Received: 29 December 2021 | Accepted: 29 December 2021

DOI: 10.1002/ep.13798

SPECIAL SECTION

ENVIRONMENTAL PROGRESS & SUSTAINABLE ENERGY

Modernizing the U.S. electric grid: A proposal to update transmission infrastructure for the future of electricity

Sara Murphy

Chemical & Biological Engineering Department, University of Idaho College of Engineering, Moscow, Idaho, USA

Correspondence
Sara Murphy, Chemical & Biological Engineering Department, University of Idaho College of Engineering, Moscow, ID 83844, USA.
Email: murphy.sara1217@gmail.com

Abstract

Electric transmission infrastructure is often undervalued in the United States. However, a recent surge of electrical blackouts due to extreme weather conditions and natural disasters has brought the United States' aging transmission infrastructure to the spotlight. Recent cyberattacks on critical energy infrastructure have also brought attention to the vulnerabilities in the U.S. electric infrastructure. Advancements such as the growth of electrification in the transportation sector and the integration of variable renewable energy critical to the decarbonization of the energy sector, further challenge the capacity of current electrical infrastructure. Addressing deficiencies within U.S. electric infrastructure requires the collaboration of many stakeholders including federal agencies, state governments, local communities, and electricity generation and distribution entities. To properly undertake the challenges to the United States transmission infrastructure, it is recommended that potential solutions are accurately modeled, that the FERC uses its rulemaking capacity to foster collaboration, and that the federal government creates a national transmission loan program to specifically fund nationally significant transmission projects.

1 | WHY DOES THE ELECTRIC GRID MATTER?

Electricity is an underemphasized asset within the United States. From heating and cooling our homes, to ensuring that all our smart devices are charged and ready for use, electricity is key. Within the past 2 years, access to reliable electricity has also empowered workers and students to continue their work and school obligations from home while COVID-19 safety protocols limited traditional attendance. Access to reliable electricity also enables the U.S. economy to produce goods and services and compete on the international market. The electric grid serves the purpose of transporting electricity from production to the American consumer, whether that consumer is a household or a production facility. In short, the United States electrical infrastructure is critical for powering all Americans' lives.

1.1 | The basics of the electric grid

The electric grid is a complex network that transmits electricity between power plants and the consumer. The components of the electric grid include power plants, transformers, transmission lines, substation transformers, distribution lines and load as highlighted in Figure 1.[1] Power plants generate electricity by converting a fuel source like natural gas, sunlight, or wind to electricity. After power plants, the next stage is transformers where generated electricity is then converted from low voltage electricity to high voltage. Transmission lines then distribute this high voltage electricity within the grid and serve as an "interstate" system for electricity.[1] Electricity is carried by transmission lines to substation transformers which then "steps down" the voltage of electricity for distribution.[1] Distribution lines serve the load of an area and serve as the local system for electricity.[1] Load can be considered as the "consumer" of electricity

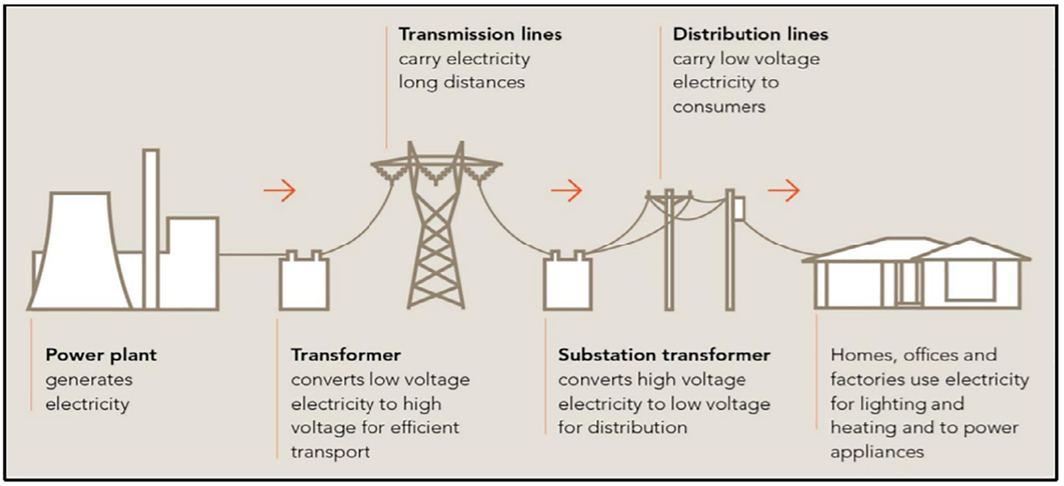

FIGURE 1 Components of the electric grid[1]

whether the electricity be for lighting, powering up appliances, or heating or cooling our homes and businesses.[1] At this stage, the electrical consumption of consumers is metered and billed.

For the scope of this policy paper, the focus is going to be on updating transmission infrastructure of the electric grid. This focus on transmission is due to its importance in transporting electricity over long distances, from generator to consumer and from rural areas with generation capacity to urban areas with high load. However, before describing transmission infrastructure, the concepts of current and voltage must be defined. In this context, current is defined as flow rate of electric charge and voltage can be thought of as the "electrical pressure" within a wire.[1] The transmission system consists of alternating current (AC), direct current (DC) and high voltage direct current (HVDC) lines. DC lines work by supplying a constant voltage while AC lines alternate voltage over time. AC lines have less power loss, which makes them more efficient and often preferred over DC lines for spanning long distances. While DC and AC transmission lines are more prevalent, the use of HVDC is growing. The prevalence of HVDC lines is expected to continue growing as it is more efficient to transport high voltage electricity over long distances. HVDC systems also contain technology that can convert AC and DC voltage and can be used to support existing systems and new infrastructure. It is for these reasons that HVDC lines and systems are seen as a possible solution to the current challenges that plague U.S. transmission infrastructure. Focusing solely on updating transmission infrastructure allows the United States to take one step toward creating a more robust, interconnected grid, without being overwhelmed with other challenges.

1.2 | The human element

Limited access to electricity can affect people's livelihoods and even their health. This is especially true when electrical blackouts occur in extreme weather events such as heat waves or winter storms. These blackouts can occur when there is damage to electrical infrastructure or equipment failure at a power plant. Electrical blackouts may also occur when the load overwhelms what the utilities can supply, resulting in complete blackouts or "rolling blackouts" where electricity is deliberately turned off in several areas sequentially for a specified amount of time to reduce demand. Brownouts are like "rolling blackouts" as they also reduce electrical load but do so by limiting the level of voltage to homes and businesses. Load tends to become an issue in extreme weather events since individuals increase their use of air conditioning or heating to remain comfortable and therefore strain the grid.

A research study from the journal *Environmental Science & Technology* found that blackouts have increased by 60% since 2015.[2] This trend is illustrated in Figure 2[3] which shows the amount of major blackout events and the average duration of said events between the years of 2015 and 2019. Blackouts in conjunction with heat waves are of particular concern, since air conditioning is not an option, and the extreme heat can cause health problems like heat exhaustion or heat stroke. These researchers estimated that two-thirds of residents from Atlanta, Georgia, Detroit, Michigan, and Phoenix, Arizona would be at risk for heat-related health conditions if a heat wave and a blackout were to occur simultaneously.[2,3] Additionally, it was noted that cooling centers which are powered by backup generators, could only provide for 2% of these three cities residents, leaving many residents at risk and in the dark.[2,3]

Utilizing Texas as an additional case study, it is evident that no matter the type of extreme weather event, the electric grid needs to be updated to be more robust and better connected. For example, in February 2021, 69% of Texans lost electricity for an average of 42 hours while the temperature in some areas reached below freezing.[4] Part of the reason these blackouts occurred in Texas was because natural gas pipelines froze and diesel engines would not start, thus forcing power plants to go offline in the extreme winter conditions.[5] Texas also faced similar problems with heat waves in the summer months of 2021. For instance, in late June 2021, Texas residents were asked to place their thermostats no lower than 78 °F in an effort to reduce the electrical demand on the grid.[6] The use of Texas as a case study is key because it highlights how a state's isolation from other generation sources can be catastrophic in extreme weather conditions. By modernizing and interconnecting current transmission infrastructure, states like Texas would be supported by additional electricity supply and the number of Texans and Americans that experience blackouts every year could be reduced.

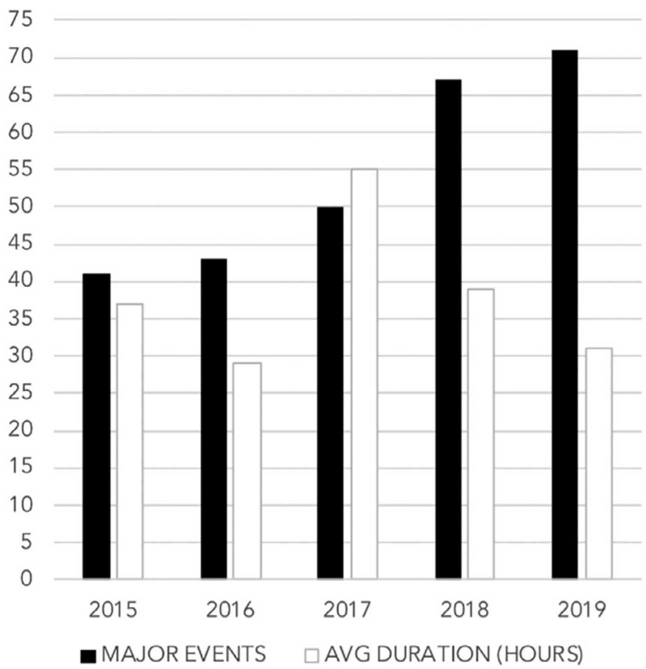

FIGURE 2 Total number of major electrical grid failure events and average event duration (hours) for U.S. power utilities (2015–2019)[4]

2 | WHY UPDATE THE GRID NOW?

2.1 | Growth of electrification

Figure 3[7] highlights the historical electricity consumption per sector in the United States from 1950 to 2020 and 2021 to 2050 projections of anticipated electricity consumption. One notable trend is the relatively limited growth of electricity consumption in the commercial, residential and industrial sectors.[7] This limited growth can be attributed to the recent focus on energy efficiency in these sectors. Utility companies have further galvanized energy efficient measures by offering rebates and incentives to facilities that are energy efficient. Many of these measures also benefit businesses as the reduction in energy use also leads to cost savings. Limited growth in the industrial sector can also be credited to the recent shift offshore of American manufacturing.

An important trend in Figure 3 is the projected increase of electricity consumption in the transportation sector. Said growth is expected to continue as electric vehicles (EVs) become more prominent in personal use and in public transportation. For example, in 2020 1.8 million EVs were registered, which was three times the

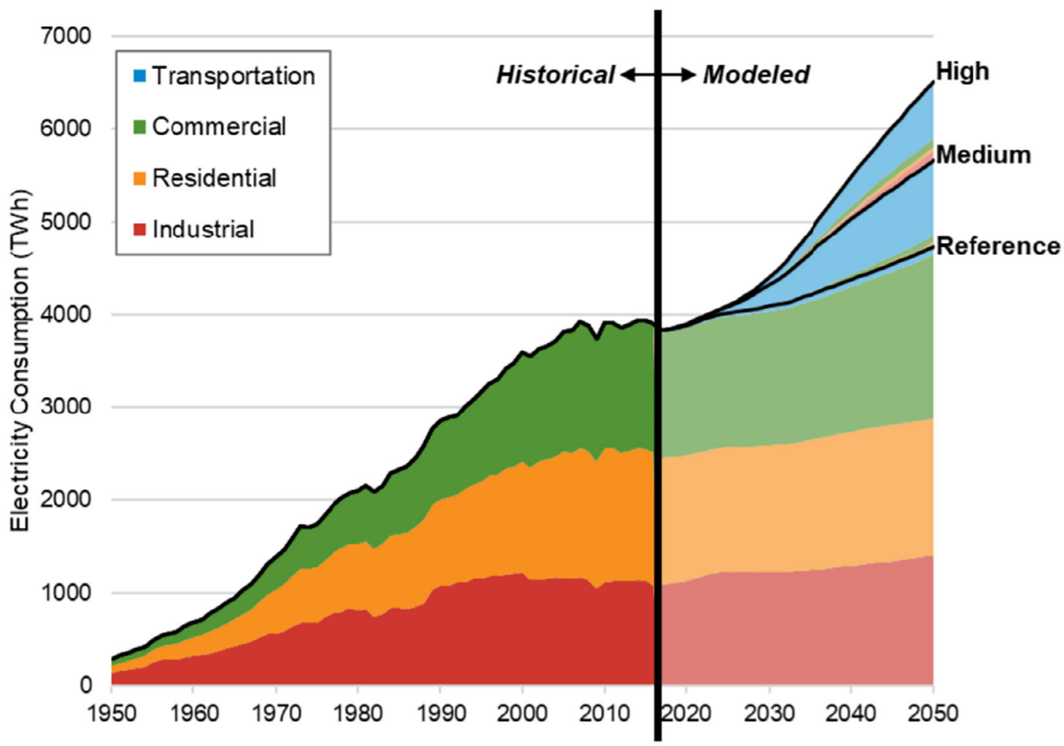

FIGURE 3 United States historical and projected annual electricity consumption[7]

amount that were registered in 2016.[8] Support for EVs is partially due to recent pushes to reduce greenhouse gas emissions in the transportation sector. President Biden emphasized this as well when in August 2021 he signed an executive order that aims to make half of the American car sales electric cars by 2030.[9] Additionally, a study conducted by Lawrence Berkley National Laboratory predicts that battery costs will continue to decline and thus EV prices will also continue to decline, allowing EVs to be a more feasible purchase for the average American.[10] Car manufacturers are also getting on board as General Motors recently announced it will no longer be selling gasoline-powered passenger vehicles by 2035 and will be expanding its offerings of EVs.[11] There are also long-term advantages for individuals who consider purchasing an EV over a traditional gasoline vehicle. One study conducted by the Department of Energy (DOE) found that an EV is about 4 cents per mile less expensive than the traditional gas vehicle when considering common maintenance costs.[12] While at first this does not sound like substantial savings, the savings add up as more miles are driven. For example, during the average lifetime of an internal combustion engine, about 200,000 miles, it will cost about $20,200 to maintain a traditional gasoline vehicle while it would cost $12,200 to maintain an EV.[12]

Electrification of public transportation is also expanding more than previously expected. This is especially the case after the Biden Administration's call for 20% of the nation's school buses to be electric.[11] Other policies such as the Low-or-No Emission Grant program or the Diesel Emissions Reduction Act (DERA) grants have further mobilized the use of EVs for public transportation. Many municipalities have also started utilizing electric buses due to their long-term cost saving opportunities despite the fact that the initial cost is double that of a traditional, diesel bus.[11] These long-term cost savings allow public transportation departments to evaluate the benefit of building an electric fleet now, for commuters of the future.

This is not to say that electric transportation does not have room for technical improvement. For EVs to truly dominate the market, on-board storage capacity will have to continue to increase to extend the current range. There will also have to be faster recharging rates for long distance applications. Updates to the current electric grid will be critical to increasing the role of EVs in transportation. As researchers from Lawrence Livermore National Laboratory found, modern power infrastructure is vital for EVs to make up a large fraction of the light-duty vehicle fleet.[10] Namely, updates to transmission infrastructure would assist in establishing widespread EV charging infrastructure. Overall, by modernizing the electric grid, the United States has the opportunity of ushering in a new era of electric transportation with reduced greenhouse gas emissions. However, without updating the current electric grid, this future will be difficult to obtain.

2.2 | Changing electricity mix

In the last 10 years, the United States has drastically shifted what sources it uses to produce electricity. As shown in Figure 4,[13] natural gas surpassed coal-fired power plants as the predominant source of electricity production in 2015. The U.S. Energy Information Administration (EIA) reported that over 121 coal-fired power plants were retired or repurposed between 2011 and 2019, with 103 being converted in natural gas-fired plants.[14] The EIA attributes the shift from coal to natural gas power generation to three factors: (1) stricter emission standards, (2) low natural gas prices and (3) updated gas turbine technology.[14] In contrast to the changes in the use of coal and

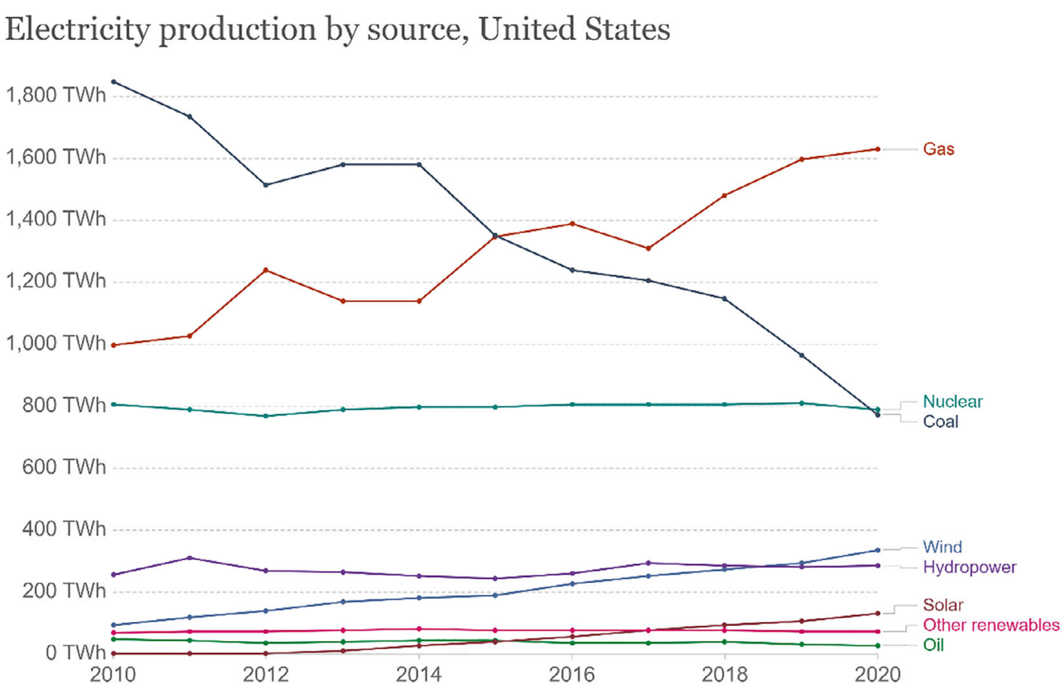

FIGURE 4 Electricity production by source, United States[13]

natural gas for electricity production, nuclear and hydropower sources have remained about constant over the last 10 years.

Another notable trend includes the expansion of renewable energy sources in producing electricity. Like natural gas, the growth of solar and wind's generation can be attributed to recent reductions in cost for the necessary materials and the demand for low and no emission electricity sources. While integrating wind and solar energy into the electricity grid is not a significant obstacle right now, it is predicted to be one in the future. EIA projects that by 2050 wind and solar energy could account for as much as 33% of the total electricity generation,[15] which is expected to create challenges.

Wind and solar energy are termed as variable renewable energy (VRE), which implies that source can only produce electricity when the conditions are right. One of the challenges with VREs is that they are frequently located in rural regions of the United States, as these areas have the best conditions to produce significant amounts of electricity. Unfortunately, the transmission infrastructure is often lacking in these areas, local communities are unable to consume all the electricity produced, and there is minimal storage capacity. Updates to transmission infrastructure would allow electricity generated in rural communities to be transmitted over longer distances and utilized in high demand, urban areas.

VREs are also difficult to merge into the electricity mix because the electric grid was designed to handle "on demand" forms of electricity, and not the intermittent nature of wind and solar generation.[15] For instance, wind speeds are frequently greater at night and thus wind farms produce more electricity, despite electricity consumption being lowest at night. And current U.S. electrical infrastructure lacks the storage capacity to store this electricity for use at another time. In short, VREs face the problem of matching up high generation times to high consumption times. Improving the transmission infrastructure would allow generated electricity to quickly reach consumers throughout the United States with less concern about overlapping VRE's high generation with high consumption times.

Another challenge that makes integrating VREs into the electricity mix difficult is grid congestion. Grid congestion occurs when existing transmission or distribution lines are unable to accommodate high demand or high generation conditions. The best metaphor for this is a traffic jam of electrons on the transmission line. Grid congestion often limits the amount of renewable energy projects that are viable within an area. One example of this occurred in the Midwest region of the United States, where 245 clean energy projects were halted between 2016 and 2020 at advanced development, with the majority of the reasons being the lack of transmission capacity.[16] From this example, it can be extrapolated that the core challenge for integrating VREs is not at the generation stage, but the transmission phase.

One idea to modernize the grid is to build a national high voltage direct current (HVDC) transmission system. Scientists from the National Oceanic and Atmospheric Administration (NOAA) found that such a grid would allow 523 GW of new wind and 371 GW of new solar to be incorporated.[17] To put these values into perspective, 1 GW is about 412 utility-scale wind turbines and can power

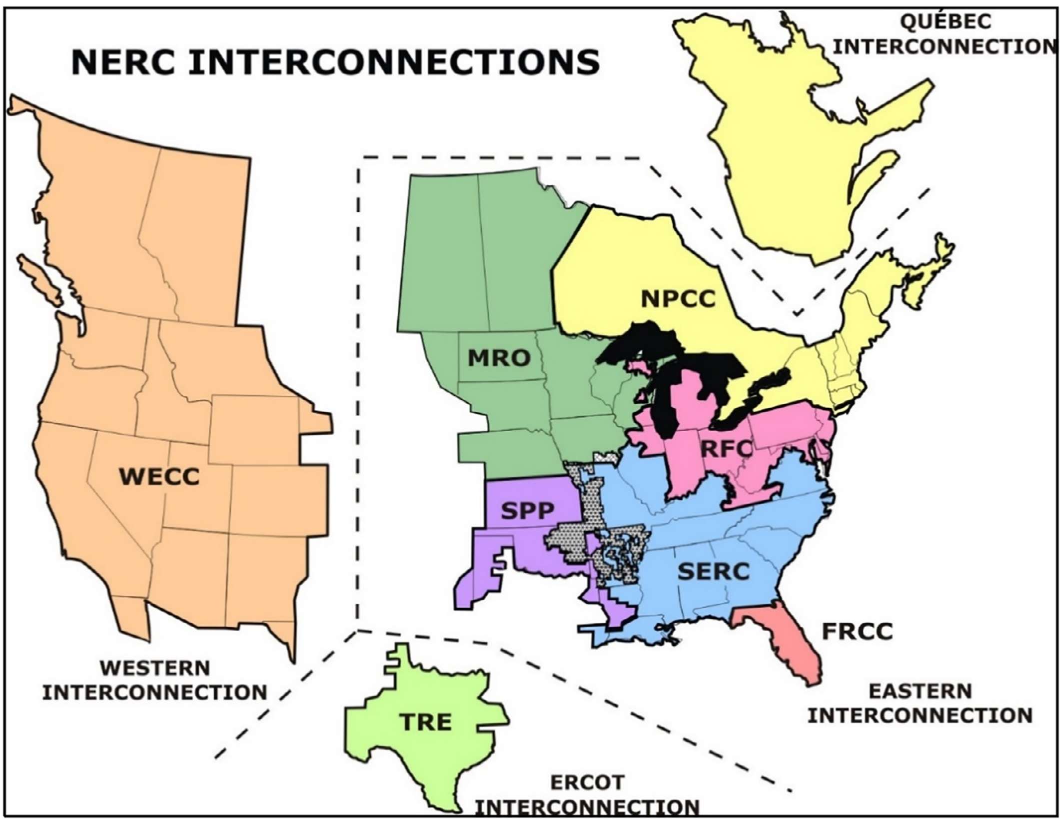

FIGURE 5 North American electric reliability corporation (NERC) interconnections map[19]

about 110 million LED lightbulbs.[18] In addition to modernizing U.S. transmission infrastructure increasing storage capacity to hold excess electricity generated. At present, storage technology is significantly limited and thus is being highly researched, as it is critical that both transmission infrastructure and storage capacity be improved and better integrated into the grid for VREs to aid in U.S. efforts to decarbonize the energy sector.

3 | THE REGULATORY ENVIRONMENT OF ELECTRICITY

3.1 | Regional electric grids

The contiguous United States' transmission system consists of three regional power grids, or interconnections, as seen in Figure 5.[19] Bulk power transmission between and reliability of the interconnections is regulated by a non-profit called the North American Electric Reliability Corporation (NERC). NERC includes parts of both Canada and the United States, making the issue of updating transmission infrastructure a national and international challenge. The two major AC grids of NERC include the Western Interconnection and the Eastern Interconnection while the minor one is the ERCOT Interconnection. ERCOT stands for the Electric Reliability Council of Texas and was created by Texas utility companies to avoid federal regulations.

Because the electric grid in the United States is broken up into regional grids there is limited exchange of electricity between the grids. In turn, this means that the three U.S. interconnections operate in isolation. This isolation is problematic when the electric generation within each individual grid struggles to meet the demand within the region. Understanding the organization of electricity regulation is critical to be able to advocate for future policies affecting transmission planning and electrical infrastructure.

Prior to the 1990s, the majority of U.S. residents received their electricity from investor-owned, vertically integrated monopolies otherwise known as IOUs.[20] During this time IOUs handled electricity generation, transmission planning, local distribution, and billing. However, reforms in the 1990s and 2000s limited the power of IOUs by separating generation owners from the transmission owners and both from distribution system operators (DSO).[20] Electricity consumers saw these reforms as an opportunity to gain access to the wholesale market while utility companies faced the reality that lower consumer prices resulted in "equivalent reductions in returns for utility shareholders."[20] As a result of these reforms, transmission planning became the responsibility of independent system operators (ISOs) and regional transmission operators (RTOs). Figure 5 highlights the various ISOs and RTOs within the United States.[19] The black cross-hatched region in Figure 5 in between the Southwest Power Pool (SPP) and the Southeastern Electric Reliability Council (SERC) represents an overlap of jurisdiction between the two regional entities. The other regional entities shown in Figure 5 include: the Western Electricity Coordinating Council (WECC), the Midwest Reliability Organization (MRO), the Reliability First Corporation (RFC), the Northeast Coordinating Power Council (NPCC), the Texas Reliability Entity (TRE), and the Florida Reliability Coordinating Council (FRCC). DSOs also known as utility companies are not included in Figure 5 as they depend on the locality and can differ even within a state. While ISOs and RTOs handle large-scale transmission planning, DSOs manage metering and billing for their respective customers.

3.2 | The role of federal government

The DOE is the main department within the U.S. government that oversees energy including electricity and electric infrastructure. Within the DOE, there are many programs, agencies, and laboratories. DOE's national laboratories such as the National Renewable Energy Laboratory (NREL) in Golden, Colorado serve as support to the federal government and state governments by providing research studies and specialty experts. Published reports by the national laboratories also assist in informing the public and policymakers about electricity trends as well as in modeling potential solutions to both current and future transmission challenges.

Regulation of energy is handled by the Federal Energy Regulatory Commission (FERC), which is a commission within the DOE. FERC was created to replace the Federal Power Commission that was formed to oversee hydropower dams in the 1920s. In 1935, Congress passed the Federal Power Act which dismantled utility monopolies and required the Federal Power Commission to set "just and reasonable" wholesale electricity prices.[21] These duties were then carried over to the mandate of FERC which was created in 1977. FERC has regulatory authority over the interstate sale of electricity and operation of regional markets.[21] FERC does this by approving the terms and rates of interstate transmission service as described in the transmission owners open access transmission tariff (OATT).[22] OATT requires all public utilities that own, control, or operate facilities used for transmitting electricity in interstate commerce to file open access non-discriminatory transmission tariffs.[23] FERC's goal with OATT was to remove impediments to competition in the wholesale bulk power market and bring more efficient and lower cost power to the U.S. electricity consumers.[23]

Congress has the ultimate authority over FERC and can call FERC commissioners, or senior staff to testify before various congressional committees.[24] The North American Electricity Reliability Corporation (NERC), as previously discussed, operates beneath FERC and oversees the more technical aspects such as power system reliability, operation as well as transmission planning.[21] Due to NERC's more hands-on involvement with electricity it often works with ISOs, RTOs, and DSOs alike.

Overall, FERC mostly serves as a rulemaking commission and is not involved in the technical aspects of electricity. FERC Order 890 outlined the general requirements for local and regional transmission planning practices and procedures. Order 1000 served as an addition to the previous Order 890 while also correcting what the previous order lacked, such as requiring public utility transmission providers to participate in a regional transmission planning process.[25]

This involved instructing these providers to work together with their respective partners in their transmission planning region to determine more efficient or cost-effective transmission plan to meet both their needs.[25] Regional transmission planning efforts were also expected to have a regional cost allocation method for new transmission facilities that met all six regional cost allocation principles.[25] Similar reforms to this were also made for interregional transmission planning efforts. The most contentious reform in Order 1000 was the one that allowed non-incumbent transmission developers to complete transmission projects within the service area of incumbent utilities.[22] This reform was created in hopes it would drive competition within these areas and that non-incumbent developers could build transmission infrastructure at lower costs. However, this reform was not well-received by incumbent utilities. While FERC's Order 890 and Order 1000 did increase spending on transmission, there are still concerns with the United States' electric transmission infrastructure. These concerns include: the lack of transmission projects that independent developers can bid on and that the current investment into transmission is not enough to meet future electricity needs.[22] Such concerns among others are why electric transmission infrastructure remains a consequential issue and why new policies must be written, and new technology must be implemented.

4 | KEY CONFLICTS AND CONCERNS

4.1 | Conflict of stakeholders' interests

There are many stakeholders involved when it comes to the issue of modernizing the electric grid. Governmental stakeholders include the U.S. federal government, state governments, and local governments, whose competing interests make planning national electric infrastructure challenging. This is especially the case as interregional and national transmission planning becomes more incentivized by the FERC. At the federal level, FERC oversees the inter-state sale and price of electricity and is also a rulemaking body that sets requirements for regional and interregional transmission planning and development. NERC also operates at the federal level, beneath the guise of FERC. At the state level, ISOs and RTOs regulate transmission planning and the wholesale energy markets within the restructured areas of the United States' grid. Additionally, state governments control the consumer prices within each respective state. Each state also has its own regulatory environment that can either support privatizing the electric grid or regulating it in efforts to protect the consumer. These various and conflicting regulatory environments is what makes it challenging to establish an interregional or national transmission plan within the United States. Local governments also influence the electric grid since transmission projects often involve various state and local agencies that determine transmission siting in states and localities.[26] Like state governments, local governments also have distinct regulatory environments that dictate their policies toward the electric grid, which is similarly problematic when integrating various localities' grids.

Besides governmental stakeholders, other entities such as utility companies or DSOs, landowners and constituents take part to determine if certain transmission projects occur in their local communities. For instance, transmission developers often struggle to find landowners who welcome the prospect of having new transmission lines built nearby.[26] Additional complexity is added when planned transmission routes pass through federal or tribal lands.[26] When it comes to regional utility companies, they have vested interest in both maintaining the current electric grid and in modernizing it. On one hand, maintaining the current electric infrastructure benefits utility companies by limiting the amount of large capital investments needed to modernize the grid. Also, modernizing and further integrating the electric grid, may threaten some utility companies that are concerned with competing on the national market. On the other hand, current transmission infrastructure limits generation capacity and the ability to get electricity where it needs to go. It is for this reason that some utility companies view investing in modern transmission infrastructure as a profitable venture. However, utility companies still have concerns including the ability to generate profit for investors, justifying large capital investments, and wanting to minimizing risk. These concerns as well as state and local government interests can be addressed by incentivizing utility companies and local and state governmental agencies to partake in interregional and national transmission planning.

4.2 | Security concerns

A more connected grid will require a higher level of security from both physical attacks on infrastructure and cyberattacks on computer systems. Cyberattacks are of particular concern as these attacks have become more prevalent as computers and embedded devices have become more integrated into critical electrical infrastructure. A report by IBM in February 2021 found that the energy industry was the third most targeted sector in 2020 by cyberattacks.[27] The heightening of electricity-related cyber incidents worldwide is shown in Figure 6 in the light blue color.[28] As stated previously, cyber vulnerabilities of the grid are largely due to the integration of intelligent electronic devices (IEDs), however other vulnerabilities can exist because of outdated equipment or software.[29] The portions of the electric grid that are expected to be the most targeted by cyberattacks include generation and transmission infrastructure.[29] This does not mean that distribution is not vulnerable to cyberattacks, only that an attack on the other components would produce more detrimental and cascading consequences.

Preventing and protecting the electric grid from cyberattacks has become a recent priority of the Biden administration. In April 2021, the administration released a 100-day plan outlining how power utilities will be incentivized to install new monitoring equipment that will be able to quickly detect hackers and alert the U.S. government.[30] Other suggested actions by the International Energy Agency (IEA) involve developing policies that foster sector-wide collaboration and response procedures and setting up research partnerships with industry and academia to promote research and development in cyber resilience of the U.S. electric grid.[28] From this discussion, it is evident that any future efforts to modernize the electric grid must not only focus on physical infrastructure but also on the security of the grid.

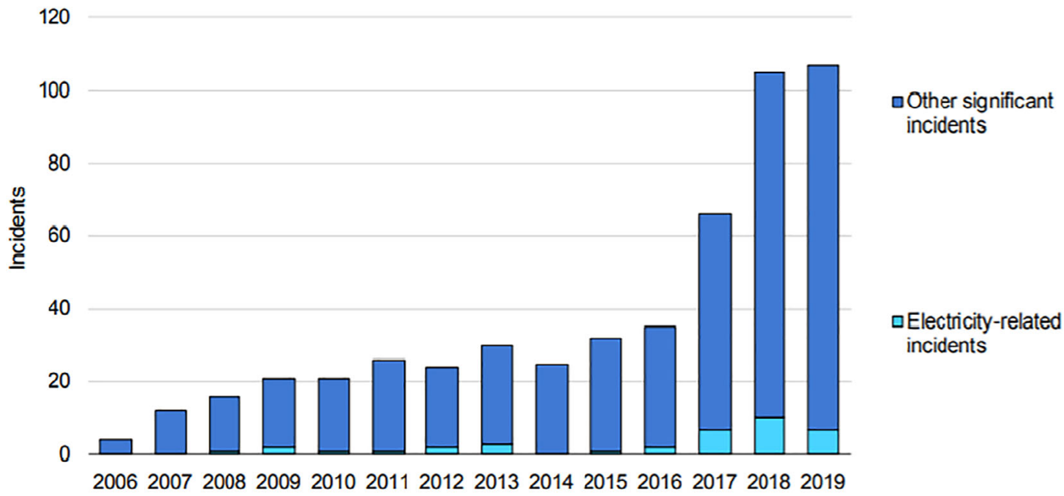

FIGURE 6 Significant cyber incidents worldwide, 2006–2019[28]

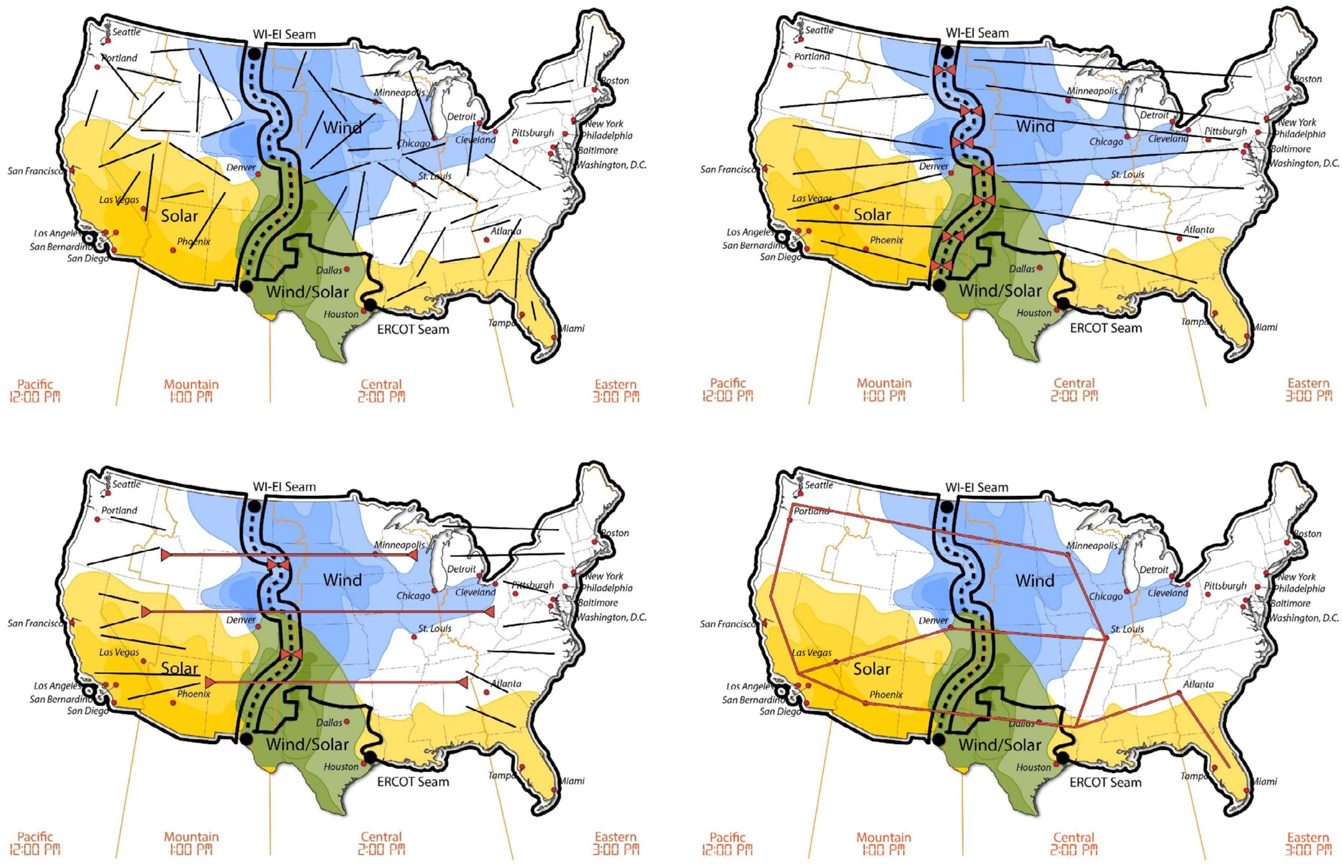

FIGURE 7 Transmission designs in the capacity expansion work[31]

5 | POLICY RECOMMENDATIONS

5.1 | Model potential solutions

One policy recommendation is to continue funding research programs that study and model the electric grid and assist in determining the most cost-effective solutions. Various models that highlight their differing benefits and detriments allow stakeholders to collaborate and establish a solution that is satisfactory to all parties. For example, the *Interconnections Seam Study* conducted by the NREL features a series of potential ideas to modernize the United States' current transmission infrastructure.[31] The study analyzed four separate scenarios and each of these scenarios' respective transmission lines are shown in Figure 7.[31]

Design 1, for instance, includes no new HVDC lines or capacity but adds more alternating current (AC) lines, which are represented in

Figure 7 as short black lines. The purpose of Design 1 is to increase transmission of electricity within each respective interconnection and serve as the standard to which the other designs are compared.[31] Design 2a, on the other hand, increases the capacity of the HVDC ties and adds additional AC lines. Increased HVDC capacity is represented as red "butterflies" along the dotted line between the interconnections in Figure 7. While Design 2a does not include the installation of new HVDC lines, it does increase the capability of electricity to be exchanged between the regional interconnections. In contrast to Design 2a, Design 2b adds HVDC lines with a few AC lines branching off.[31] These additional HVDC lines are portrayed in Figure 7 as red lines. While Design 2b establishes three HVDC lines that stretch across the United States, Design 3, models a complete, national HVDC grid with some new AC lines.[31] Nonetheless, all of the designs proposed in the NREL study were found to reduce electricity costs and meet reliability and demand requirements.

The *Interconnections Seam Study* also incorporated a cost–benefit analysis of each of the designs in the study. Said analysis utilized the investment costs and operating costs for the years between 2024 and 2038 and an additional 20 years with no increase in load or generation after 2038.[32] In addition, since Design 1 had limited adjustments to our current transmission infrastructure it was used as the standard design to compare Designs 2a, 2b and 3.[32] This is represented in Table 1 as the delta notation before Designs 2a, 2b and 3. As stated previously, the cost–benefit analysis included examination of investment costs, generation investment costs and operation cost with each being reported in billions of dollars. Additionally, the analysis determined the 35-year net cost charge which is the difference between the gross cost of operation and investment and the potential benefits gained from the cost. Also shown in Table 1 is the benefit cost ratio over a 35-year period to express which designs have more respective benefits when compared to Design 1.

One thought-provoking finding from the study is that Designs 2a, 2b and 3 all provide cost savings relative to Design 1 and illustrate the financial advantages of investing in each of the modeled designs. From this analysis, it also appears that Design 2a has the greatest benefit to cost ratio within 35 years therefore emphasizing the need to increase HVDC capacity along the seam between the interconnections. Overall, studies like the *Interconnections Seam Study* are useful for clearly demonstrating the costs and benefits of various potential designs for modernizing the United States' transmission infrastructure. This study and similar studies can also be employed to highlight the advantages of transmission updates to stakeholders who are hesitant to invest as well as assist in sparking public support for updated transmission infrastructure. Continued or increased support to further explore opportunities to improve transmission infrastructure will benefit decision-makers in deciding among competing alternatives.

5.2 | Require cooperation in transmission planning

Besides modeling potential transmission solutions, it is also critical for more cooperation to be established between the stakeholders involved in transmission planning. Cooperation, however, is challenging to create since reforms in the 1990s and 2000s consolidated oversight of transmission planning to investor-owned, vertically IOUs. As a result, the transmission planning process has remained nontransparent and unchecked, with limited access for journalists and public interest groups to investigate and report on the transmission planning process.

The FERC has attempted to promote more cooperation in transmission planning through its rulemaking capacity. For instance, in 2007 FERC Order 890 set the baseline for regional planning and open-access transmission service.[22] However, by 2010, FERC recognized that Order 890 was lacking and utilized Order 1000 (2011) to further strengthen the planning process.[22] Order 1000 both expanded on requirements for public utility transmission providers to participate in regional transmission planning and for them to satisfy the nine principles contained in the prior Order 890.[22,25] These nine principles include: coordination; openness; transparency; information exchange; comparability; dispute resolution; regional coordination; economic planning studies; and cost allocation.[22] FERC's main goal with utilizing its rulemaking capacity in this way was to foster collaboration between various stakeholders to thus develop cost-efficient transmission developments that would benefit all involved parties and distinct regional portions of the electric grid.

Despite previous rulemaking by FERC, IOUs still maintain control over transmission planning. This has allowed IOUs to focus on local developments rather than regional planning. FERC should require IOUs to be a part of RTO to foster greater regional cooperation.[33] FERC making this a requirement is significant as IOUs currently have substantial leverage over RTOs by being able to pull out of their respective RTO at any time. By requiring IOUs to be a part of RTOs, RTOs would have more capability to act as a regional body, foster collaboration between various IOUs, and ensure more regional transmission planning occurs.

FERC should also have greater oversight of IOUs transmission planning efforts by holding IOUs responsible for justifying the costs of transmission projects.[33] Instead of shifting the burden onto IOUs,

TABLE 1 Summary of CGT-Plan benefit/cost (B/C) results for base scenario[32]

Capacity or cost item	D1	ΔD2a	ΔD2b	ΔD3
Transmission investment cost, $B	40.03	2.57	6.76	8.19
Generation investment cost, $B	555.23	3.6	10.44	4.17
Operation cost, $B	2376.50	−8.79	−21.70	−15.30
35-year net cost charge, $B	-	−2.62	−4.5	−2.94
35-year B/C ratio	-	2.02	1.66	1.36

CGT, co-optimized generation and transmission.

FERC could also involve or create an independent agency that would assess the proposed costs for transmission projects. Said FERC rulemaking would establish a precedent of more cost-effective spending on and expect IOUs to be both more transparent and collaborative with their development of transmission projects.

5.3 | Finance significant transmission projects

The loan programs office (LPO) within the DOE serves as a financer for large scale energy projects throughout the United States. These projects and the respective companies funded through LPO have led to the creation of jobs and the enabling of budding industries to grow. One example, Tesla Inc. received funding through the LPO in the form of loan guarantees, which were then utilized to develop their facility in Fremont, California.[34] This facility then went on to produce the Model S sedan and usher Tesla in as a world leader in EVs.[34]

When it comes to financing transmission projects, the Title 17 Innovative Energy Loan Guarantee Program and Tribal Energy Loan Guarantee Program allows the LPO to distribute about $3 billion for projects that involve innovative technology such as HVDC lines, off shore wind transmission, and electrical infrastructure along transportation corridors determined by the Department of Transportation (DOT).[35] In addition, Title 17 also appropriates $2 billion in partial loan guarantees to projects that are owned by federally recognized tribes or the Alaska Native Corporation.[35] However, the LPO's method of financing of transmission projects falls short. The first problem is the amount of funding being allocated to transmission projects. $3 billion is simply not enough funding to complete larger scale, collaborative projects that are required to create a more robust, resilient grid. For example, transmission projects planned for the New England region had estimated price points of between $1.2 and $2.2 billion in 2013.[36] While modern technology may have slightly reduced this price point, it still unrealistic to think that $3 billion in loan guarantees can spur the national transmission planning and development that the United States so desperately needs.

In April 2021, the Biden Administration began to address some of the challenges with financing transmission projects. This was done by announcing the availability of up to $8.25 billion in loans from the LPO and the Western Area Power Administration (WAPA).[37] Unlike the LPO, WAPA works by awarding loan guarantees through its transmission infrastructure program (TIP) which was created to incentivize "the delivery of reliable, affordable, clean power in the Western United States."[37] The main goal of this additional funding was to encourage efforts to expand and update the nation's transmission infrastructure.[37]

Federal policymakers have also begun to see the need to modernize current transmission infrastructure. H.R. 3684 otherwise known as the Infrastructure Investment and Jobs Act contains extensive policy related to U.S. transmission infrastructure.[38] As of November 15, 2021, H.R. 3684 was signed by President Biden and become Public Law No. 117-58.[38] The significance of H.R. 3684 is that it addresses a myriad of issues that involve the United States' outdated transmission infrastructure through the creation of federal programs and the allocation of grants. For instance, policy in H.R. 3684 directly confronts issues regarding electrical blackouts by defining what a disruptive event is, how they are frequently related to natural disasters, extreme weather, and wildfires.[38] H.R. 3648 also details the creation of a federal financial assistance program titled the "Upgrading Our Electric Grid and Ensuring Reliability and Resiliency."[38] Said program would provide competitive financial assistance to and collaborate with electric sector owners and operators to "demonstrate innovative approaches to transmission" and other technologies.[38] Cybersecurity is also addressed in H.R. 3684 with the creation of several programs including "Energy Cyber Sense" program and technical assistance programs for rural and municipal utilities.[38]

A good avenue for additional funding for transmission infrastructure would be to create a national transmission loan program modeled like the Transportation Infrastructure Finance and Innovation Act (TIFIA) programs within the DOT which were created to prioritize transportation projects that are regionally or nationally significant.[39] Said program would incentivize interregional and national transmission planning as well as increase the likelihood that large-scale transmission projects would be funded and completed. It would also provide a wider variety of funding options which would provide more flexibility and thus stimulate a more competitive market and likely produce more cost-effective transmission projects. In general, a national transmission loan program would bring U.S. transmission infrastructure into focus and would serve as a mechanism to finance up-and-coming developments that will be crucial to updating current transmission infrastructure.

6 | CONCLUSIONS

Access to on-demand electricity is both expected and needed throughout the United States whether it is by a homeowner, a production line, or a hospital. However, access to reliable electricity has been facing challenges related to the aging electrical infrastructure of the United States, and its need to be reformed. Difficulties with dated transmission infrastructure have been further exacerbated by the progress in other sectors such as the growth of electrification in transportation and the role of VREs in electric generation. While these developments are essential to decarbonize the United States' energy sector, they have further highlighted the deficiencies of current infrastructure.

The relationship between electrical blackout events and extreme weather also emphasizes that the limited resiliency of current infrastructure is not only a technological issue, but also a potential health concern. Other concerns regarding the security, specifically the cybersecurity of critical infrastructure like electricity, have further established the need to modernize transmission infrastructure to be able to prevent attacks from bad actors.

Due to the vastness of electrical infrastructure in the United States, it is not a simple undertaking and will require the collaboration of many stakeholders at both the federal, state, and local level as well as entities from the private sector. To begin addressing the various deficiencies of present transmission infrastructure, it is recommended that:

1. Potential transmission designs are modeled, and their respective costs and benefits evaluated.
2. The FERC utilize its rulemaking capacity to cultivate collaboration among stakeholders, specifically between investor-owned, vertically IOUs and RTOs by requiring all IOUs are members of their appropriate RTO.
3. Additional funding and attention be allocated to U.S. transmission infrastructure, through the creation of a national transmission loan program modeled the well-established TIFIA programs.

Fortunately, policymakers have started to identify the importance of electric infrastructure within the United States, with both members of Congress and the Biden Administration creating policy that allocates funding to aging infrastructure. The work of the Biden Administration and success of H.R. 3684 reveals that policymakers are ready to tackle the nationally significant challenges such as electric infrastructure, which serves a hopeful focal point for the future of United States' electricity.

ACKNOWLEDGMENTS

I would like to thank the American Institute of Chemical Engineers (AICHE) for sponsoring my participation in the WISE program and their continued support throughout the program. Dr. Martin Abraham, my AICHE mentor also deserves acknowledgement for his supportive role during the development of my paper. I would also like to thank Mark Ames who served as the Faculty Member-in-Residence (FMR) this year and took the time to share his extensive knowledge of the public policymaking process with me and my fellow WISE interns. It was an honor to work alongside my fellow WISE interns and hear about their respective passions and insights. This public policy paper also would not have been possible without the encouragement of my family members, friends and my significant other, Andrew Bonilla. Thank you all for all your support, this would not have been possible without all of you.

ORCID

Sara Murphy https://orcid.org/0000-0001-8236-1317

REFERENCES

1. McCoy A. Transmission 101: the fundamentals of high voltage transmission. Presented at the Electric Transmission Infrastructure; 2017. Accessed July 19, 2021. https://www.eesi.org/briefings/view/021617wires
2. Flavelle C. A new, deadly risk for cities in summer: power failures during heat waves. The New York Times; 2021. Accessed June 21, 2021. https://www.nytimes.com/2021/05/03/climate/heat-climate-health-risks.html
3. Stone B, Mallen E, Rajput M, et al. Compound climate and infrastructure events: how electrical grid failure alters heat wave risk. *Environ Sci Technol.*. 2021;55(10):6957-6964. https://pubs.acs.org/doi/10.1021/acs.est.1c00024?fig=fig1&ref=pdf
4. Watson K, Cross R, Jones M, et al. The winter storm of 2021. Hobby School of Public Affairs, University of Houston; 2021. Accessed June 22, 2021. https://uh.edu/hobby/winter2021/storm.pdf
5. Englund W. The Texas grid got crushed because its operators didn't see the need to prepare for cold weather. The Washington Post; 2021. Accessed July 14, 2021. https://www.washingtonpost.com/business/2021/02/16/ercot-texas-electric-grid-failure/
6. Schwartz J, Penn I. Texas power grid, strained last winter, now faces an early heat wave. The New York Times; 2021. Accessed June 22, 2021. https://www.nytimes.com/2021/06/15/climate/texas-heat-wave-electricity.html?searchResultPosition=1
7. Mai T, Jadun P, Logan J, et al. Electrification futures study: scenarios of electric technology adoption and power consumption for the United States. National Renewable Energy Lab (NREL); 2018. Accessed June 28, 2021. https://www.nrel.gov/docs/fy18osti/71500.pdf
8. Desilver D. Today's electric vehicle market: slow growth in U.S., faster in China, Europe. Pew Research Center; 2021. Accessed June 19, 2021. https://www.pewresearch.org/fact-tank/2021/06/07/todays-electric-vehicle-market-slow-growth-in-u-s-faster-in-china-europe/
9. Shepardson D., Mason J. Biden seeks to make half of new U.S. auto fleet electric by 2030. Reuters; 2021. Accessed August 19, 2021. https://www.reuters.com/business/autos-transportation/biden-set-target-50-evs-by-2030-industry-backs-goal-2021-08-05/
10. Jones P, Levy J, Bosco J, et al. The future of transportation electrification: utility, industry and consumer perspectives. Lawrence Berkley National Laboratory, Report No. 10; 2018. Accessed June 20, 2021. https://eta-publications.lbl.gov/sites/default/files/feur_10_transportation_electrification_final_20180813.pdf
11. Boll C. As consumers focus on electric vehicles, municipalities look to electrify their bus systems. The National Law Review; 2021; XI (168). Accessed June 20, 2021. https://www.natlawreview.com/article/consumers-focus-electric-vehicles-municipalities-look-to-electrify-their-bus-systems
12. Spencer C. Finally, here's the exact cost of owning an electric car vs gas car. The Hill; 2021. Accessed July 18, 2021. https://thehill.com/changing-america/sustainability/energy/559971-finally-heres-the-exact-cost-of-owning-an-electric-car
13. University of Oxford. Share of Electricity Production by Source, United States. Our World in Data; 2021. Accessed June 21, 2021. https://ourworldindata.org/grapher/share-elec-by-source?time=2010..2020&country=~USA
14. Aramayo L. More than 100 coal-fired plants have been replaced or converted to natural gas since 2011. Today in Energy; 2020. Accessed June 21, 2021. https://www.eia.gov/todayinenergy/detail.php?id=44636
15. Lawson A. Variable renewable energy: an introduction. Congressional Research Service; 2019. Accessed June 21, 2021. https://crsreports.congress.gov/product/pdf/IF/IF11257
16. Lydersen K. Grid congestion a growing barrier for wind, solar developers in MISO territory. Energy News Network; 2020. Accessed July 11, 2021. https://energynews.us/2020/09/29/grid-congestion-a-growing-barrier-for-wind-solar-developers-in-miso-territory/
17. MacDonald A, Clack C, Alexander A, et al. Future cost-competitive electricity systems and their impact on US CO2 emissions. *Nat Clim Change*. 2016;6:526-531. https://www.nature.com/articles/nclimate2921
18. Mueller M, Rumph M. How Much Power is 1 Gigawatt? Office of Energy Efficiency & Renewable Energy; 2019. Accessed July 11, 2021. https://www.energy.gov/eere/articles/how-much-power-1-gigawatt
19. Roberts D. We've been talking about a national grid for years. It might be time to do it. Vox; 2018. Accessed June 23, 2021. https://www.vox.com/energy-and-environment/2018/8/3/17638246/national-energy-grid-renewables-transmission

20. Borenstein S, Bushnell J. The U.S. electricity industry after 20 Years of restructuring. National Bureau of Economic Research, NBER Working Paper No. 21113; 2015. Accessed June 23, 2021. https://www.nber.org/papers/w21113
21. Hein J, Hulburt D, Milligan M, Coles L, Green B. Transmission planning process and opportunities for utility-scale solar engagement within the Western Electricity Coordinating Council (WECC). National Renewable Energy Laboratory Technical Report; 2011. Accessed July 01, 2021. https://www.nrel.gov/docs/fy12osti/51279.pdf
22. Stanek J, Rickert A, Ellertson W, et al. Examining the state of electric transmission infrastructure: investment, planning, construction, and alternatives. U.S. House of Representatives Committee on Energy and Commerce; 2018. Accessed July 10, 2021. https://docs.house.gov/meetings/IF/IF03/20180510/108283/HHRG-115-IF03-20180510-SD002.pdf
23. Federal Energy Regulatory Commission. Order No. 888. 2020. Accessed July 07, 2021. https://www.ferc.gov/industries-data/electric/industry-activities/open-access-transmission-tariff-oatt-reform/history-oatt-reform/order-no-888
24. Federal Energy Regulatory Commission. About FERC. 2021. Accessed July 07, 2021. https://www.ferc.gov/what-ferc
25. Federal Energy Regulatory Commission. Order No. 1000—Transmission planning and cost allocation. 2021. Accessed July 07, 2021. https://www.ferc.gov/electric-transmission/order-no-1000-transmission-planning-and-cost-allocation
26. Brown M, Sedano R. Electricity transmission: a primer. National Council on Electric Policy; 2004. Accessed August 05, 2021. https://www.energy.gov/sites/prod/files/oeprod/DocumentsandMedia/primer.pdf
27. Plumer B. Pipeline hack points to growing cybersecurity risk for energy system. The New York Times; 2021. Accessed August 05, 2021. https://www.nytimes.com/2021/05/13/climate/pipeline-ransomware-hack-energy-grid.html
28. International Energy Agency. Power Systems in Transition. 2020. Accessed August 05, 2021. https://www.iea.org/reports/power-systems-in-transition
29. Idaho National Laboratory. Cyber threat and vulnerability analysis of the U.S. electric sector. Mission Support Center; 2016. Accessed August 06, 2021. https://www.energy.gov/sites/prod/files/2017/01/f34/Cyber%20Threat%20and%20Vulnerability%20Analysis%20of%20the%20U.S.%20Electric%20Sector.pdf
30. Department of Energy. Biden administration takes bold action to protect electricity operations from increasing cyber threats. 2021. Accessed June 23, 2021. https://www.energy.gov/articles/biden-administration-takes-bold-action-protect-electricity-operations-increasing-cyber-0
31. Novacheck J. Interconnections Seam Study. National Renewable Energy Laboratory. Accessed June 30, 2021. https://www.nrel.gov/analysis/seams.html
32. Bloom A, Novacheck J, Brinkman G, et al. The value of increased HVDC capacity between eastern and western U.S. grids: the interconnections seam study. National Renewable Energy Laboratory; 2020. Accessed June 30, 2021. https://www.nrel.gov/docs/fy21osti/76850.pdf
33. Roberts D. Transmission week: how to start building more big power lines. Volts; 2021. Accessed June 25, 2021. https://www.volts.wtf/p/transmission-week-how-to-start-building
34. Alexander B. The lesson from DOE's latest loan default? Invest more. Forbes; 2020. Accessed July 27, 2021. https://www.forbes.com/sites/brentanalexander/2020/08/05/the-lesson-from-does-latest-loan-default-invest-more/
35. Department of Energy. Transmission loan guarantees. Loan Programs Office; 2021. Accessed July 27, 2021. https://www.energy.gov/sites/default/files/2021-04/DOE-LPO_Program_Handout_Transmission-April2021.pdf
36. Courchesne C. What would burial of high-voltage transmission lines cost? Conservation Law Foundation; 2013. Accessed July 27, 2021. https://www.clf.org/blog/going-underground-northern-pass-alternatives-part/
37. Department of Energy. DOE Announces Up to $8.25 Billion in Loans to Enhance Electrical Transmission Nationwide. 2021. Accessed July 27, 2021. https://www.energy.gov/articles/doe-announces-825-billion-loans-enhance-electrical-transmission-nationwide
38. DeFazio P. Infrastructure investment and jobs act. Congress.gov; 2021. Accessed December 28, 2021. https://www.congress.gov/bill/117th-congress/house-bill/3684/text
39. United States Department of Transportation. TIFIA Program Overview. Transportation.gov; 2021. Accessed July 27, 2021. https://www.transportation.gov/buildamerica/financing/tifia

AUTHOR BIOGRAPHY

Sara Murphy is a senior at the University of Idaho in Moscow, ID, majoring in chemical engineering and working toward a minor in political science. She has worked on several research projects during her undergraduate career with one involving bio-jet fuel and the other working to improve the performance of lead-acid batteries. In addition to her research, Sara has also worked as an energy engineer intern for the Department of Energy's Industrial Assessment Center program where she performs energy audits of local industries. Sara is the President of the Vandal Clean Energy Club, a member of the American Institute of Chemical Engineers, and a member of the Society of Women Engineers. Upon graduating in May 2022, Sara plans on pursuing graduate degrees in both engineering and public policy.

How to cite this article: Murphy S. Modernizing the U.S. electric grid: A proposal to update transmission infrastructure for the future of electricity. *Environ Prog Sustainable Energy*. 2022;e13798. doi:10.1002/ep.13798