ESIG

Transmission Planning for 100% Clean Electricity

About ESIG

The Energy Systems Integration Group (ESIG) is a non-profit organization that marshals the energy and expertise of the electricity industry's technical community to support grid transformation and energy systems integration and operation, particularly with respect to clean energy. ESIG has been working for three decades to improve and expand the international understanding and use of clean energy resources necessary to achieve a reliable and economic grid transformation. Now that U.S. federal leaders have embraced the need for rapid decarbonization of America's electricity system and entire economy, ESIG offers this analysis on the critical role of transmission planning and construction in enabling grid transformation and achieving decarbonization goals.

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System Planning Working Group

Special Sessions on Transmission Planning for 100% Clean Electricity

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The Need for National-level Transmission Planning in America

The widespread adoption of clean energy goals by many U.S. states and businesses is underway, spurred by accelerating commitments to combat climate change and the growing cost-competitiveness of renewable resources. In January 2021, the Biden administration adopted ambitious decarbonization plans that aim to reach 100 percent clean electricity by 2035 and net-zero emissions across the economy by 2050. Reaching these goals efficiently will require a doubling or tripling of the size and scale of the nation's transmission system.

Decarbonizing the electricity system, and ultimately achieving net-zero emissions, will require action on a transformative scale. Between 2001 and 2019, the nation's share of clean electricity increased from 28 percent to just 38 percent, with the addition of approximately 200 gigawatts (GW) of wind and solar to the U.S. power system, as shown in Figure 1.[1] Dramatic amounts of additional utility-scale and distributed zero-carbon generation will be needed to decarbonize the power system and maintain grid reliability to meet the 2035 and 2050 goals.

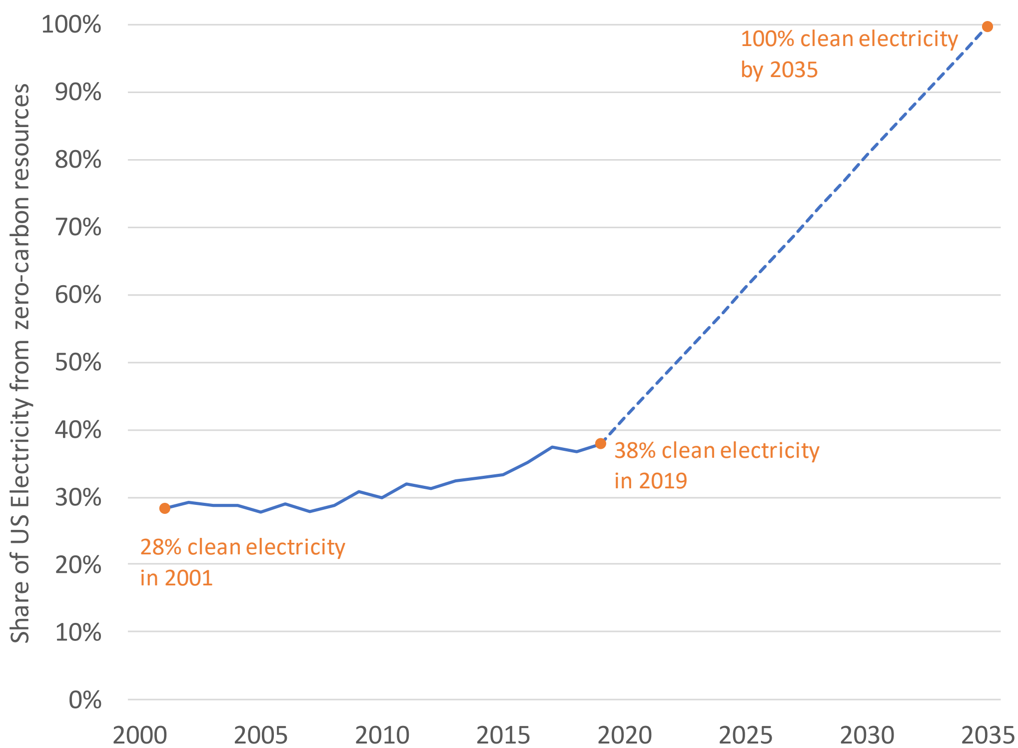

Figure 1. *Percentage of U.S. electricity generation from clean energy resources from 2001 to 2035.*

The United States has vast clean energy resources and the technical ingenuity to leverage existing low-carbon technologies and create new ones. But, proactive national transmission planning is critical to meet the current goals quickly and affordably. In a 100 percent clean electricity future, large amounts of wind, solar, and storage will be needed in varying densities in many locations, and transmission will be critical to ensuring that energy can be delivered from where it is produced to where it is needed.

As the continent pushes to decarbonize, significant geographic pockets of wind and solar resources will be built primarily in remote areas with the strongest wind and solar resource potential. However, to decarbonize the electricity system a well-designed macro grid is needed to deliver affordable, clean electricity where it is needed any hour of the day or night.

1 Clean electricity refers to electricity that does not have carbon emissions as a byproduct of generation. Examples of clean electricity resources are wind, solar, hydroelectric, and nuclear energy. Renewable energy refers to electricity sources that rely on energy that can be easily replenished. Wind, solar, and hydroelectric sources are generally referred to as renewable.

Although zero-carbon wind and solar energy dominate the new electricity generation built over the past decade, as well as proposed generation in the coming years, it is important to accelerate the development of all types of clean electricity generation. But there is not enough electricity transmission available to connect all of the proposed new generation to the grid and deliver energy to customer centers. Transmission capacity has not expanded to meet the need in part because there was insufficient consensus about the need for massive nation-wide transmission expansion, and no single entity has the responsibility or authority to direct the building of transmission that serves national policy goals. Transmission has been constructed to meet incremental needs, but the pace of transmission needed to facilitate the clean energy transition is lagging. There are two main reasons: (1) a lack of agreement about where the future generation will be located, and (2) a lack of agreement about who benefits from the transmission and therefore who should pay for the transmission expansion.

Due to the lack of transmission capacity expansion, many proposed generation and storage resources have been unable to interconnect to the grid. Because the highest-quality wind and solar resources are often located where the existing grid is the least developed, transmission interconnection queues have amassed over 600 GW of proposed generation capacity as many projects are unable to go forward due to a lack of grid access. Without a system-wide approach to transmission planning and a significant expansion of interregional transmission, studies show that effective economy-wide decarbonization will be much more expensive. A continuation of local and regional-focused transmission planning will slow the integration of low-cost renewable and other clean generation sources into the grid.

ESIG reviewed and synthesized key research studies investigating energy sector decarbonization and developed a conceptual design for reaching the United States' clean energy goals using proactive transmission planning and development. In November and December 2020, ESIG convened more than 50 U.S. and international electricity experts for a series of five workshop sessions to refine this conceptual design for the U.S. power system. This white paper is the culmination of those meetings.

A decade's worth of energy system studies focused on the decarbonization of the U.S. electricity system and economy have found that significant transmission expansion is essential to realize effective low-carbon energy systems at the lowest cost. ESIG's recommendations for decarbonizing the electricity system, and ultimately the U.S. economy, are based on three complementary recommendations:

1 **National transmission planning**: The United States should establish a national transmission planning authority and initiate an ongoing national transmission planning process.

2 **Renewable energy zones:** Wind and solar energy are currently the lowest-cost sources of zero-carbon energy. The United States should designate renewable energy zones for large-scale wind and solar resource development and build large-scale transmission to those regions to expedite coordinated generation and transmission expansion.

3 **Macro grid concept:** The United States should develop and implement a national transmission network (the macro grid) of multi-regional, high-voltage transmission that unites the country's power systems.

ESIG's macro grid concept addresses both clean energy production and transmission in light of the nation's need for affordable, rapid decarbonization. It identifies renewable energy zones that are cost-effective for development and proposes an interregional transmission network that links a variety of resources and loads. This macro grid will enable nation-wide access to all clean energy sources. It will use proven transmission technologies for a scalable, no-regrets solution to develop the great magnitude of clean generation resources that will be needed to meet national decarbonization goals.

This white paper reviews key research studies that evaluated different pathways to significantly reduce carbon emissions from the power sector and achieve a low-carbon electricity grid. It explains why transmission is essential and facilitates the low-cost transition to a decarbonized economy. The paper outlines ESIG's recommendations for the creation of a national transmission plan, the identification of renewable energy zones, and the design of a macro grid necessary to meet local, state, and national clean energy goals.

SYNTHESIS OF CLEAN ENERGY STUDIES

A number of research studies have been conducted on the future of the U.S. power system and the various pathways to significantly reduce carbon emissions from the power sector (see Appendix A for a full list of studies). These studies use sophisticated models to assess a range of generating resource mixes and transmission system configurations that would be able to meet projected electricity demand on a least-cost basis, consistent with regulatory and reliability requirements. The studies consistently found that, of the energy technologies available today, wind and solar generation enabled by storage and transmission are the lowest-cost options available to meet clean energy targets.[2] These studies also show that the scale of new wind, solar, storage, and transmission needed to meet these goals is much larger than recent deployment levels.[3]

2 While some of the studies offered advanced nuclear, carbon capture technology, and hydrogen as clean energy investment options, these technologies were not selected in the studies for extensive development because of their comparatively high cost.
3 Plans to electrify current fossil-fired energy uses such as transportation and home heating will further increase requirements for clean energy and transmission, even as current and electrified uses are moderated by improved energy efficiency.

The ESIG recommendations draw from six leading energy-sector transformation studies examining the needs for achieving a high renewables grid: the 2035 Report (University of California, Berkeley),[4] the Electrification Futures Study (National Renewable Energy Laboratory),[5] the Interconnections Seam Study (National Renewable Energy Laboratory),[6] the Massachusetts Institute of Technology's (MIT)[7] study of the value of inter-regional coordination and transmission in decarbonizing the U.S. electricity system (referred to here as the MIT study), the Midcontinent Independent System Operator's (MISO) Renewable Integration Impact Assessment,[8] and the ZeroByFifty study (Vibrant Clean Energy).[9] These studies all set ambitious energy goals comparable to those outlined in the Biden administration's clean energy plan. All were rigorously designed and modeled to incorporate multiple years of weather data, a range of scenarios, and state-of-the-science tools to develop least-cost plans to achieve those clean energy system goals. These studies, summarized in Table 1, offer common findings that support our recommendations.

Study	Region	Renewable Capacity	Clean Energy Level(s)	Annual Electricity Demand	Target Year
The 2035 Report	United States	1,100 GW (wind and solar)	90% clean electricity	4,500 TWh	2035
Electrification Futures Study	United States and Canada	600 GW (wind) 1,000 GW (solar)	23% to 75% renewable energy	7,000 TWh	2050
Interconnections Seam Study	United States (except Texas) and Canada	600-900 GW (wind and solar)	63% to 95% carbon free electricity	4,900 TWh	2038
MIT study	United States	1,200 GW (wind) 1,100 GW (solar)	100% clean electricity	5,000 TWh	2040
Renewable Integration Impact Assessment	United States - Eastern Interconnection	411 GW (wind) 677 GW (solar)	Up to 100% clean electricity for the eastern interconnection	2018 demand	N/A
ZeroByFifty	United States	1,100 GW (wind) 1,000 GW (solar)	100% clean energy	9,000 TWh	2050

Table 1. *Leading Energy-Sector Transformation Studies' Assessments of Renewable Energy Needed to Meet Decarbonization Goals*

4 Goldman School of Public Policy, University of California, Berkeley, https://www.2035report.com/.
5 National Renewable Energy Laboratory, https://www.nrel.gov/analysis/electrification-futures.html.
6 National Renewable Energy Laboratory, https://www.nrel.gov/analysis/seams.html
7 P. R. Brown and A. Botterud, "The Value of Inter-Regional Coordination and Transmission in Decarbonizing the U.S. Electricity System," Joule 5(1)(2020): 115-134, https://doi.org/10.1016/j.joule.2020.11.013.
8 Midcontinent Independent System Operator, https://www.misoenergy.org/planning/policy-studies/Renewable-integration-impact-assessment/#nt=/riiatype:Background%20and%20Results.
9 Vibrant Clean Energy, "ZeroByFifty," presentation at the Energy Systems Integration Group technical workshop (online), November 11, 2020, https://www.vibrantcleanenergy.com/wp-content/uploads/2020/11/ESIG_VCE_11112020.pdf.

WIND AND SOLAR GENERATION MUST GROW EXPONENTIALLY

Meeting clean energy goals will require significant expansions of wind and solar capacity. The United States currently has about 1.1 terawatts (TW) of electricity generation capacity, including 112 GW of wind and 85 GW of solar capacity.[10] Many studies show that most existing fossil generation will need to be replaced due to age, economics, and decarbonization goals. At least 1 TW of new wind and solar will be necessary to reach 100 percent clean electricity by 2035, or more depending on the speed at which other energy sectors are electrified. According to several studies, the electrification necessary for broader decarbonization of the economy—including transportation, buildings, and industrial processes—will require significant resource expansion over the next 30 years, even with aggressive energy efficiency efforts. Figure 2 shows that electricity demand could more than double by 2050, dramatically increasing the need for electricity-generating capacity and the transmission to support it.

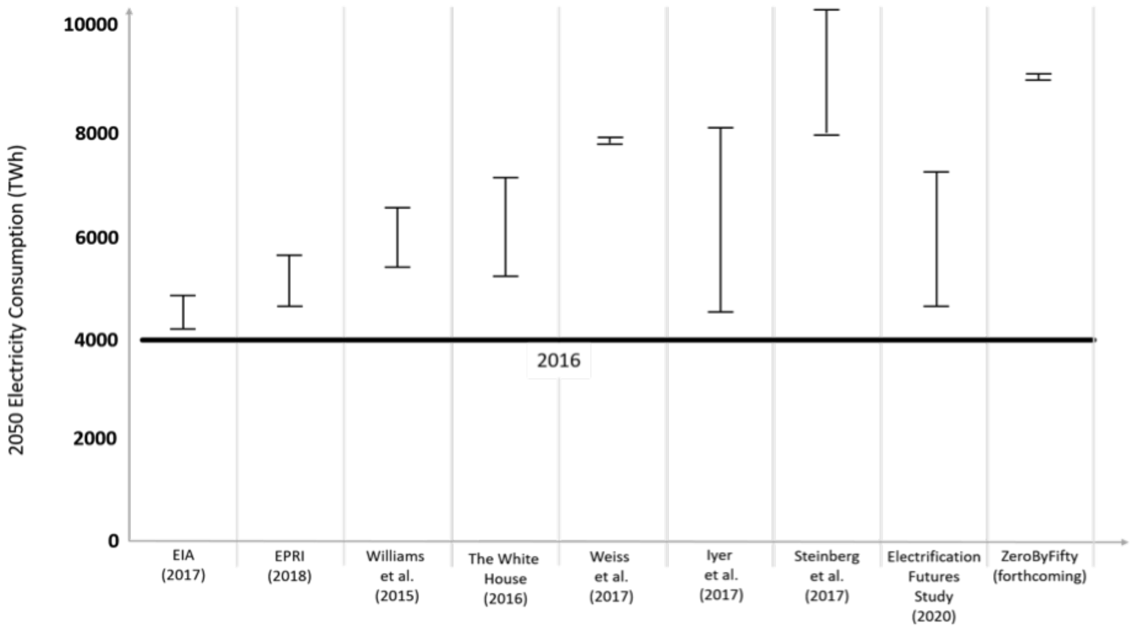

Figure 2. *Estimates of annual electricity demand in 2050 assuming various levels of electrification and energy efficiency.*

Many of the richest wind and solar resources are located far from the urban load centers where most of the country's energy is consumed (Figure 3 and Figure 4). Each of the studies referenced in Table 1 include substantial expansions of transmission to reach clean energy targets, and three of the studies show that a national macro grid has substantial economic savings compared to an incremental transmission approach. Most of the national-scale studies examining the least-cost pathway toward 100 percent clean energy build hundreds of GWs of wind in the central United States from North Dakota to Texas (shown by dark blue regions in Figure 3). In a few recent studies, offshore wind proves to be a valuable option for the Northeast and Mid-Atlantic coastal regions of the United States, which, like northern Europe, have an exceptional offshore wind resource and limited land suitable for wind development. Some states are aggressively planning for offshore wind resources, with nearly 29 GW of capacity planned along the east coast from North Carolina to Maine.[11]

Solar resources are expected to be developed widely across the country, with higher concentrations (hundreds of GWs) of utility-scale solar in the southern states and high amounts of distributed energy resources in major metropolitan areas. Some studies include the generating potential of Canada's considerable wind and hydroelectric resources. With appropriate transmission, Canadian hydroelectric resources could provide grid flexibility for the Northeast, upper Midwest, and Pacific Northwest of the United States.[12]

10 For the total GW, see https://www.eia.gov/energyexplained/electricity/electricity-in-the-us-generation-capacity-and-sales.php; for wind, see https://www.awea.org/wind-101/basics-of-wind-energy/wind-facts-at-a-glance; and for solar, see https://www.seia.org/us-solar-market-insight.
11 National Renewable Energy Laboratory, 2019 Offshore Wind Technology Data Update, October 2020, https://www.nrel.gov/docs/fy21osti/77411.pdf
12 R. Cowart, R. Sedano, F. Weston, J. Raab, P. Abergel, and P. Burke, A Collaborative for Greater Coordination and Integration Among the Electric Grids of Eastern Canada and the Northeastern United States (2020), https://transitionaccelerator.ca/assessing-the-feasibility-of-a-regional-neda-collaborative/

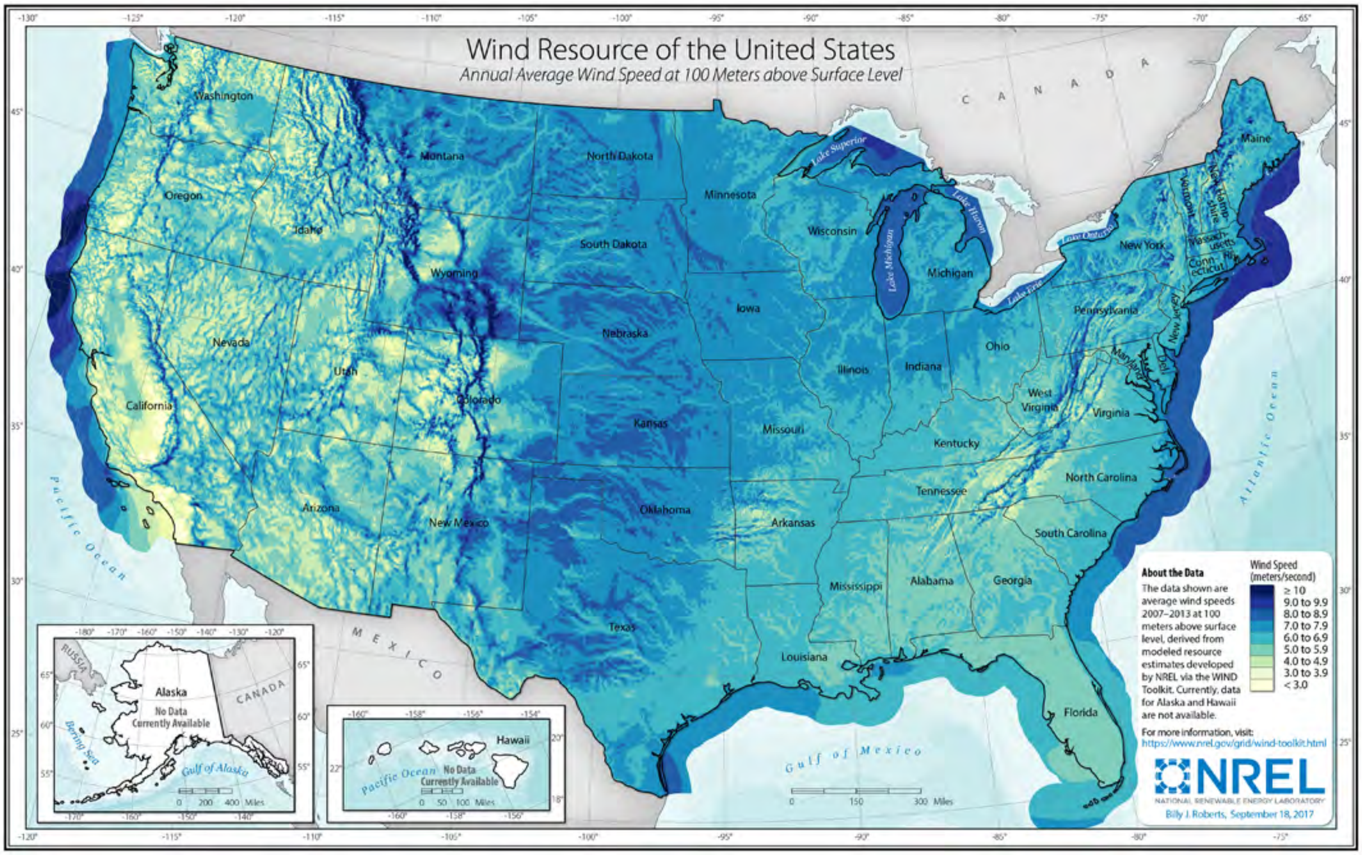

Figure 3. *Wind resource in the United States in 2012*

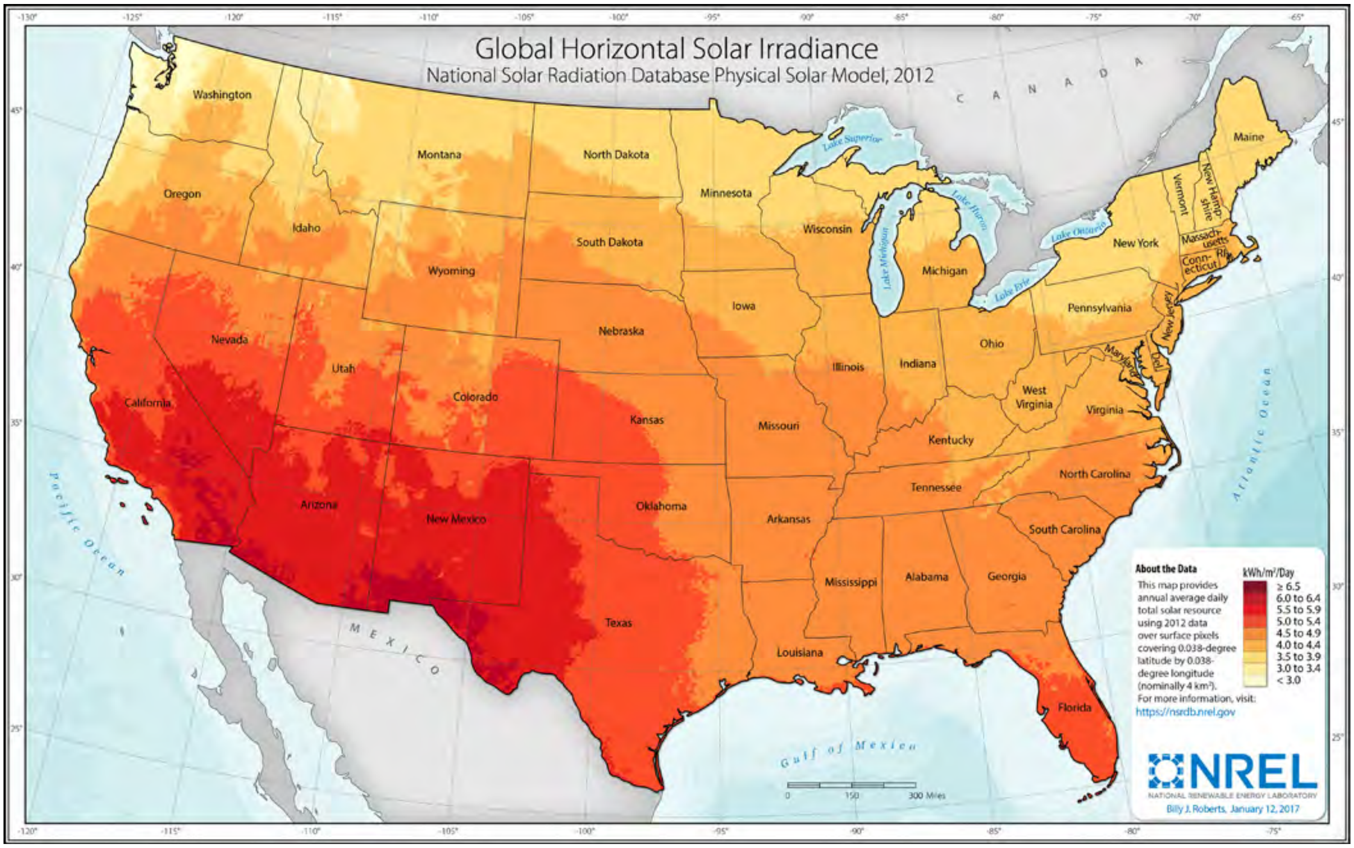

Figure 4. *Solar resource in the United States in 2012*

TRANSMISSION SMOOTHS ALL TIME SCALES OF WEATHER VARIABILITY

Supply and demand in the electricity system vary on annual, seasonal, daily, and sub-minute time scales. This variability is driven by the impact of weather on energy consumption as well as the generation of electricity from wind, solar, and hydroelectric resources. Weather-driven variability is not a new challenge for power systems, in fact it underpins the resource adequacy and system balancing constructs that drive power systems planning and operations requirements.[13] Until the power system has much higher levels of transmission, active load management, energy storage, and flexibility services, higher levels of variable renewable generation will magnify the challenge of reliable power system operation.

Numerous studies have examined these challenges (see Appendix A). The consensus of this wide body of work is that the wide-scale aggregation of variable renewable resources, load, storage and other balancing resources significantly reduces system costs. The ability of geographic diversity to smooth out aggregated resource output across annual, seasonal, and daily time scales is well known—for instance, transmission has been used to balance seasonal needs by connecting northern winter-peaking loads and generation with southern summer-peaking loads and generation for decades. Moment-to-moment variability has been managed using coordinated operations in regional transmission organizations and joint operating agreements for more than 20 years.

Without the addition of significant multi-regional transmission, system planners will need to significantly overbuild local renewable resources in order to manage weather patterns and meet demand. This will require extreme curtailment of local wind and solar resources, even if high levels of storage capacity are available. Deliberately overbuilding generation and storage capacity is expensive. While storage has many valuable characteristics and is an enabling technology for achieving reliable 100 percent clean electricity, current storage technologies have limited ability to manage multi-day, seasonal, and inter-annual weather variations. Transmission can provide flexibility across all of these time scales today, without any need for further technological advances. Storable carbon-free fuels such as hydrogen offer a potential solution, although the creation of a hydrogen economy—particularly powered by excess clean renewable energy—would benefit substantially from a more interconnected power system.

A NETWORK OF CROSS-COUNTRY TRANSMISSION IS CRITICAL TO MINIMIZING COST AND MAXIMIZING FLEXIBILITY

The general consensus in the literature and among the experts preparing this paper is that interregional transmission dramatically lowers the cost of achieving 100 percent clean electricity by reducing the amount of wind, solar, storage, and other generation capacity that must be built. Transmission allows grid owners and operators to optimize high-quality generation resources without overbuilding, or to exploit highest-quality resource areas without building in lower-quality resource areas. The research referenced in Appendix A concludes that it is difficult to serve forecasted levels of U.S. electricity demand without expanding the transmission system. In fact, all six studies highlighted in this white paper find that a reliable power system that depends on very high levels of renewable energy will be impossible to implement without doubling or tripling the size and scale of the nation's transmission system.

Multi-regional transmission provides diverse and important economic and reliability benefits at a relatively low cost. It enables deliverability of resources to load; it provides resource and load diversity to facilitate system balancing, enables resource adequacy, and helps the grid weather extreme events; and it helps to strengthen the grid, making it more resilient to operational failures. For example, the ZeroByFifty study found that the United States will need to add about twice as much transmission as we have today in order to fully decarbonize by 2050. It also found that if we do build a macro grid, we will save $1 trillion in reaching these decarbonization goals compared to a future where we do not build a macro grid.

13 System planners use various methods to ensure adequate capacity to meet defined long term reliability targets, and they must balance supply against demand at all times.

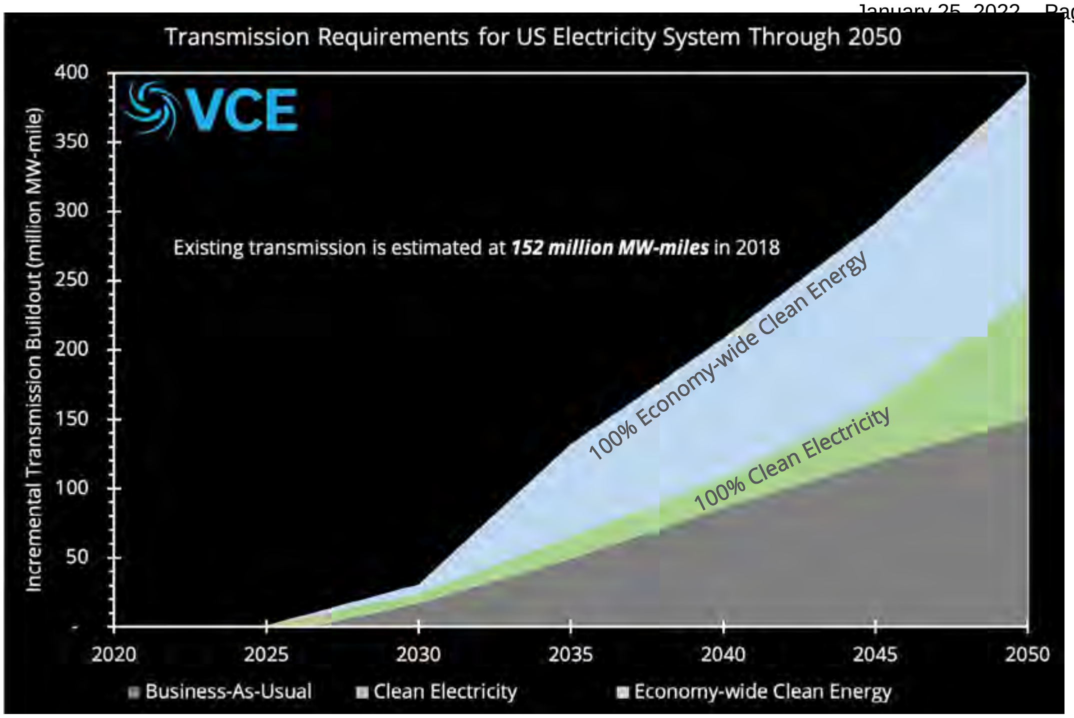

Figure 5. *ZeroByFifty's transmission expansion for a business as usual case, a clean electricity case (100 percent), and an economy-wide clean energy (100 percent) case by 2050.*[14]

The Interconnections Seam Study, MIT study, and ZeroByFifty show that an interregional transmission macro grid using high voltage direct current (HVDC) technology provides greater benefits than numerous, smaller alternating current (AC) transmission expansions. HVDC transmission has lower costs when transmitting electricity over hundreds of miles, and energy flows can be directed to minimize inadvertent impacts on the AC system, for example, to minimize loop flows.

One lesson learned from the many clean energy and high penetration renewable energy studies conducted to date is that national planners should not let the perfect be the enemy of the good. Every study that evaluated a macro grid identified significant total system cost savings from using the macro grid to move and balance generation across the larger system. While more work is needed by engineers and economists to develop operable macro grid solutions, these findings show that even a macro grid concept that is not a perfect, optimal solution can still provide significant benefits that increase the affordability and speed of our country's decarbonization.

ESIG MACRO GRID CONCEPT

The United States needs a national transmission plan to achieve cities', states', and the nation's clean energy goals, and needs construction of that planned transmission as quickly as possible. This section outlines the engineering requirements for creating a national transmission plan and offers a conceptual design for reaching decarbonization goals. The national transmission plan is driven by ambitious policy goals and economic opportunities, and is based on the findings of major research studies. It has three components.

The first component is the creation of a national transmission planning authority to develop the initial set of macro grid concept and engineering power system analyses that serve the entire nation's needs for reliable, economic, rapid and full economy decarbonization. This planning effort must be conducted in conjunction with a broad suite of stakeholders and experts including regional, state, local, utility and competitive transmission providers, grid operators, generators, energy service providers, and nongovernmental public interest organizations. In the long term, the national transmission planning authority will need to work with regional authorities and others to facilitate the construction of

14 Vibrant Clean Energy. 2020. "ZeroByFifty Study," presentation at the Energy Systems Integration Group technical workshop (online), November 11, 2020. https://www.vibrantcleanenergy.com/wp-content/uploads/2020/11/ESIG_VCE_11112020.pdf.

successive stages of the macro grid, and to adapt and update macro grid plans for evolving technology, economic, and policy changes such as the pace of electrification, changes in generation mix and location, and actual transmission development.

The second component is the identification of renewable energy zones that can support major levels of wind or solar development concentrated in favorable locations with the availability of rapid, large-scale transmission facilities and interconnection capacity. Renewable energy zones will be essential to unlock and enable the massive levels of renewable production capacity necessary to meet the 2035 and 2050 goals. Some wind and solar has already been developed in many of these high-capability regions, but it must increase by at least a factor of five, scaling from 0.2 TW today to at least 1 TW to meet even the 2035 clean electricity goals.

The third component of the ESIG macro grid concept is to identify a network of multi-regional transmission infrastructure that can be integrated into a macro grid to allow the sharing of renewable resources across the country. The macro grid can be implemented in a staged approach, beginning with the construction of individual HVDC transmission lines that are ultimately linked into a wide network of HVDC lines and collector systems. Much of the current transmission system is highly utilized and cannot support interconnection of incremental generation, much less massive renewable generation expansion. Without strategic, targeted investment in a new transmission macro grid, the continued development of wind and solar will be slow, costly, and insufficient to meet ambitious decarbonization goals.

The initial macro grid concept is only the first step to move toward decarbonization within the budgets and timelines identified by various policymakers. The initial design will require detailed engineering studies and an ongoing process to annually or biennially review system performance and generation interconnection queues, assess and adjust as needed for significant technology changes, and make course corrections as needed. This will require long-term commitment and efforts of national and state policymakers, planners, regulators, transmission owners, entities that provide financing, and others.

NATIONAL TRANSMISSION PLANNING ORGANIZATION

Broad foundational research has established that a well-designed transmission system is critical to efficiently meeting high-electrification, low-carbon policy goals. In fact, U.S. power grids and transmission interconnection queues are already so congested that more transmission is needed to support the nation's reliability and economic growth even without ambitious power system decarbonization goals.

ESIG recommends that a national transmission planning authority be created to develop and implement an ongoing transmission planning process. The United States needs an organization with the authority and responsibility to conduct national-level planning that transcends regional and parochial interests. Such an organization will not obviate the need for regional planning, but should work with the regional planners and others to coordinate top-down and bottom-up needs and optimize solutions according to the national public interest.

A long-term, ongoing transmission planning process is needed because the results of a "one-off" planning exercise would quickly become outdated. The speed with which the United States needs to build clean energy resources and the speed with which technology innovations occur necessitate ongoing, frequent planning cycles.

A Comprehensive Planning Effort

Given the widespread policy and corporate support for reducing carbon emissions from energy use as quickly as possible, it is essential to begin grid and power system design, analysis, and construction now. The national transmission planning authority will guide the designation of renewable energy zones and the design of a macro grid to be used to efficiently develop those zones. Given the complexity of power system planning at the national and continental scale, ESIG's macro grid concept is offered as a starting point to begin such analysis. Much work is needed to refine the final location of renewable energy zones, determine the location of macro grid nodes and the size of transmission lines, and identify the network of supporting transmission lines before final engineering plans and construction of the macro grid can begin.

A comprehensive approach is needed to examine the full range of transmission's benefits. This approach must include reliability analyses over multiple time scales regarding resource adequacy, capacity expansion, system balancing, steady-state stability, and dynamic stability. This national planning effort will essentially look like an integrated resource and transmission planning effort—even though the resource deployment is often left to developers, regulators, and utilities to plan and build—because transmission availability dominates where and how much generation is built. Because the ESIG proposal does not change the authority for resource planning, which rests at the state and local level, entities that are responsible for resource planning must be at the table and bought into the national planning effort.

Modeling Upgrades and Engineering Analysis

The macro grid will need to be planned at the national, regional, and local levels. National macro grid planning processes stitch together regional models, seed the models with the locations of transmission hubs, and use extensive data and scenarios to assess the value of the resulting grid options. Given current computational constraints, a national transmission planning model should be initialized with a macro grid concept, similar to the design shown here and in other studies, and tested with multiple scenarios and configurations to refine it.[15] The performance of this high-level plan must be tested for resource adequacy and for system balancing that capture operational processes and uncertainties in detail. This analysis needs to be completed both at the national as well as on the regional/local levels. The comprehensive national plan will need to be adjusted so that it meets appropriate performance metrics and to ensure that sufficient system services are provided to support frequency, voltage, and other system needs during normal operation as well as during grid disturbances. Extensive engineering analysis is needed to ensure that the planned grid will operate effectively and reliably.

Additional engineering analysis must assess AC power flows (real and reactive power) and system security under contingency conditions. This includes engineering to determine transmission technology (AC vs. DC; line-commutated converters vs. voltage source converters), line configuration (single vs. double circuit, bipole vs. monopole), voltage level and mega-volt ampere rating of facilities (e.g., lines, converters, transformers, breakers, reactive power support), grid-enhancing technologies (e.g., dynamic line rating, topology optimization), and other considerations (e.g., relaying, protection). The adjustment of the transmission plan through considerations of steady-state thermal and voltage stability (normal operation and during events) should yield a refined plan that can be retested in production simulations. Additional tests will need to assess the modeled system's dynamic stability—its ability to operate reliably over time under stressed operating conditions.

RENEWABLE ENERGY ZONES

As discussed above and indicated in Figures 3 and 4, the best wind and solar resources are located predominantly in regions that are distant from customer urban load centers. Significant geographic pockets of wind and solar resources are being built in these locations, but most of these regions are transmission-constrained and cannot support additional wind and solar expansion without additional transmission construction. Additional resources in these areas are locked out because of a lack of transmission infrastructure. A proactive approach to using these resources efficiently requires the creation of renewable energy zones – large areas in which the development of wind and solar is prioritized. These zones must be connected by deliberately planned transmission corridors, followed by rapid construction of the planned transmission for collection systems within the zones.

15 As discussed above, the national value of a macro grid has already been established, but these studies should also confirm the value of the macro grid by comparing macro grid options against models without the macro grid.

Utility-scale Wind and Solar

The Electric Reliability Council of Texas (ERCOT) offers a good example of proactive transmission planning, where Competitive Renewable Energy Zones (CREZ) were designated specifically to ensure that new renewable generation would be built in areas with high-quality wind resources and that new transmission would be built to access that generation and deliver it to loads.[16] The most important aspect of CREZ was not merely that the renewable energy zones were identified, but that these transmission lines were legislatively deemed to be "used and useful," which allowed for assured cost recovery of the CREZ transmission projects. This allowed the transmission to be properly sized to the renewable energy zone, rather than developed and justified incrementally as the generation projects were approved. This approach saved money through proactive planning and "right-sizing" of projects. It also allowed better coordination between the longer timeline of transmission construction and the fast construction times of wind and solar plants.

Other factors behind the success of the Texas CREZ effort include fast time requirements set by the statute upon planners and regulators to design and process the CREZ plans, competitive transmission provider selection, and siting approvals, in addition to ERCOT's practice of assigning transmission expansion costs directly to customers rather than requiring new generators to pay for transmission upgrades (the latter of which yields incremental rather than large-scale transmission expansion).

Given the scale of development necessary to achieve and exceed 1 TW of wind and solar and other zero-carbon generation and storage capacity, the ESIG macro grid concept follows the CREZ model in the analyses described in Appendix A, designating broad areas where very high-quality renewable resources are located.

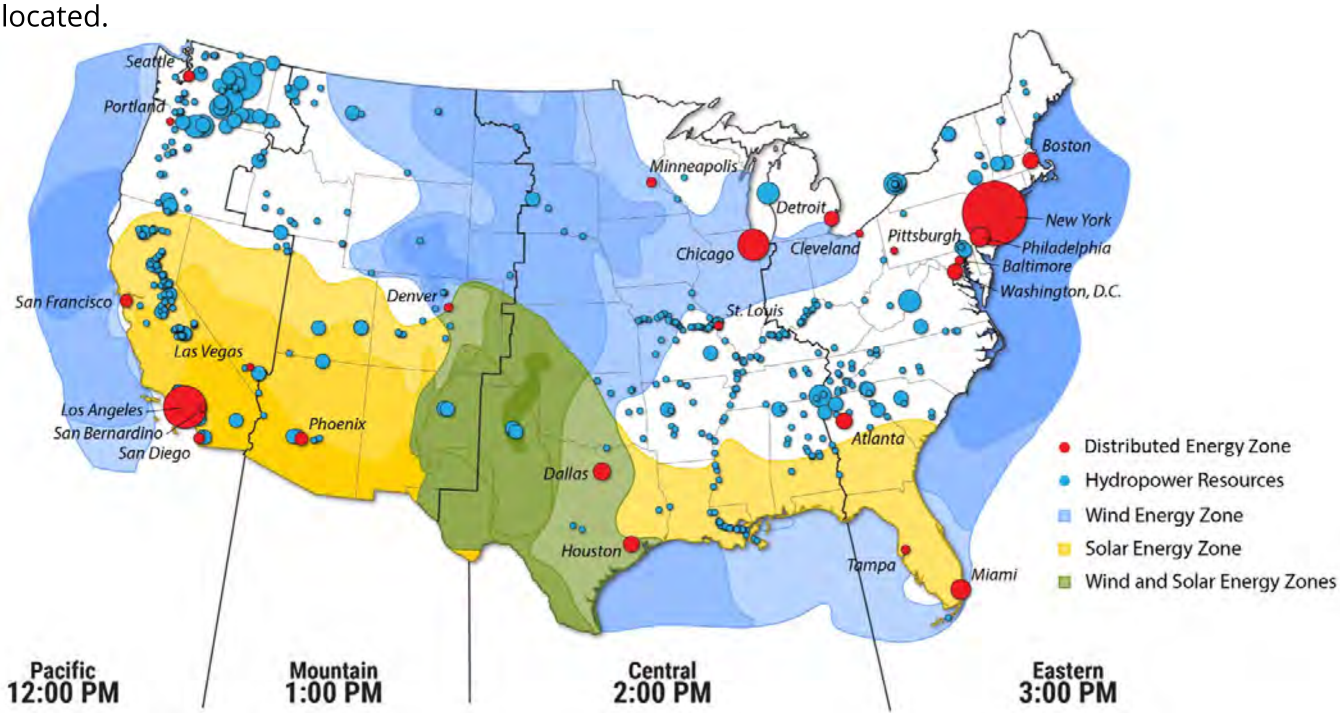

Figure 6. *Renewable energy zones that must be connected to efficiently transition to a clean energy economy.*

Figure 6 shows the areas of the United States with the richest wind and solar generation potential that could host development of much of the 1 TW of new wind and solar generation needed to reach 100 percent clean electricity by 2035. World-class wind resources (in blue) are located in the central United States and offshore in the Atlantic and Pacific oceans. To realize the value of these resources, significant transmission collector systems will be needed to aggregate resources and deliver their energy to customers. Because wind generation is driven by weather patterns and time-of-day performance characteristics, there is significant value in using transmission to connect wind regions that have different patterns rather than concentrating all wind generation in a single region with similar weather.

16 https://www.utilitydive.com/news/texas-crez-lines-delivering-grid-benefits-at-7b-price-tag/278834/

Similarly, the United States possesses exceptional solar resources (shown in yellow) across the South, particularly in the desert Southwest. Collector systems will be needed to aggregate this energy and transmit solar power across the country during daytime hours. Resource diversity across the southern latitudes allows grid operators to leverage resource diversity across climatological patterns, weather variations, and time zones.

Finally, the carbon-free, flexibly operating hydroelectric resources—critical to decarbonizing the electricity sector—can be expanded with the assistance of a macro grid by connecting vast amounts of existing and potential hydroelectric resources to regions and load centers. This includes existing and expanded hydroelectric resources in Canada and in the United States as well as adding generators to thousands of yet-unpowered dams across North America. In addition, hydroelectric pumped storage, which is significantly location-constrained, will be a prime consideration for future large-scale energy storage.

Distributed Energy Resources

Distributed energy resources have substantial potential to be developed in major population centers, including the top 25 metropolitan areas shown in Figure 6. Distributed solar, storage, and demand response will be critical to equitably and efficiently reaching clean energy goals. However, land scarcity and the high correlation of weather-driven generation within concentrated urban areas will limit the ability of these resources to meet all energy demand. Recent analysis shows that the addition of hundreds of GWs of distributed energy resources will enhance the benefits of a macro grid,[17] particularly as distributed generation sources become better integrated with customer loads to reduce net variability. When these resources are bountiful, the macro grid provides access to a broader market for this energy. When they are in lower supply, the macro grid provides energy from other regions. These benefits exist even with large amounts of distributed storage.

DESIGN AND CONSTRUCTION OF A U.S. MACRO GRID

The United States should establish an ongoing planning process to design and build a robust macro grid to allow carbon-free technologies to connect and compete in a national, and potentially international, market. Without the transmission infrastructure to trade energy with neighboring systems, regions will be limited to using local carbon-free resources; this will become even more problematic as transportation and other energy sectors become electrified. This will likely raise local electricity costs, slow decarbonization, and require each region to over-build local generation and regional transmission capacity because without a macro grid, multiple regions cannot effectively share energy resources. ESIG's macro grid concept builds on successful regional transmission expansion efforts including the interconnection of the federal hydropower system in the 1930s, the integration of high levels of renewables in Texas, and significant network expansion to improve grid efficiencies across the Midwest. Based on common attributes of macro grids proposed in multiple rigorous research studies in recent years, ESIG's macro grid concept unites offshore, distributed, and land-based resources on a transformative scale. It reflects both announced resource builds and high-quality solar and wind resources.

Given the scale of electrification needed to decarbonize large portions of the economy, each proposed HVDC transmission hub interconnection should support multiple GWs of generation and load, and potentially many more GWs of transfer capacity in some locations (subject to detailed regional analysis of electricity demand, resource potential, and cost). Estimates of the transmission costs necessary to decarbonize existing electricity demand (without further electrification) are at least $100 billion, and transmission costs could be significantly higher to reach net-zero emissions through electrification of demand.[18] The Interconnections Seam Study found that the benefit-to-cost ratio of building the macro grid was 2.9 over 35 years at 95 percent clean electricity. The MIT Study found that including the macro

17 Vibrant Clean Energy, Why Local Solar For All Costs Less: A New Roadmap for the Lowest Cost Grid, 2020, https://www.vibrantcleanenergy.com/wp-content/uploads/2020/12/WhyDERs_TR_Final.pdf

18 A. Bloom, J. Novacheck, G. Brinkman, J. McCalley, A. L. Figueroa-Acevedo, A. Jahanbani-Ardakani, H. Nosair, A. Venkatraman, J. Caspary, D. Osborn, and J. Lau. 2020. "The Value of Increased HVDC Capacity Between Eastern and Western U.S. Grids: The Interconnections Seam Study." Preprint, submitted October 28, 2020. Golden, CO: National Renewable Energy Laboratory, https://doi.org/10.2172/1696787.

grid reduced overall system costs by 46 percent compared to the state by state approach to reaching a zero carbon electricity system. In areas along the eastern continental shore, large-scale HVDC technology would be advantageous to transport and integrate offshore wind to the mainland electricity system.

A well-designed macro grid will:

- **Connect regions with diverse load and generation profiles.** The macro grid will connect regions that have different wind, solar, and load characteristics as well as connect renewable energy zones to load centers.

- **Have the smallest cost and footprint possible.** The national macro grid's cost and footprint should be kept as low as feasible, for example, by maximizing the use of existing transmission, highway, and railway rights-of-way.[19]

- **Take advantage of existing surplus transmission capability.** Future interconnection points must take advantage of existing "brownfield sites" with surplus transmission capability, thereby reducing the need for "greenfield sites" where entirely new substation facilities must be constructed. The integration of the macro grid into existing and planned AC systems serving regional needs will require unprecedented political and engineering coordination to leverage expected regional and interregional transmission capability to the maximum extent possible.

- **Be both tightly integrated and able to separate safely when necessary.** The transmission grid should be tightly integrated, thereby facilitating the sharing of the resources that provide reliability services essential to maintaining healthy system frequency. But at the same time, it should have the capability to separate or break apart quickly and safely to protect regions from a widespread cascading collapse in the event of an attack or operational failure.

- **Have a network of transmission lines to minimize risk of failure.** The macro grid network must use looped (redundant) transmission where possible for layered defense in depth against multiple operational contingencies and extreme weather events.

- **Be built out in several stages.** For effective execution and to maintain balanced, reliable operation over time, the macro grid network must be built out in several stages over time, as discussed below.

Drawing from these principles and common features of the studies, ESIG created a macro grid concept, shown in Figure 7. This design is informed by the Anbaric/Brattle Offshore Wind Studies, the Interconnections Seam Study, the MIT study, the Renewable Integration Impact Assessment, and ZeroByFifty (see Appendix B). These studies include comprehensive transmission build-outs for integrating large amounts of wind and solar generation. While offshore wind was not considered in all studies, it is clear that offshore wind will be a critical component of decarbonization, as evidenced by the significant interconnection queues, interest of generation off takers and state regulators, and significant offshore builds internationally. The offshore HVDC backbone that we propose along the eastern seaboard will interconnect offshore wind resources and provide a parallel path for lowering energy costs and increasing resilience along the eastern seaboard.

19 https://theray.org/2020/09/19/next-generation-highways/

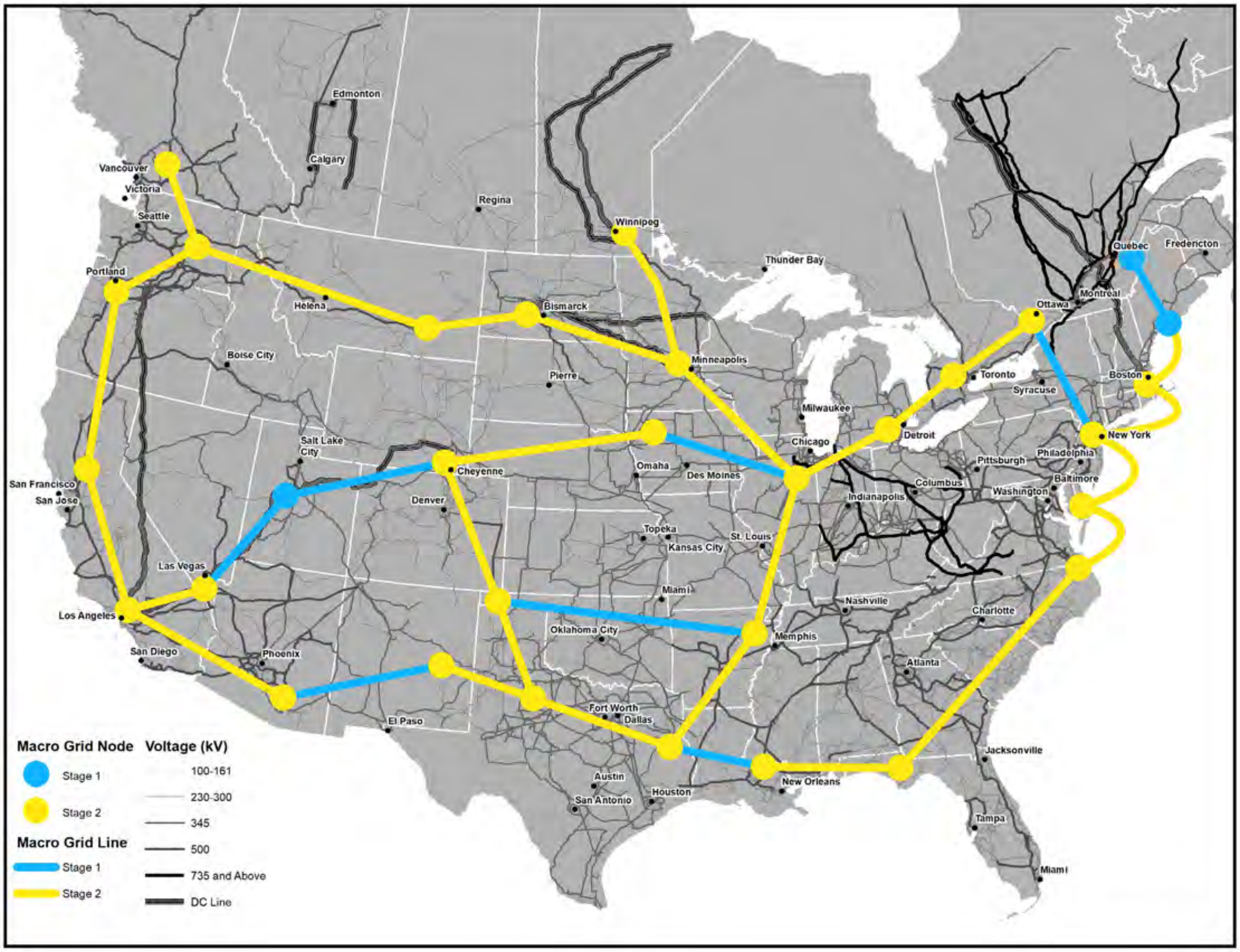

Figure 7. *ESIG's conceptual design for a U.S. macro grid laid over the existing electricity transmission system.*

Stage 1: Complete the Approval and Construction of Individual HVDC Transmission Lines

After the design and engineering stage, the ESIG macro grid infrastructure begins with the approval and construction of individual HVDC transmission lines. Several transmission lines proposed in the last 10 years offer promising routes and technologies for the macro grid and have been studied and analyzed in detail (in blue in Figure 7 and described in Table 2). In some cases, land acquisition and permitting processes have started. These lines could begin construction as early as 2025 and are advantageous because they unite high load zones with exceptional renewable energy zones. Additional lines that are under development could be included in Stage 1 of the macro grid and should be considered by a national macro grid transmission plan.

The MIT study, Interconnections Seam Study, and ZeroByFifty study all indicate that tens of GWs of transfer capability would be essential to reaching decarbonization goals. The Stage 1 lines are smaller than necessary to reach ambitious decarbonization goals associated with reaching 100 percent clean electricity or decarbonizing the entire energy sector, but it is appropriate to start with these lines in Stage 1 because they connect exceptional wind and solar resources to strong elements of the existing AC system, thereby facilitating broader distribution. These lines can be built in the near term while additional macro grid efforts get underway. It would be advantageous to oversize these rights of way and plan the first stage of the macro grid with the expectation that the initial lines and routes will be expanded with additional lines or higher transmission capacity in later years.

The Stage 1 lines must ultimately be connected into a broader network to maximize their value and accelerate the transition to a clean energy grid, and more work is needed to determine the optimal way to integrate those lines into a macro grid. Additional studies will include working with current transmission developers and planners to see how these lines could be used, expanded, or supplemented for maximum value and effectiveness.

Project Name	Capacity	Point of Injection	Point of Receipt
Champlain Hudson Express	1,000 MW	Canada	New York
New England Clean Energy Connect	1,200 MW	Canada	Maine
Plains & Eastern	4,000 MW	Oklahoma	Tennessee
Soo Green	2,100 MW	Iowa	Illinois
Southern Cross	2,000 MW	Texas	Alabama
Sunzia	4,500 MW	New Mexico	Arizona
Transwest Express	3,000 MW	Wyoming	Nevada

Table 2. *Some of the Stage 1 Lines for the Macro Grid*

Stage 2: Create a Wide Network of HVDC Lines and Collector Systems

Stage 2 of the ESIG macro grid concept expands the bulk electricity transmission system to serve 100 percent clean electricity by 2035. In this stage, regional collector systems unite the Stage 1 lines into a wide national transmission network that is complemented by deep levels of storage, flexible demand management, energy efficiency, and distributed generation. In parallel, regional collector systems are developed in renewable energy zones offshore in the Atlantic, the southern United States, and the central United States wind belt to feed growing amounts of clean renewable generation into that network. Similarly, pathways between major load pockets and distributed energy resources should be integrated with the collector systems to minimize system-wide variability in supply and demand. When designing and developing Stage 2, planners should consider the potential to expand Stage 1 lines as clearer regional plans for meeting 2050 net-zero energy goals develop. For example, it may be prudent to install towers that can easily be upgraded with additional conductors as electricity demand rises.

A critical step in Stage 2 will be the identification of existing network elements that will require upgrades to enable the macro grid to function efficiently. It is likely that each hub presented in Figure 7 will require substantial expansion and updates to the underlying transmission network. Major elements of the existing transmission system should be analyzed to determine how they can serve the overall efficiency of the macro grid.

National-scale design plans for Stage 2 could be completed by 2025, with construction beginning before 2030. Deeper integration with Canada and Mexico should be considered in this stage as the country aims to efficiently reach 100 percent clean electricity by 2035.

Stage 3: Add New and/or Expanded Lines as Needed

The final stage of the macro grid construction will depend upon the rate and scale of electrification across the United States' economic sectors. While some electrification of other sectors will occur as the United States works to meet the 2035 target of 100 percent clean electricity, it is likely that expansive electrification will be needed to meet the 2050 target of net-zero emissions economy-wide. While several of the studies reviewed in this paper show the need for tens of GWs of transfer capability across major corridors, more analysis of the optimal sequencing of network expansions is needed. Stage 3 could include the addition of new paths and expansion of paths developed in Stages 1 and 2.

NEXT STEPS

Research has shown that there are clear benefits from widely expanding the United States' transmission infrastructure to decarbonize the nation's power system. Substantial economic savings and reliability protection are associated with coordinated generation and transmission planning on a national scale. But to date, there has been no significant investment in planning, designing, and analyzing the power system the nation needs to realize the goals of carbon-free electricity system and decarbonized economy within three decades.

The value of thoughtfully planned national transmission infrastructure arises from its ability to: (1) help expand wind, solar, storage and other clean resources by more than 1 TW of capacity; (2) balance weather-driven variability in wind, solar, and hydro resources; and (3) reduce costs by pooling renewables and other resources across multiple regions rather than operating each region individually.

Only the federal government has the capacity to support and coordinate the planning and development of a cross-country network of high voltage and extra-high voltage transmission that unites the country to achieve common clean energy policy goals. Because generation siting and development lies with state authorities while interstate transmission is a federal authority, a national transmission plan should be led by an organization with a national view that includes state authorities, and be based on the best available information on renewable resource potential and other clean energy options. Renewable energy zones should be designated across the country to guide development of generating resources and the addition of intraregional, interregional, and multi-regional transmission.

ESIG's macro grid concept is a starting point for the development of a national transmission system that can lower the costs of reaching the clean energy goals of 100 percent clean electricity by 2035 and net-zero emissions economy-wide by 2050. ESIG recommends that presidential leadership be used to bring together relevant stakeholders toward these goals. Federal expertise and funding will also be needed to achieve the administration's goals in an inclusive, productive, and expedient manner. The next steps to reach long-term clean energy goals are to:

Start immediately. A multi-regional transmission plan is essential as the foundation for developing a clean, reliable, and affordable power system. That plan must have enough flexibility and functionality to accommodate regional variations in energy resources and diverse resource, technology, and economic options. It will not be easy to design and build large-scale transmission to interconnect regions and resources. It will take time and require agreement and support from many groups across large areas. Immediate action is imperative to change the trajectory of U.S. carbon emissions and electrify our economy.

Articulate the decarbonization vision and convene the major players. The Biden administration has articulated the vision and need for a decarbonized U.S. energy economy; next comes the commitment to more than double existing transmission capacity and expand clean energy production by an order of magnitude. The administration should quickly convene governors, state public utility commissions, the Federal Energy Regulatory Commission, the North American Electric Reliability Corporation, the Department of Energy, Independent System Operators and Regional Transmission Operators, municipal utilities, cooperatives, investor-owned utilities, and many sectors of customers and stakeholders to rise to this challenge.

Designate an authority. A national transmission planning authority must be designated and endowed with the responsibility to conduct national-level planning in coordination with regional planning authorities. This authority should establish an inclusive, ongoing planning process that takes a systems perspective of the entire country to develop detailed transmission plans and periodically update them. Consideration should be given to whether existing authorities such as the Department of Energy's National Electric Transmission Congestion Study could support the needs of a national transmission planning authority or whether new planning authorities are necessary.

Leverage national capabilities and industry expertise. The federal government possesses vast capabilities for studying and improving the power system through the Department of Energy, national laboratories, power administrations, the Federal Energy Regulatory Commission, and the Department of the Interior. These capabilities should be organized and coordinated to facilitate the industry's design and construction of a national macro grid. New capabilities should be developed and made accessible to the national transmission planning authority and industry at large.

Provide seed funding for new transmission planning and financing. In the 1950s, federal funding supported the planning and construction of the national highway system that transformed our nation's transportation system. From 2009 to 2012, federal stimulus funds supported the development of new electricity planning methods, analyses, and transmission technologies and co-financed new electricity generation and system investments. Looking forward, federal leadership and funding is critical to kick off the new generation of power system planning and investment that will harness American ingenuity and realize our goals for a clean energy, carbon-free future.

Appendix A
TECHNICAL STUDIES THAT UNDERPIN THIS WHITE PAPER

A variety of engineering and economic studies have been conducted in the last decade that provide a justification for developing and implementing a national transmission plan. The ESIG macro grid concept is a composite view based on the combined experience of its members, other experts we invited into the process, and these detailed studies. Many studies have examined future capacity expansions and operations to determine how to manage increased levels of renewable resources. Some studies have also examined resource adequacy and tail events of weather patterns, while others examine steady-state and dynamic stability.

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APPENDIX B
SUMMARY OF STUDIES CONSIDERED IN ESIG MACRO GRID CONCEPT

Anbaric/Brattle Offshore Wind Studies

Pfeifenberger, J., S. Newell, and W. Graf. 2020. Offshore Transmission in New England: The Benefits of a Better Planned Grid. Wakefield, MA. https://newengland.anbaric.com/wp-content/uploads/2020/07/Brattle_Group_Offshore_Tranmission_in_New-England_5.13.20-FULL-REPORT.pdf.

Pfeifenberger, J., S. Newell, W. Graf, and K. Spokas. 2020. Offshore Wind Transmission: An Analysis of Options for New York. Wakefield, MA. http://ny.anbaric.com/wp-content/uploads/2020/08/2020-08-05-New-York-Offshore-Transmission-Final-2.pdf.

The Anbaric/Brattle Offshore Wind Studies compared the benefits of integrating offshore wind in the Independent System Operator - New England (ISO-NE) and the New York Independent System Operator (NYISO) using a generator lead line approach and a planned offshore network. Their examination of offshore wind found that a coordinated offshore transmission network offers a variety of operational and economic benefits compared to an approach that uses individual generator tie lines. Figure B-1 shows their proactive, planned approach of an HVDC offshore grid that interconnects 8.6 GW of offshore wind in New England. The anticipatory planning approach eliminates the need for HVAC upgrades coming out of all the landing sites, especially on lines out of the Cape Cod region. This approach also fosters competition among offshore developers, reduces wind energy curtailment, and saves $1 billion in onshore transmission upgrades. A similar study conducted by Anbaric/Brattle for the state of New York has similar findings and shows savings of at least $500 million for a planned offshore grid compared to individual generator tie lines for each plant.

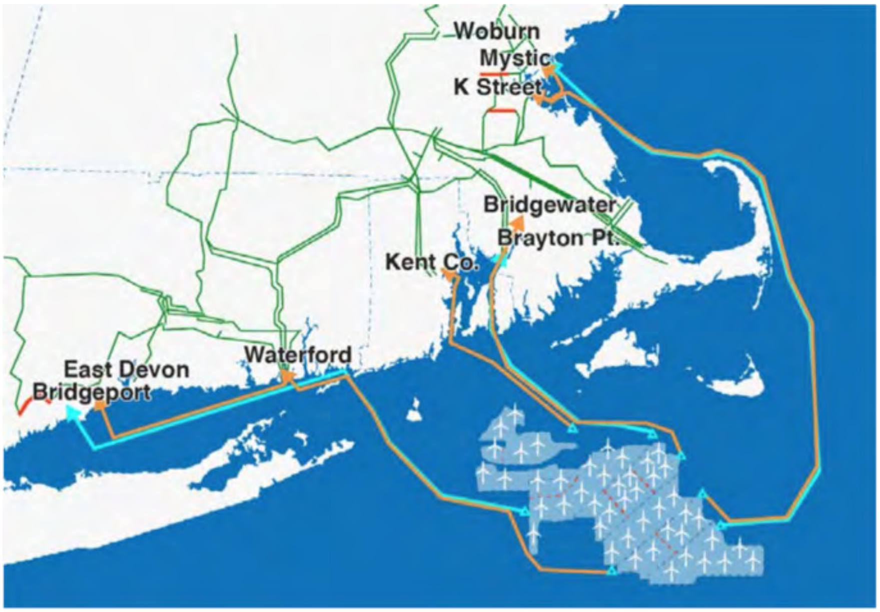


Figure B-1. *Anbaric/Brattle study showing offshore HVDC grid design to enable 8.6 GW of wind without requiring major onshore grid updates.*

INTERCONNECTIONS SEAM STUDY

Bloom, A., J. Novacheck, G. Brinkman, J. McCalley, A. L. Figueroa-Acevedo, A. Jahanbani-Ardakani, H. Nosair, A. Venkatraman, J. Caspary, D. Osborn, and J. Lau. 2020. “The Value of Increased HVDC Capacity Between Eastern and Western U.S. Grids: The Interconnections Seam Study.” Preprint, submitted October 28, 2020. Golden, CO: National Renewable Energy Laboratory. [https://doi.org/10.2172/1696787.](https://doi.org/10.2172/1696787)

Figueroa-Acevedo, A. L., A. J. Ardakani, H. Nosair, A. Venkatraman, J. D. McCalley, A. Bloom, D. Osborn, P. J. Caspary, J. Okullo, J. Bakke, and H. Scribner. “Design and Valuation of High-Capacity HVDC Macrogrid Transmission for the Continental U.S.” IEEE Transactions on Power Systems. [https://doi: 10.1109/TPWRS.2020.2970865](https://doi.org/10.1109/TPWRS.2020.2970865).

The National Renewable Energy Laboratory’s Interconnections Seam Study analyzed the value of national-scale transmission. This study investigated 63 - 95 percent carbon free electricity with modest increase in demand (i.e., not a full economy-wide decarbonization scenario). It found a substantial financial benefit associated with building transmission to unite the eastern and western interconnections (the Texas interconnection was not studied). Both capacity expansion and production cost models (PLEXOS) were used in the Interconnections Seam Study to evaluate investment and operation of the system.

Figure B.2 details the HVDC and AC transmission build-outs across a selection of scenarios. The high-bookend D3 scenario originated from an earlier national-level examination by the Midcontinent Independent System Operator of load and renewable energy diversity and aggregation of resources. Other scenarios with varying levels of transmission between the eastern interconnection and western interconnection were also studied. Increasing the amount of HVDC transmission across the seam allowed for increased solar development with the excellent resources in the western interconnection and increased wind development with the excellent resources in the eastern interconnection, lowering total system costs. In one scenario, the team investigated 85 percent renewable electricity using only the capacity expansion model. In this scenario the transfer capability between the eastern interconnection and western interconnection increased to 40 GW, and the combined installed capacity of wind and solar was 900 GW.

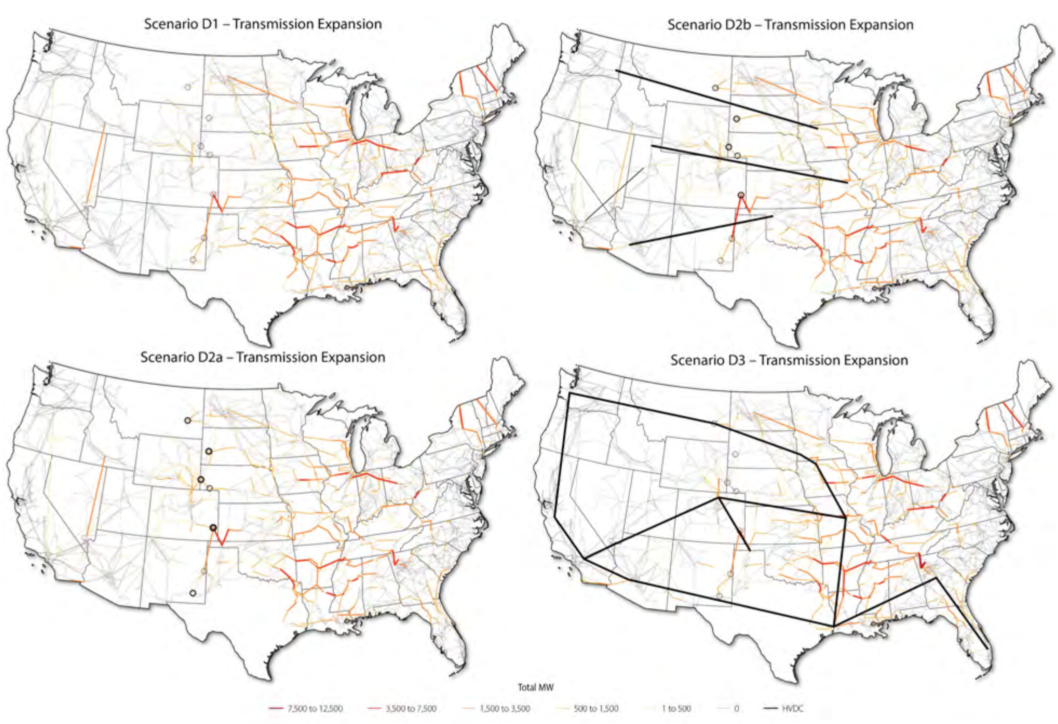


Figure B-2. *Select scenarios from the Interconnections Seam Study.*

MIT STUDY

Brown, P. R., and A. Botterud. "The Value of Inter-Regional Coordination and Transmission in Decarbonizing the U.S. Electricity System." Joule 5(1) (2020): 115-134. https://doi.org/10.1016/j.joule.2020.11.013.

The MIT study found that using a broad, interregional approach for grid planning and dispatch together significantly reduces the average cost of electricity to $73/MWh (from $135/MWh based on an every-state-for-itself approach). It found a 90 percent increase in transmission MW-mile capacity (240 TW-km) compared to today's infrastructure. Transmission for the least-cost plan (the USA+AC+DC scenario) is shown in Figure B-3. Their modeling approach divides the United States into 11 regions, approximating much of today's regional transmission organization (RTO) and planning regions, so that it links somewhat to existing institutional transmission planning and system operations. Within each region, the model expands interstate transmission (not shown in the figure), then it optimizes interregional transmission (shown in red). The routing shown is representative of the modeled expansions, showing the sizes of the transfer capacity (only one route was allowed between the eastern interconnection and western interconnection; all transmission was constrained as AC except for asynchronous connections).

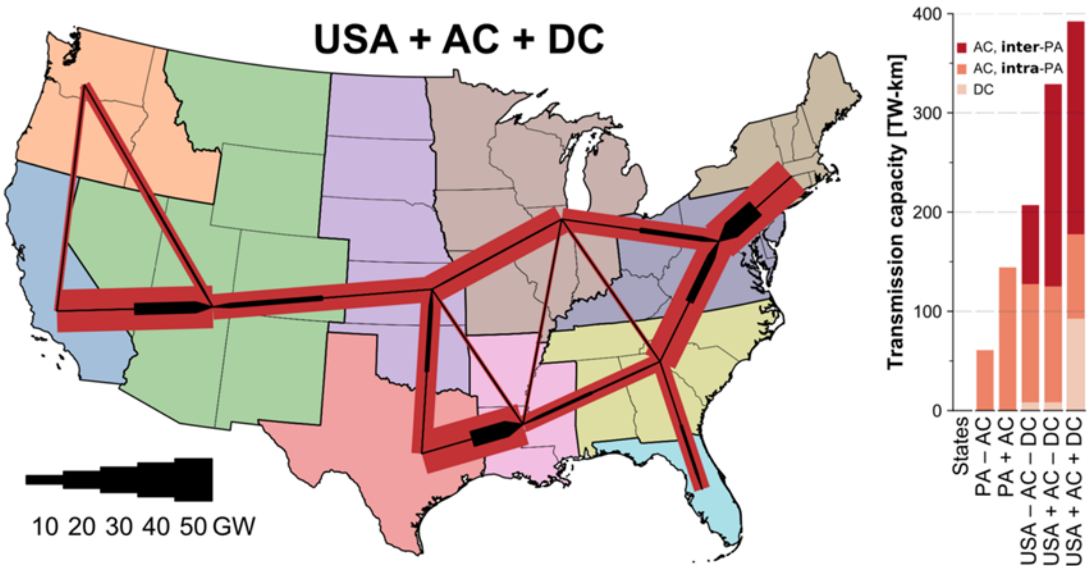


Figure B-3. *Left: installed interregional transmission capacity (red) and average hourly power flow (black) with capacity and flow indicated by line thickness. Each link shows average flow in both directions, with average flow into a node shown by the thickness of the black line on the side of the link closest to that node. Right: transmission capacity built in each scenario, broken down into interregional, intra-regional, and inter-interconnection HVDC transmission.*

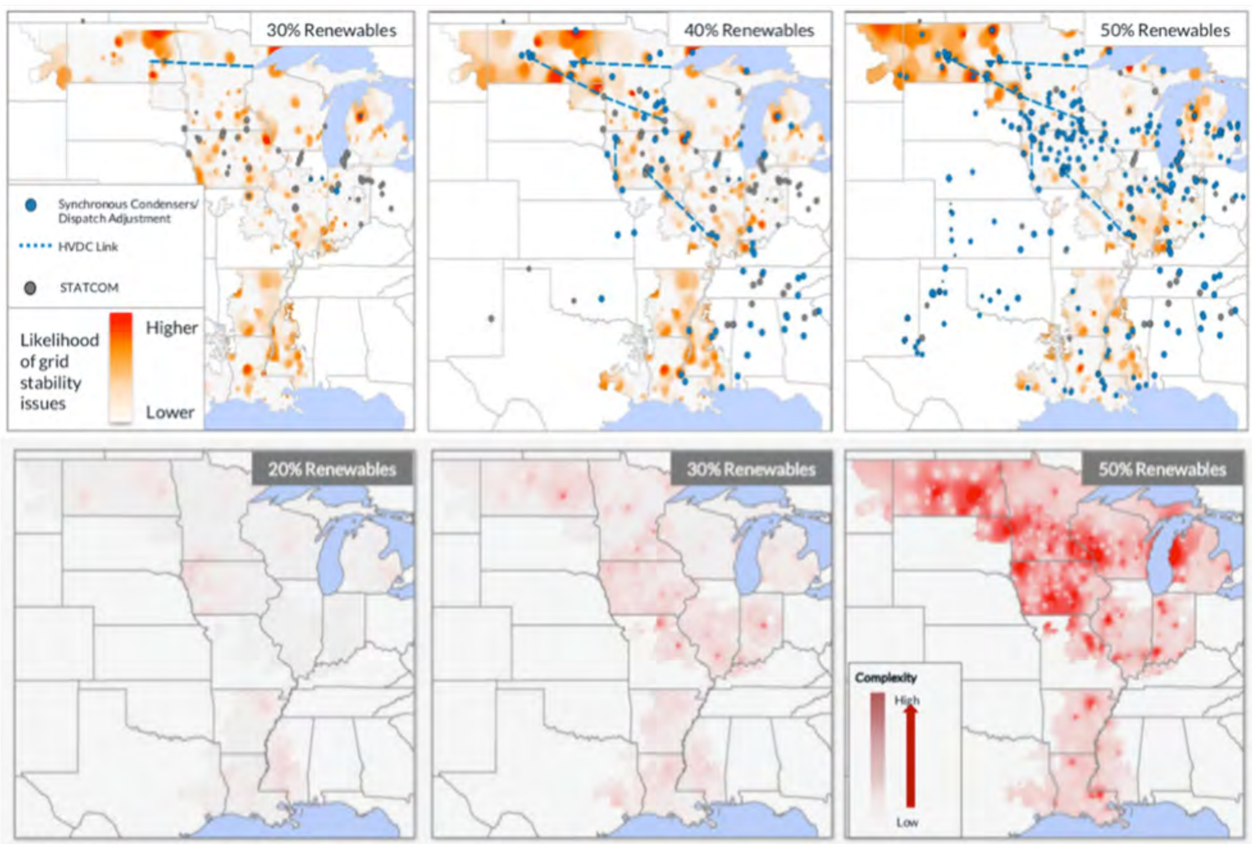
The MIT study builds 29 GW of new transmission capacity between the eastern interconnection and western interconnection and 74 GW of new capacity between Texas and the eastern interconnection, split between a northern and southern route. There are significant interregional transfers, most notably the 43 GW from California to the mountain west and 47GW connecting the Northeast to the Mid-Atlantic. The big takeaway from this transmission plan is not so much the specific plan, because of the modeling constraints, but rather which regions are connected and what size of connection is required. As a macro grid concept like this gets refined, the 29 GW of transfers between the eastern interconnection and western interconnection would be broken down into smaller lines and probably spaced out north to south to provide closer hubs to resource zones, to allow operability in case of contingencies, to build on existing DC ties and right-of-way, to phase in capacity as generation gets built, and to size systems that can be practically built today.

Interregional transmission enables better-quality wind and solar resources, reducing the amount of wind and solar capacity needed, and provides diversity to mitigate balancing needs, thus reducing the amount of storage capacity needed. With a macro grid, much less capacity can be built in regions like the mountain west, Midwest, South, or Mid-Atlantic because imports from oversupply in neighboring regions are often adequate to meet demand. The macro grid also reduces the duration of storage needed.

RENEWABLE INTEGRATION IMPACT ASSESSMENT

Midcontinent Independent System Operator. 2017. Renewable Integration Impact Assessment. Carmel, IN. [https://www.misoenergy.org/planning/policy-studies/Renewable-integration-impact-assessment/#t=10&p=0&s=&sd=.](https://www.misoenergy.org/planning/policy-studies/Renewable-integration-impact-assessment/#t=10&p=0&s=&sd=)

The Midcontinent Independent System Operator's (MISO's) Renewable Integration Impact Assessment (RIIA) investigates system reliability with very high levels of renewables by assessing resource adequacy, system balancing, and steady state and dynamic stability requirements. It is among the most comprehensive studies of very high levels of renewables. The RIIA built incremental transmission infrastructure as appropriate at each step: for thermal violations in steady state, to provide diversity for system balancing, and to mitigate dynamic instabilities. The resulting transmission infrastructure is shown in Figure B-4 for various wind and solar scenarios. The table in the figure shows the significant jump in transmission expansion between the 30 percent and 50 percent scenarios. RIIA completed comprehensive analysis up to 50 percent renewable energy, and resource adequacy analysis up to 100 percent renewable energy. Note that RIIA models the eastern interconnection, but detailed analysis is focused on the MISO region. Given the regional focus of RIIIA, a full macro grid was not included in the study. However, it is important to recognize the foundational role that MISO played in creating the macro grid concept and guiding subsequent studies. RIIA and the associated body of work indicate that the value of a macro grid may grow substantially when reliability benefits are quantified.



* Maps reflect cumulative indicative solutions across milestones

Incremental Transmission Mitigation at 10-20%			
kV	161 and Below	230	345 & above
Ckt*Mile	1,500	200	400

Incremental Transmission Mitigation at 30%				
kV	161 & Below	230	345 & above	HVDC
Ckt*Mile	1,600	200	500	400

Incremental Transmission Mitigation at 50%				
kV	161 & Below	230	345 & above	HVDC
Ckt*Mile	500	700	5000	600

Figure B-4. *The Renewable Integration Impact Assessment's transmission mitigations for various aspects of reliability for a number of wind/solar scenarios.*

ZEROBYFIFTY STUDY

Vibrant Clean Energy. "ZeroByFifty." Presentation at the Energy Systems Integration Group technical workshop (online), November 11, 2020. https://www.vibrantcleanenergy.com/wp-content/uploads/2020/11/ESIG_VCE_11112020.pdf.

The ZeroByFifty study co-optimized generation, transmission, and storage in a combined capacity expansion and production simulation model[20]. It also co-optimized across the distribution interface to build distributed generation and storage. More than twice today's transmission capacity gets added to today's existing network to decarbonize the entire economy by 2050. Importantly, ZeroByFifty finds that if the HVDC macro grid is not built, the cost of the full decarbonization increases by $1 trillion.

Transmission expansion in this study is optimized down to each 69 kV substation. Figure B-5 summarizes the interstate HVDC expansion. For equity purposes, the model was seeded with an HVDC transmission hub in every state, and it optimized the size of connections to the hub. Key elements of the ZeroByFifty macro grid are the need to connect the wind-rich central and northern regions of the country with the solar-rich coastal and desert regions and with major load centers on the coasts and in the eastern interconnection. As a result, there is significant east-west transmission capacity especially through the Midcontinent Independent System Operator and Southwest Power Pool regions, where without the HVDC macro grid wind gets trapped and curtailment doubles. This macro grid allows for much less generating capacity to be built overall, including much less storage and much less nuclear generation. Vibrant Clean Energy notes that with the HVDC macro grid, some of the more polluting technologies such as coal plants run for more years even as faster electrification of other sectors takes place; the net effect is to reduce overall emissions more rapidly.

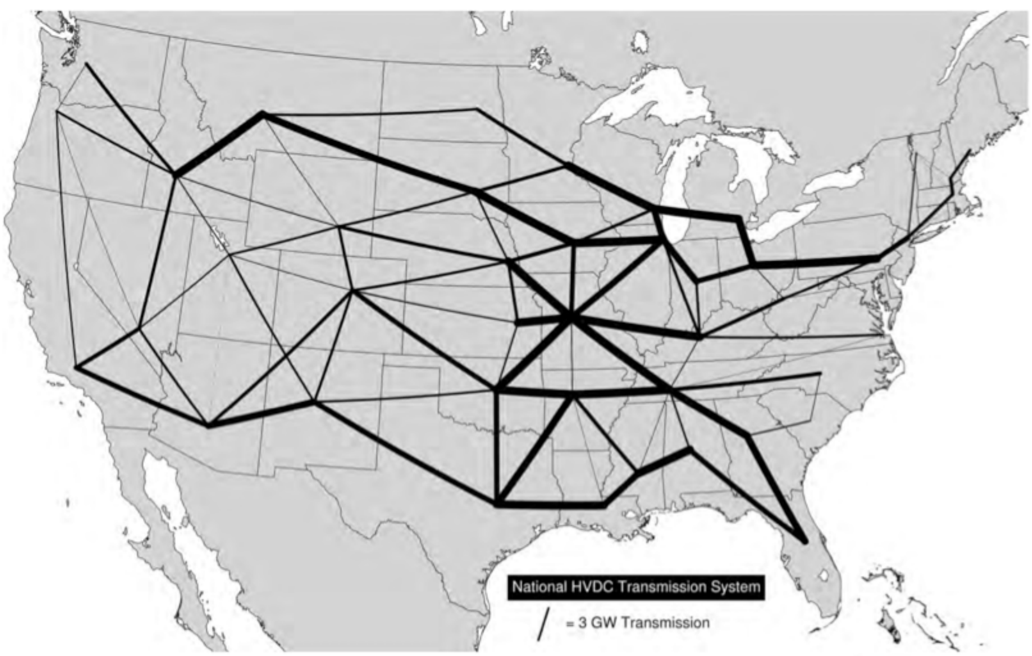


Figure B-5. *ZeroByFifty HVDC transmission expansion.*

20 https://vibrantcleanenergy.com/wp-content/uploads/2020/08/WISdomP-Model_Description(August2020).pdf.