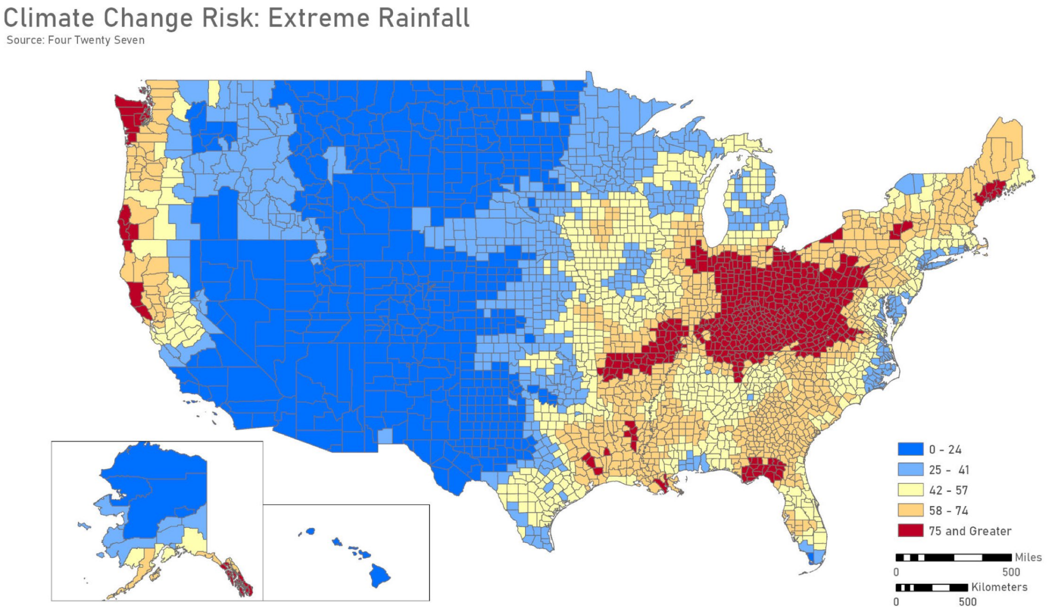
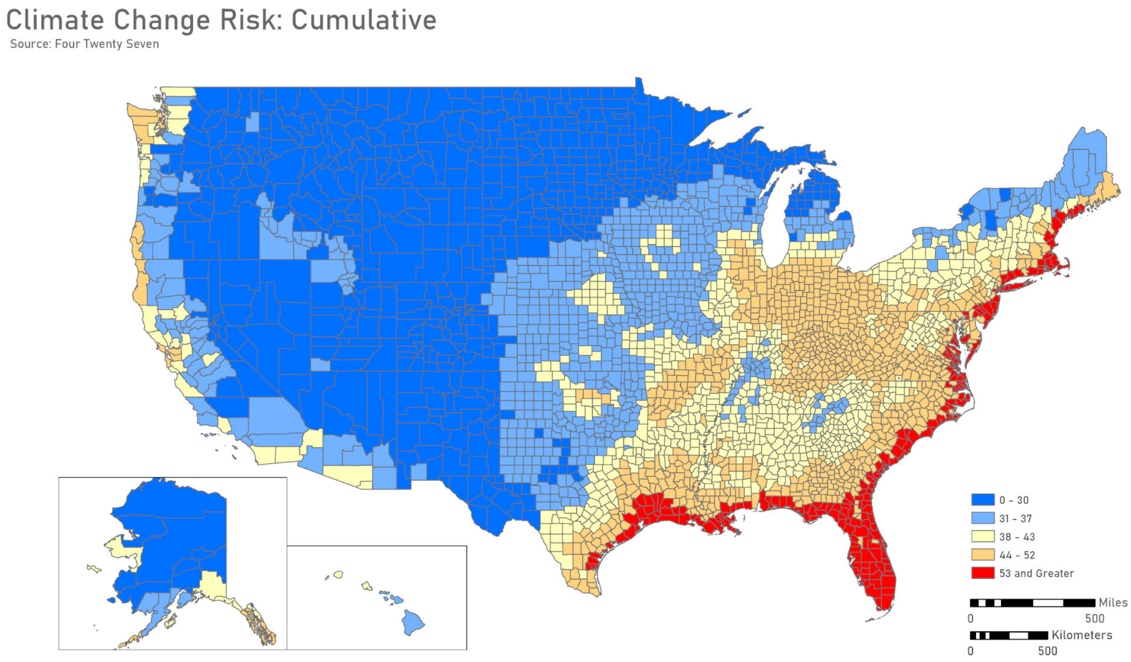


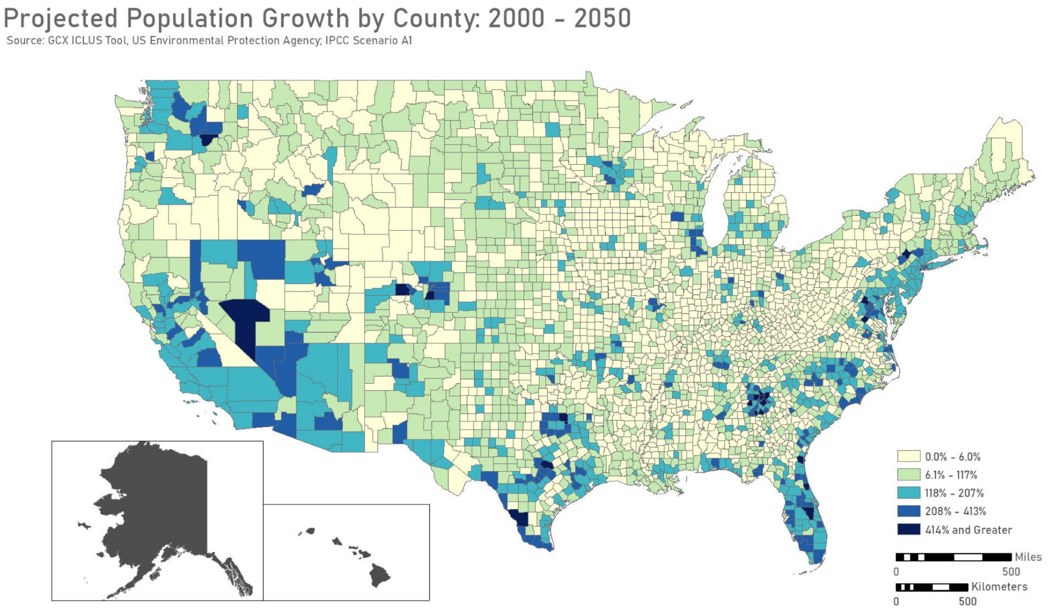
Figure 13: Extreme rainfall. Source: 427mt

shows projected population growth between 2000 and 2050, taken from the EPA's Integrated Climate and Land-Use Scenarios Tool. This maps uses Scenario A1, as determined by the IPCC, in which there is significant population growth in states in the South and Southwest. When intersected with the climate risks data from Four Twenty Seven, we identify a number of counties that are both highly exposed to climate change hazards and are expected to experience significant population growth under this scenario.


Climate Change Risk: Cumulative

Source: Four Twenty Seven

Figure 14: Cumulative risk. Source: 427mt.


Projected Population Growth by County: 2000 - 2050

Source: GCX ICLUS Tool, US Environmental Protection Agency; IPCC Scenario A1

Figure 15: Projected population growth. Source: EPA GCX ICLUS tool, IPCC Scenario A1.

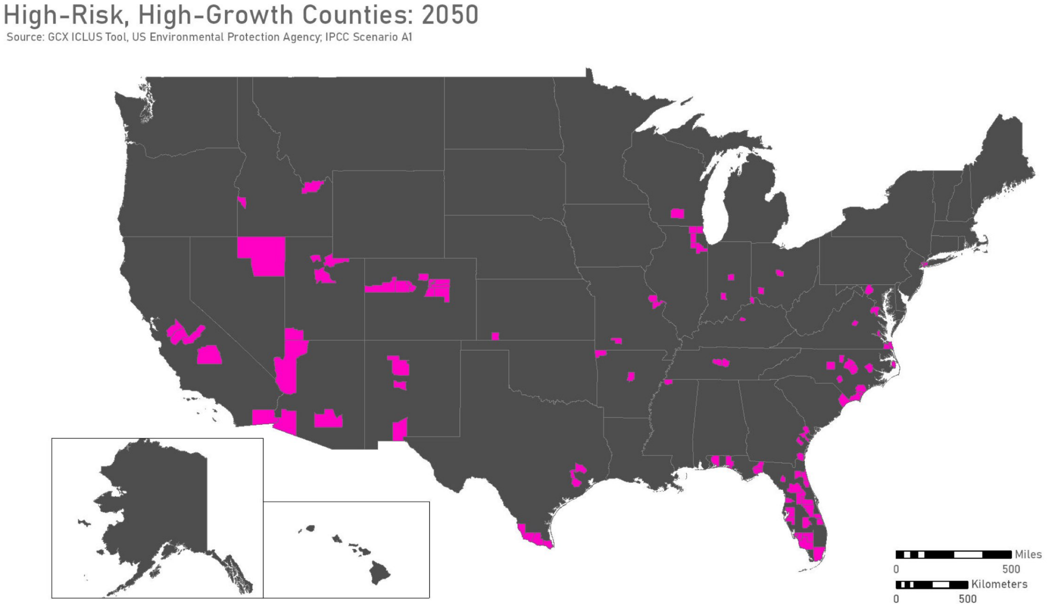


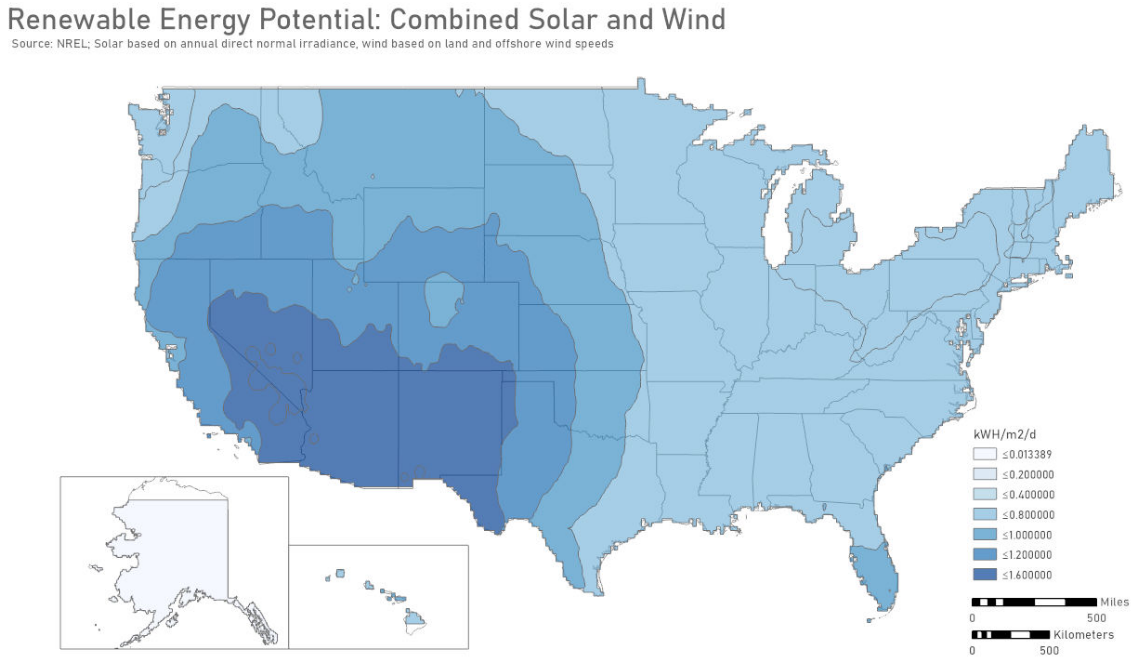
Figure 16: High risk, high-growth countries in 2050. Source: 427mt, EPA GCX ICLUS tool, IPCC Scenario A1.

6.5 Combined maps and layers

Balancing the competing and intersecting challenges described above will all require coordination between the federal government and state and local jurisdictions. It is important to recognize that each locality will face a unique combination of climate risks, fossil fuel assets and renewable energy resources, and institutional and technical capacities.

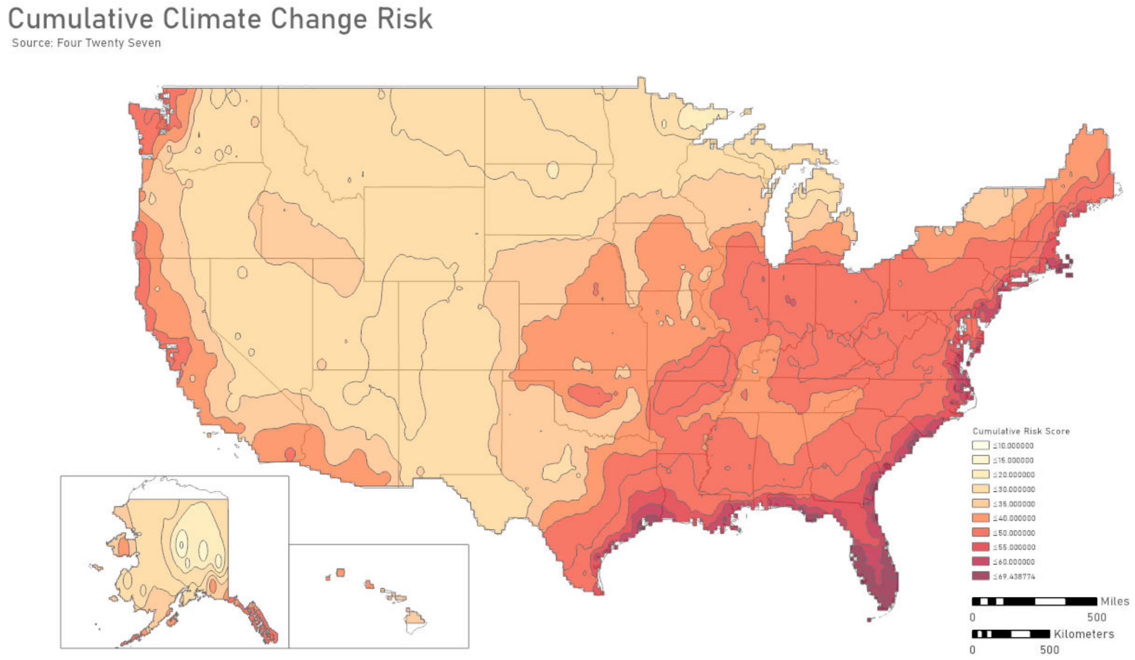
The following map sequence summarizes the complex landscape of threats and opportunities from the previous analyses. The yellow layer of the maps shows the U.S.'s existing fossil fuel infrastructure; areas in blue indicate sites with high renewable potential, largely in the Southwest (solar), upper Midwest (onshore wind), and coastal (offshore wind) regions; and areas in red indicate regions that are at high risk from climate change. Deep decarbonization policies and programs therefore must be designed to respond effectively to many combinations of phenomena. For example:

- The Southwest and upper Midwest regions have high renewable potential and relatively low population, but are at risk of extreme heat and water stress.
- Florida has high renewable potential, but also high population as well as significant risks of cyclones, rainfall, and sea level rise.
- Appalachia has a great deal of existing fossil fuel infrastructure, little or no renewable potential, moderate population density, and risks of heat stress and extreme rainfall.
- Certain states like Nevada have low population concentration and fossil fuel infrastructure, but significant renewable energy potential and are relatively lower at risk for climate change hazards.


Renewable Energy Potential: Combined Solar and Wind

Source: NREL; Solar based on annual direct normal irradiance, wind based on land and offshore wind speeds

Figure 17: Combined renewable resources in terms of energy density per land area. Calculated from NREL and MacKay (2009).


Cumulative Climate Change Risk

Source: Four Twenty Seven

Figure 18: Cumulative climate risks. Source: 427mt.

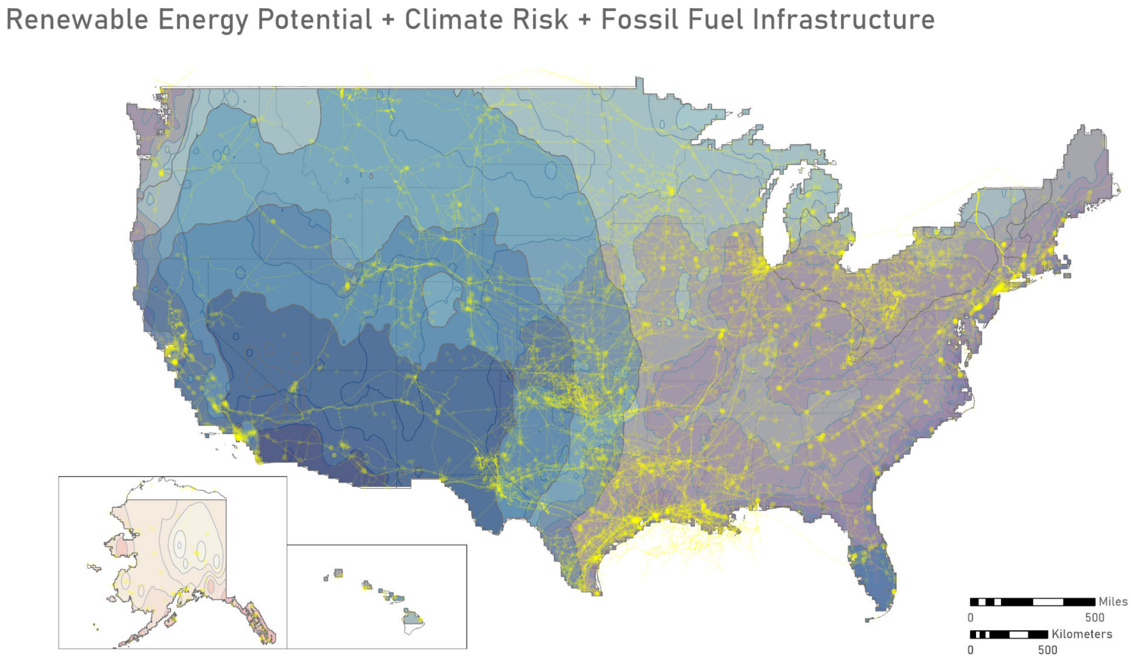


Figure 19: Overlay of fossil fuel infrastructure, renewable energy potential, and cumulative climate risks.

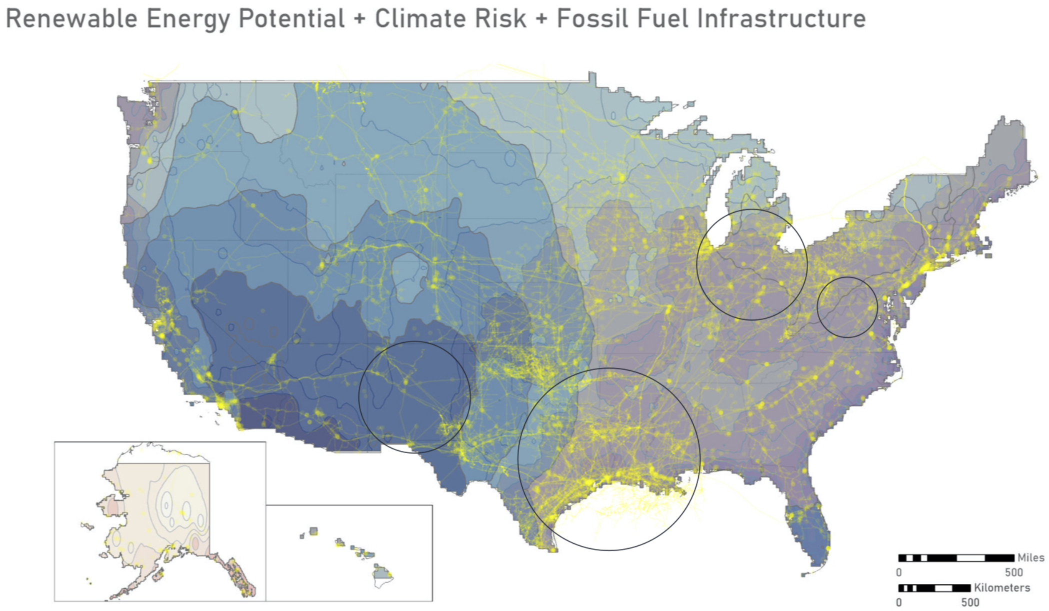


Figure 20: Overlay of fossil fuel infrastructure, renewable energy potential, cumulative climate risks, and proposed study areas.

7 Conclusions and synthesis

This paper analyzes how and where necessary energy infrastructure must be built for the U.S. to achieve deep decarbonization. Here, we will conclude by summarizing the key findings of this paper, and how they can be implemented in recommendations and future work.

Section 2 briefly described key needs for infrastructure towards deep decarbonization, including: new clean and renewable resources; the development of replacement fuels for the sectors that are difficult to electrify, like industry and aviation; new transmission and storage infrastructure for the expected carriers of electricity and hydrogen; and the need to change uses and processes to reduce our energy use drastically.

Section 3 recounted the history of major energy systems in the U.S., including existing fossil-fuel resources of coal, oil, and natural gas; large-scale hydropower in several major river basins; and the nucleation of electricity grids in urban areas, spreading to rural areas, and eventually interconnecting into a continental grid. In general, the private sector developed fossil fuel resources depending on their geological distribution, the federal government developed large-scale hydropower for multiple uses such as electricity, flood control, irrigation, and navigation; and the electrical grid was developed by investor-owned utilities regulated by public utility commissions, as well as municipally-owned utilities and privately-owned rural co-operatives.

Section 4 describes how our federal political system of government translates into the financing of infrastructure by state and local governments. The federal government has designated but limited powers that preempt state and local governments, but state and local governments retain considerable powers and jurisdiction to plan, build, operate, and maintain infrastructure. Relying on state and local governments to execute national priorities has led to both good experiments and unnecessary fragmentation. Stimulus spending projects in the New Deal and the 2009 ARRA stimulus found it necessary to spread their spending across many states in order to remain politically viable, but also created different projects to suit each state in order to build useful public works and infrastructure.

Combining the analyses in Sections 2, 3, and 4 shows how a national strategy for deep decarbonization will be different in many ways from the building of infrastructure in previous eras. Deep decarbonization will largely be driven by policy rather than the private sector, yet in the first twenty years of this century we have been unable to execute similarly large and visionary projects. Therefore, in order to develop a coordinated and efficient strategy to build new infrastructure rapidly, this paper then examined a number of mechanisms by which all levels of government – federal, state, and local – can coordinate towards building national infrastructure in an efficient and equitable way. Section 5 examines a number of possible financial mechanisms as well as legislative, regulatory, and legal changes. The most studied proposed program is a national infrastructure bank similar to the existing international infrastructure banks, but competitive grants and regional development funds are two other ways by which national goals have been implemented in decentralized, federal systems. Legislative, regulatory and legal changes can and should be implemented at all levels of government in order to enable both markets and policies to act as quickly as possible.

The mapping analysis in Section 6 shows how existing fossil fuel infrastructure, renewable energy potential, and climate adaptation risks are unevenly distributed throughout the U.S. These maps are useful to identify specific areas of concern, and representative locations for regional planning efforts that can contribute the national-level goal of deep decarbonization. For example, the Southwest and upper Midwest have high renewable potential, relatively low population, but are at risk of extreme heat and water stress; Florida has high renewable potential, but also high population as well as significant risks of cyclones, rainfall, and sea level rise; Appalachia has a great deal of existing fossil fuel infrastructure, little or no renewable potential, high population, and risks of heat stress and extreme rainfall; and certain states like Nevada have a low concentration of population and fossil infrastructure, but significant renewable energy potential and are relatively lower at risk for climate change hazards.

Taking these findings into account, a key strategy that emerges is that deep decarbonization will require a diverse set of infrastructure systems that must be built throughout the entire U.S., ranging from new renewable resources to efficiency investments in buildings, industry, and transportation. Both a reduction in energy use and substitution of existing fuels are necessary in order to achieve deep decarbonization. We therefore propose that the overall national plan remains flexible enough to allow local, state, and regional plans to determine the best local investments towards deep decarbonization, while still fulfilling national goals. For example, the following regions might pursue the following strategies:

- the Northeast, where there are relatively dense populations along with relatively little renewable energy potential except for the promise of offshore wind, the best possible investment might be transmission lines to import renewable energy and allow offshore wind to feed into the grid, as well as investing in energy efficiency for existing uses;
- the Midwest, where there are dense populations that stand to lose substantial fossil fuel infrastructure, replacing existing fossil fuel jobs with manufacturing jobs for new infrastructure is a possibility;
- the Southwest, where there is ample renewable potential and relatively lesser climate risks, may become a major exporter of renewable energy given sufficient transmission capacity
- and so on.

Many of the proposals for a national infrastructure bank emphasize its ability to decide on the most efficient and best investments, rather than our currently haphazard process of allocating funds to states and local governments, either on the basis of existing formulas or earmarks. However, the sheer size and speed of the necessary investment in energy infrastructure for deep decarbonization means that prioritizing among projects may be less important. For example, while both tasks are necessary, when compared to the difficult task of designing an optimal energy transmission system, energy efficiency investments in public buildings might be much more quickly and equitably distributed according to population. A national infrastructure bank, however, could play a critical role in providing technical expertise and the processes to coordinate large, complex, long-term infrastructure projects, as well as maintaining the stable long-term goals needed to stimulate private investment.

In addition, based on experience in the New Deal, policymakers often found themselves deciding between trying to build employment or long-term infrastructure. Now, in order to achieve the project of deep decarbonization, we too must decide whether our goal is to build people, projects, or whether we can do both, keeping in mind that what we decide will in turn affect the long-term political and economic viability of the project. Any decisions that the U.S. makes now will only be the first of many more that will be required to mitigate and adapt to climate change, but the only alternative to making these decisions is to do nothing.

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