Transmission Planning for 100% Clean Electricity

By Debra Lew, Jordan Bakke, Aaron Bloom, Patrick Brown, Jay Caspary, Christopher Clack, Nicholas Miller, Antje Orths, Alison Silverstein, John Simonelli, and Robert Zavadil

©SHUTTERSTOCK/.COMWILLIAM POTTER

1540-7977/21©2021IEEE

Enabling Clean, Affordable, and Reliable Electricity

NUMEROUS COUNTRIES, STATES, UTILITIES, CITIES, AND CORPORATIONS HAVE adopted 100% clean electricity goals to slow climate change. Typical goals are to achieve 100% clean electricity by 2035 and 100% clean energy by 2050 while maintaining an affordable, reliable energy system. This article explores the role of high-voltage transmission as an enabler for achieving 100% clean electricity and a largely decarbonized economy in an affordable, reliable fashion. It synthesizes the results from several recent studies on decarbonization pathways to examine implications for transmission expansion needs and approaches in the United States and Europe.

As presented in Table 1, various efforts have examined the expansion and performance of alternative electricity decarbonization pathways to understand the solutions and identify common needs. Such studies typically use capacity expansion models to optimize resource mixes and transmission system configurations, on a least-cost basis, and then use production cost models to assess performance and refine systems. These studies include the following:

- ✔ The 2020 10-Year Network Development Plan (TYNDP) conducted by the European Network of Transmission System Operators for Electricity (ENTSO-E), which examined various scenarios up to 78% clean electricity for the European Union. A capacity expansion/production cost model with a detailed representation of the existing transmission network is used in this study. The development plan assessed 154 transmission projects, 26 storage projects, hydrogen for long-duration storage, and high levels of distributed energy resources (DERs).
- ✔ The Interconnections Seam Study conducted by the National Renewable Energy Laboratory (NREL), which investigated the value of additional transmission across the seam between the Eastern Interconnection (EI) and Western Interconnection (WI) for up to 95% clean (85% renewables) electricity by 2038. This study co-optimized generation and transmission expansion and then assessed operational performance, with a detailed production cost model that included 13,000 generating units, 98,000 transmission buses, and 96,000 transmission lines.
- ✔ A recent study from Brown and Botterud at the Massachusetts Institute of Technology (MIT) [referred to here as the *MIT study*], which explored the impact of interregional coordination and transmission expansion at the state, regional, and national level for 100% clean electricity systems by 2040. This study co-optimized generation, storage, and transmission investment and operations over seven years of hourly weather data to ensure resource adequacy during uncommon weather events. This study does not consider security or stability constraints, and the spatial resolution is also lower than the other studies listed here.
- ✔ The Renewable Integration Impact Assessment (RIIA) by the Midcontinent Independent System Operator (MISO), which examined comprehensive grid reliability for the EI with up to 50% wind and solar resources (yielding 63% clean electricity) and examined long-term reliability for the EI with up to 100% clean electricity.

Digital Object Identifier 10.1109/MPE.2021.3104127
Date of current version: 18 October 2021

table 1. A summary of recent clean electricity studies.

Study	Region	Wind/Solar Capacity	Target	Annual Electricity Demand	Target Year
ENTSO-E's TYNDP 2020	Europe (EU 28)	✓ 497–613 GW (wind) 396–686 GW (solar) direct use ✓ + 89–464 GW (wind) ✓ 18–28 GW (solar) [used for hydrogen (H_2) and derived fuels]	75–78% clean electricity (57–61% wind/solar)	3,380–3,930 TWh (direct use) + 284–1,460 TWh (used for H_2 and derived fuels)	2040
NREL's Interconnections Seam Study	United States (except Texas) and Canada	✓ 600–900 GW (wind and solar)	up to 100% clean electricity	4,900 TWh	2038
MIT study	United States	✓ 1,200 GW (wind) ✓ 1,100 GW (solar)	100% clean electricity	5,000 TWh	2040
MISO's RIIA	United States EI	✓ 411 GW (wind) ✓ 677 GW (solar)	up to 100% clean electricity	2,623 TWh	Not applicable
Vibrant Clean Energy's ZeroByFifty	United States	✓ 1,100 GW (wind) ✓ 1,000 GW (solar)	100% clean energy (including 100% clean electricity)	9,000 TWh	2050

TYNDP: 10-Year Network Development Plan; ENTSO-E: European Network of Transmission System Operators for Electricity; NREL: National Renewable Energy Laboratory; MISO: Midcontinent Independent System Operator; RIIA: Renewable Integration Impact Assessment; EU: European Union.

This study employed the most detailed representation of transmission facilities of the studies listed here. The analyses included capacity expansion, loss-of-load expectation, production cost, steady-state stability, and dynamic stability.

- ✓ Vibrant Clean Energy's ZeroByFifty, which co-optimized generation, transmission, storage, novel fuel production, and DERs to decarbonize the United States' energy economy by 2050. The existing transmission topology, down to the 69-kV level, was used as a starting point. A fully combined capacity expansion and production cost model was utilized to compute the least-cost system under various policy pathways.

Decarbonization Requires a Massive Transformation of the Grid

Wind and solar photovoltaics (PVs) are the fastest-growing generation resources in the United States, with approximately 200 GW of wind and solar now installed. But even these huge strides in wind and solar deployment over the last two decades have only increased the clean energy share of electricity from 28 to 38% (the solid blue line in Figure 1). This deployment pace (dashed blue line) will be insufficient to achieve 100% clean electricity by 2035 (dashed green line).

The scale of new clean energy resource deployment will be even larger than indicated if significant electrification occurs. Most of the decarbonization pathways studies call for the significant electrification of transportation, buildings, and industry to replace current fossil energy uses with low-cost, zero-carbon energy. Even if those end uses are made much more energy efficient, electrification will materially increase total electricity demand (defined here as *grid-connected* demand, including that which is met by behind-the-meter distributed generation). NREL's Electrification Futures Study

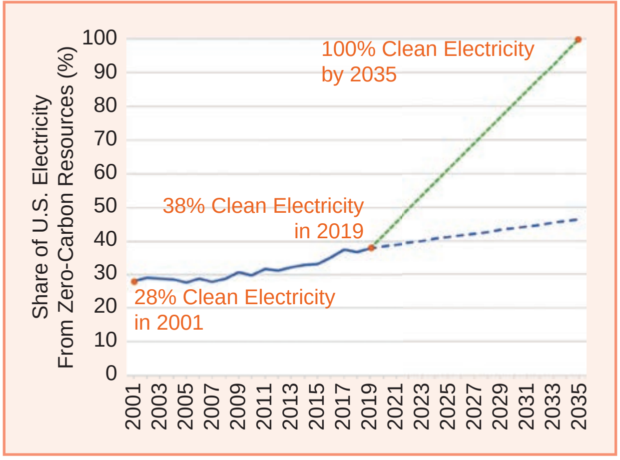


figure 1. The clean share of U.S. electricity from 2001 to 2019 (solid blue line), projections to 2035 at the same rate of clean electricity progress (dashed blue line), and projections to 100% clean electricity by 2035 (dashed green line).

> ZeroByFifty and the MIT study both find that current high-voltage transmission will have to double (in megawatt-miles) to reach 100% clean electricity.

predicts demand nearly doubling by 2050, depending on the pace of electrification. ZeroByFifty forecasts a doubling of current demand by 2050 to reach full energy-economy-wide decarbonization. Electrification will change the magnitudes, profiles, and locations of demand.

To serve this increased demand, a significant capacity of new clean resources will be required. Due to the low and declining cost of energy from wind and PVs, many studies project significant expanded development. At least 1 TW of new wind and PV capacity may be needed to reach 100% clean electricity, and twice that may be needed to reach 100% clean energy. For example, ZeroByFifty finds 1 TW of new PVs and 1 TW of new wind by 2050 needed to meet 100% clean energy [Figure 2(a)]. RIIA finds 1 TW of new wind/PVs is required to meet 100% clean electricity within the EI.

Significant transmission will be needed to deliver these resources to loads. ZeroByFifty found that transmission expansion is required under all future scenarios to decarbonize. The amount of new transmission varies depending on scenario and future demand levels. ZeroByFifty and the MIT study both find that current high-voltage transmission will have to double (in megawatt-miles) to reach 100% clean electricity. To reach 100% clean energy, ZeroByFifty finds that nearly 400 million MW-mi of transmission will be needed on top of today's levels [see Figure 2(b)].

Transmission Costs Are a Tiny Portion of the Total System Costs

In ZeroByFifty, the sum of annualized transmission investments between now and 2050 needed to reach 100% clean electricity is approximately US$200 billion. To reach 100% clean energy, this increases to US$350 billion. Figure 3 shows that transmission costs are less than 10% of total system costs in the MIT, Interconnection Seam, and ZeroByFifty studies.

A Proactive, Planned Approach Saves Money

Brattle's Offshore Wind Studies examined offshore wind integration in both the New England and New York ISO systems. They found that a coordinated offshore transmission network offered a variety of operational and economic benefits compared to the conventional approach using individual generator tie lines. For example, proactive planning and investment in a single high-voltage dc (HVdc) offshore grid interconnecting 8.6 GW of offshore wind in New England will be less expensive than the conventional planning approach of interconnecting each wind

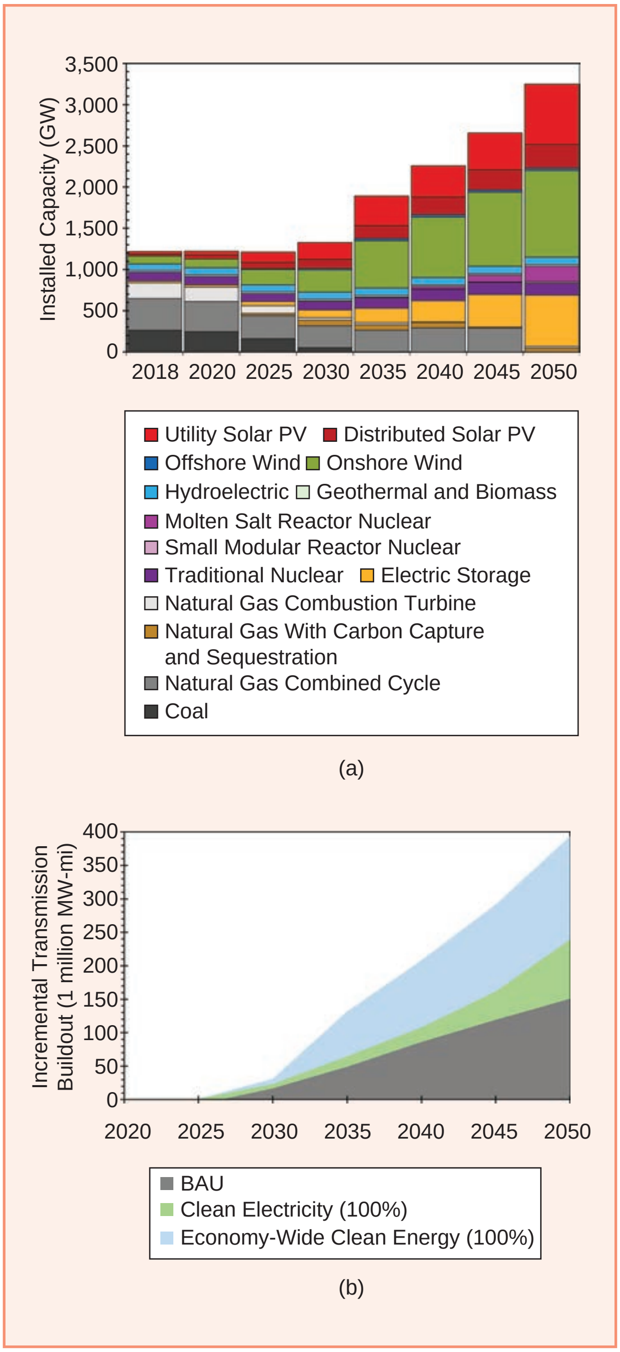
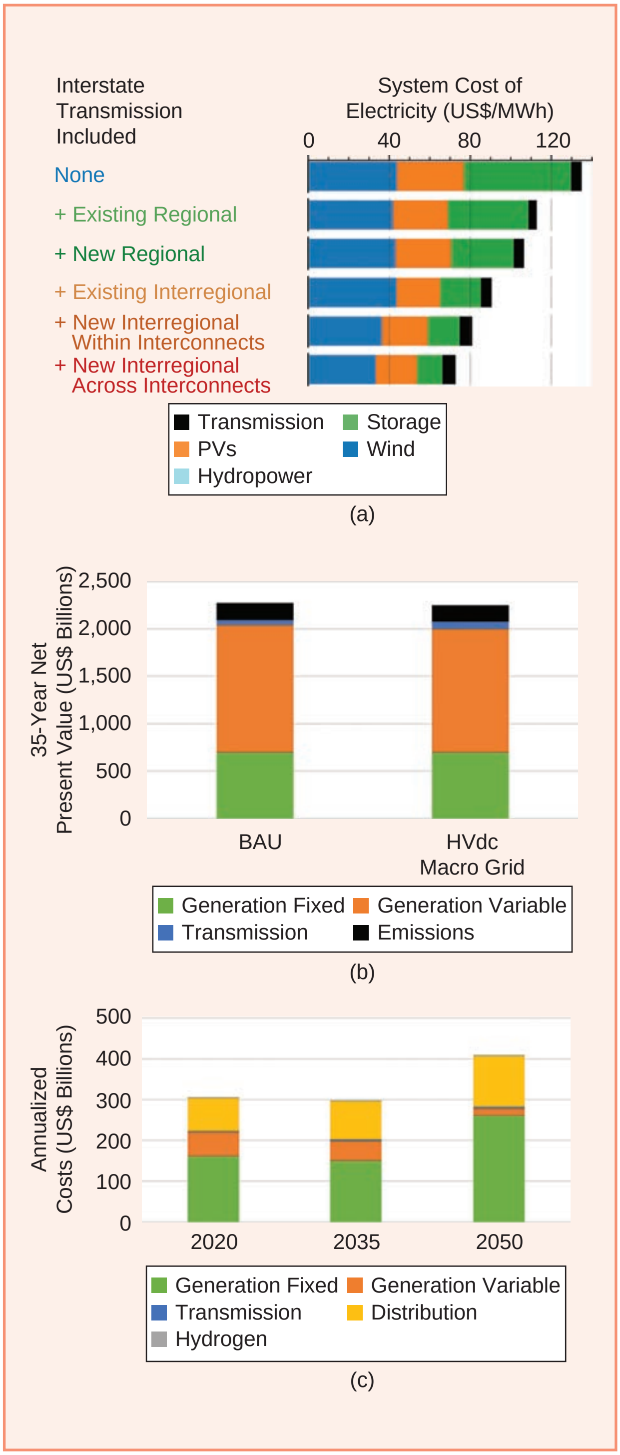


figure 2. The ZeroByFifty results. (a) Resource mix required to reach energy-economy-wide decarbonization by 2050 and (b) new transmission in ZeroByFifty for business as usual (BAU) (gray), 100% clean electricity (green), and 100% clean energy (blue) scenarios.



(a)

(b)

(c)

figure 3. (a) The MIT study's system electricity costs broken down by transmission, storage, PV, wind, and hydropower resources for each of the scenarios; (b) the Interconnections Seam Study's 35-year net present value of system costs for 50% renewables case; and (c) ZeroByFifty's annualized system cost components for 100% clean energy in 2018 U.S. dollars for the years 2020, 2035, and 2050. The fixed costs include capital investments and variable costs comprise fuel and operations and maintenance costs. BAU: business as usual.

plant individually. The proactive planned approach can significantly reduce the amount of onshore HVac upgrades at the landing sites, including in the Cape Cod region, saving money and reducing project risk. This approach would also foster competition among offshore developers, reduce wind energy curtailment, and save US$1 billion in onshore transmission upgrades. For New York, Brattle similarly found savings of at least US$500 million for a planned offshore grid approach.

The Electric Reliability Council of Texas (ERCOT) offers a good example of proactive transmission planning. Competitive renewable energy zones (CREZ) were designated in areas with high-quality wind resources, and new transmission was planned and built to deliver that new generation to loads. This process did not merely identify resource zones, but legislatively deemed these transmission lines "used and useful" to assure cost recovery of the CREZ transmission projects. Transmission could then be properly sized to the zones rather than developed and justified incrementally as the generation projects were approved, saving money through the "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. The statute imposed short-time requirements upon planners and regulators to design and process the CREZ plans, select competitive transmission providers, and approve line routes. Texas' practice of assigning transmission expansion costs directly to customers, rather than requiring new generators to pay for transmission upgrades (as the latter yields incremental rather than large-scale transmission expansion), also contributed to the success of CREZ.

Optimizing Capacity and Transmission Expansion Over Larger Regions Saves Money

The MIT study found that conducting electric system coordination and expansion over increasingly larger geographic areas reduces system cost, generation capacity, and storage capacity needed for an equivalent level of reliability. It found that the system cost of electricity (including annualized capital, operating cost of generation, transmission, and storage, but excluding distribution and administration costs) in the nationally optimized zero-carbon system to be US$62/MWh (46%) lower than the average system cost in the every-state-for-itself alternative [shown previously in Figure 3(a)].

A Macrogrid Saves Money

A macrogrid is a large-scale, interregional network of transmission that can include HVac and dc components. HVdc has many benefits, including lower cost for long-distance, high-capacity transfer capability and more efficient use of right of way. It also can benefit stability in weak grids using voltage source converters (as discussed below). In addition, HVdc connects asynchronous ac systems such as the EI, WI, and ERCOT. Multiterminal HVdc can be used to provide off-ramps along long distances, albeit at a higher cost. Dc terminals can connect into HVac collector systems at source and sink regions.

Point-to-point flows of HVdc may make it a superior solution for long-distance transfers to avoid issues on the underlying network and for managing interregional operations and market transactions. A macrogrid potentially adds another layer of market operations and coordination to existing grid management. Research is needed to explore options for the operations and operability of such a system in a secure and economic manner.

It is computationally difficult for a capacity expansion model to optimize a macrogrid for a large, complex transmission network, such as that of the United States. Studies tend to stitch together regional models, seed the models with the locations of transmission hubs, and evaluate extensive scenarios to assess the value of the resulting grid options. ZeroByFifty is unique in that it models the entire contiguous United States simultaneously, along with a selection of HVdc transmission lines that are competing with other options (storage, ac transmission, generation, and DERs). The expansion model algorithm selects lines it deems are the most cost-effective resources from the various alternatives.

These studies found that macrogrids save money, especially when decarbonization goals are more aggressive:

- ✔ The MIT study found the nationally optimized transmission system to be the least costly scenario to achieve a decarbonized energy system. The national-scale, cost-optimized transmission system added tens of gigawatts of transmission capacity within and between planning areas, including 29 GW of new HVdc capacity between the EI and WI and 74 GW between ERCOT and the EI [Figure 4(a)].

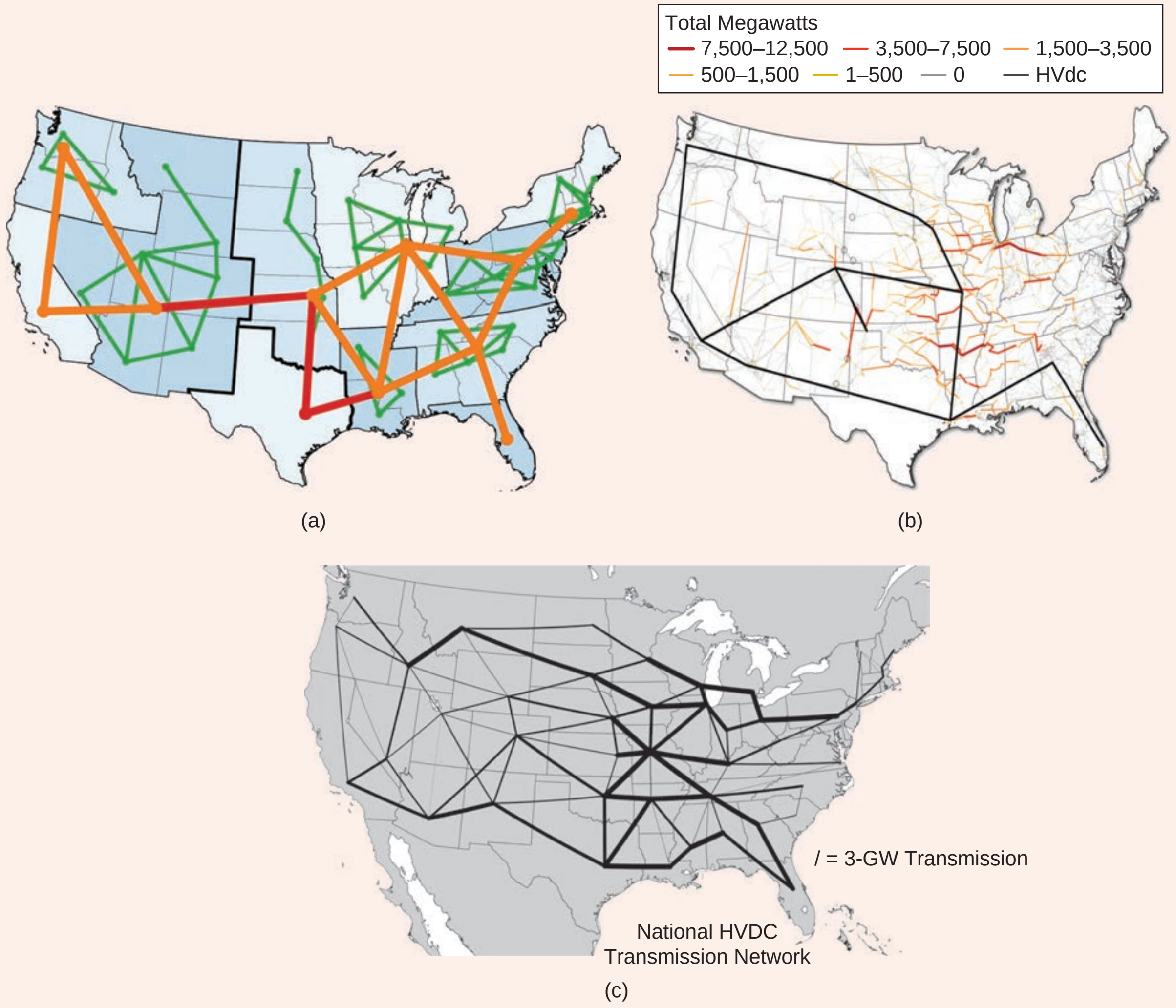


figure 4. (a) The MIT study's "transmission representation" with green, orange, and red lines depicting transmission that is regional, interregional within interconnections, and HVdc interregional across interconnections, respectively; (b) the Interconnections Seam Study's HVdc macrogrid; and (c) ZeroByFifty's HVdc Interstate Transmission Network. The transmission shown here is not meant to represent actual routing but rather the connectivity and transfer capacities among states, regions, or interconnections.

- ✓ The Interconnections Seam Study compared various levels of increased connection between the EI and WI. The HVdc macrogrid design [Figure 4(b)] saved money compared to not building across the EI-WI seam. For the 50% renewables case, the macrogrid scenario cost US$18.9 billion more in transmission but saved US$3.5 billion in new generation capacity, US$35.7 billion in operations and maintenance, and US$8.6 billion in emission costs (compared to not building across the seam). This yields a benefit-to-cost ratio of 2.5. At 95% clean electricity (85% renewables), the benefit-to-cost ratio was even better: 2.9 for a macrogrid compared to not building the macrogrid. In the 95% clean electricity scenario, the transfers across the EI to the WI seam were roughly 40 GW, 30 times the current 1,300-MW transfer capability.
- ✓ ZeroByFifty found that an HVdc network linking neighboring states [shown in Figure 4(c)] would be near optimal in terms of capital cost while removing some siting hurdles. It also found that to reach 100% clean energy, the total system costs by 2050 would be US$1 trillion higher if the network is not built. ZeroByFifty's HVdc capacities between the interconnections vary by scenario, but the approximate transfer capacities are 38 GW between the EI and WI, 30 GW between the EI and ERCOT, and 8 GW between the WI and ERCOT.
- ✓ There are similar findings outside the United States. The European TYNDP 2020 identified that by 2040, an additional 93 GW of transmission infrastructure would be needed on top of the 2025 grid status to serve the national trends scenario with 75% of renewable electricity. This would have an annual investment cost of €3.4 billion but save €9.6 billion in generation costs annually across Europe, at a benefit-to-cost ratio of 2.8. The European proposals for decarbonization are more futuristic and ambitious than America's. An HVdc/hydrogen grid is one example, as described in "Transmission for Energy Islands in the North Sea."

Transmission Enhances Resource Adequacy

Transmission does more than deliver resources to load: it connects regions to provide a diversity of wind, solar, and hydro resources as well as to provide load diversity. For example, the RIIA found significant increases in wind and solar effective load-carrying capability (ELCC) when those resources were aggregated using MISO-wide transmission rather than only serving local resource zones and customers. The RIIA found, at the 100% renewables penetration level, that MISO's wind and solar had an ELCC of 12.5% if it served only MISO load, and a much higher ELCC of 24.6% if it served the combined loads of MISO, PJM, the Southwest Power Pool (SPP), and the Southeastern Electric Reliability Council because of the greater load diversity.

Diversity benefits have been demonstrated in the SPP. It reduced its planning reserve margin (PRM) from 17.6% before 1998 (before the SPP's formation) to 13.6% during 1998–2016 to 12% in 2017. The expanded transmission network and balancing area footprint that led to the reduced PRM in 2017 was expected to save US$90 million annually in deferred capacity investments.

A potential future resource mix that is very high in wind and solar resources could potentially be vulnerable under severe weather conditions, which create very high net loads covering large regions over multiple days in a row. Large-scale, interregional transmission (far exceeding the current levels) will likely make the grid more resilient under such conditions.

Transmission Helps System Balancing

The RIIA differs from many other studies in that it steps through 10% increments of wind and solar penetration over time, conducts a comprehensive evaluation of grid reliability, identifies reliability violations, and applies mitigation options to those violations before moving to the next increment. This approach mimics real life, as opposed to snapshot studies that optimize around a future end state, such as 100% clean electricity.

The RIIA used a production cost model to ensure the hourly performance of each penetration level. The study also examined changes in ancillary services requirements due to increased renewables and the deliverability of those ancillary services. The RIIA found that major transmission solutions were not needed for energy adequacy at lower (⩽30%) renewables' penetrations because an overbuild of wind and solar capacity [the purple bars in Figure 5(a)] was sufficient. However, at higher penetrations, additional transmission expansion [the gray areas show ac, orange shows dc additions in Figure 5(a)] was required to provide diversity in renewables and load.

Transmission Helps Steady-State Reliability

The RIIA's load flow analyses examined thermal and voltage violations under steady-state conditions for normal and abnormal operations. The operating violations started occurring at 30% renewable penetration, requiring transmission expansion [Figure 5(b)]. Additional higher-voltage transmission solutions were required as renewable penetration increased.

Transmission Needed for Dynamic Stability

The RIIA's analyses addressed frequency response, transient stability, small-signal stability, and converter stability to examine dynamic stability in the event of a transmission fault or the loss of the largest generator. At 40% renewable penetration, the pockets of the system with high penetrations of inverter-based resources experienced weak grid issues. These resulted in undamped voltage oscillations and control interactions [Figure 5(c)]. The RIIA first applied low-cost, commercial solutions, such as controls tuning and generator redispatch, but as voltage and converter stability issues became more severe, more expensive solutions were required.

HVdc with voltage-source converters can help stability, but line-commutated converters did not help and synchronous condensers created new stability issues. New technologies, such as grid-forming inverters, were not considered in this study but are likely to be helpful mitigations in the future.

Figure 5(d) shows the sum of all the RIIA reliability-mitigation solutions accumulated across the successive renewable levels analyzed. The majority of the mitigations were transmission lines and other transmission infrastructure. Some renewables' overbuild was used for balancing, and a small number of gas plants were used for resource adequacy. There may be opportunities to reduce costs by optimizing for a desired future state rather than accumulating incremental improvements over time.

Transmission for Energy Islands in the North Sea

Decarbonization of the power sector and electrification of other sectors are closely linked opportunities. The European offshore renewable energy strategy aims to develop 300 GW of offshore wind capacity and 40 GW of ocean energy by 2050. This will require a massive expansion of energy infrastructure. It is expected that electricity will not be the only energy carrier but will be supplemented with green hydrogen (H_2) (hydrogen generated via electrolysis using excess wind power), which can be used directly or transported to further usage [e.g., power to other forms of energy or other uses (P2X)].

Denmark already sources more than 50% of its electricity from variable renewables. But to realize its 100% renewable electricity target together with the 70% decarbonization target (compared to 1990), the Danish government plans to install two energy islands by 2030. These islands will first connect 3 GW of offshore wind (North Sea) and 2 GW in the Baltic Sea, totaling 75% of the country's current peak demand. The islands could eventually be connected to other nations as well. This idea has been investigated since 2016 in the North Sea Wind Power Hub project, a joint effort between Denmark's Energinet, The Netherlands' Gasunie, and Germany's Tennet (see Figure S1). Several studies have been executed to investigate the market frameworks, potential locations and integration routes, and planning and permitting options.

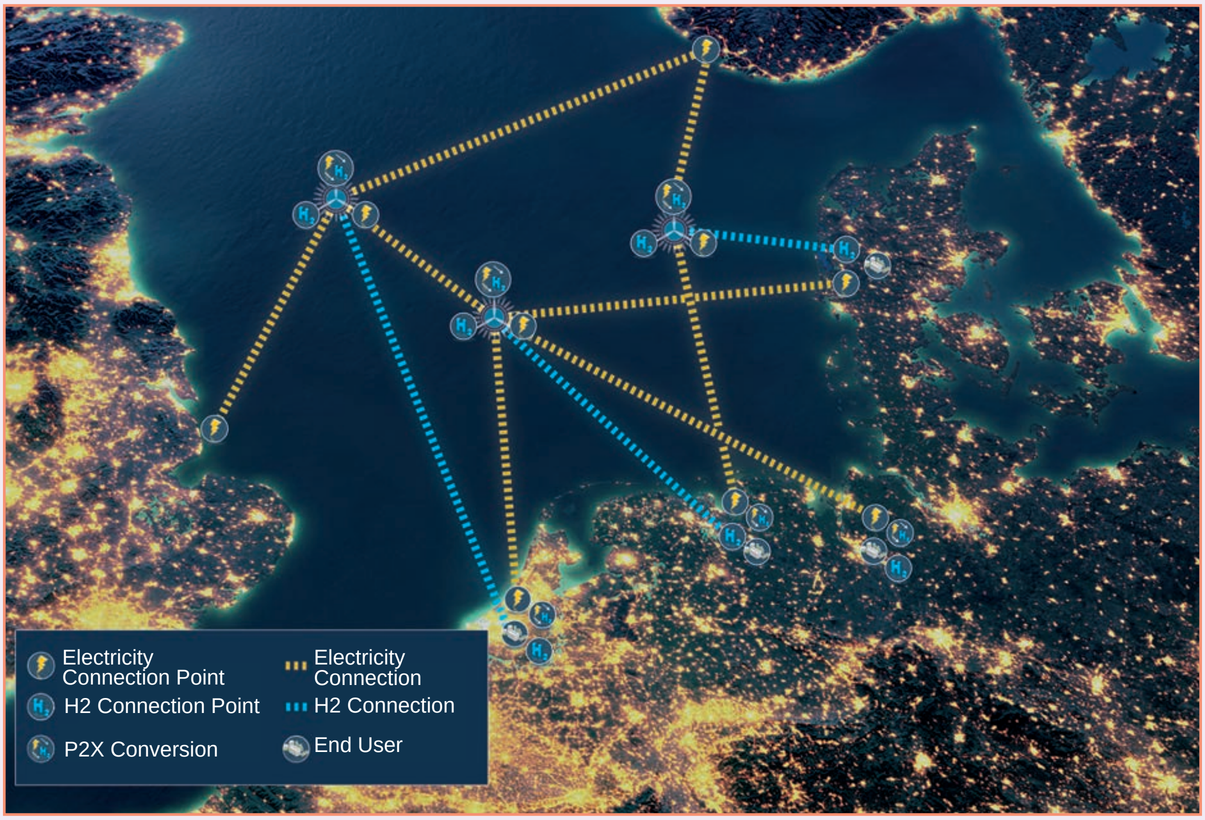


figure S1. The principal idea of the hub-and-spoke concept, including potential electricity (yellow) and hydrogen (blue) infrastructure. (Source: North Sea Wind Power Hub Program. The project is cofinanced by the Connecting Europe Facility of the European Union.)

Is Storage a Transmission Replacement?

Storage and transmission may augment each other and both will be needed to decarbonize the grid. The amount of storage needed may be reduced by taking advantage of an optimized transmission system, but storage plus transmission will give system operators the flexibility to maintain reliability at lowest cost.

For 40% renewable penetration, the RIIA's storage-only optimization led to an expensive solution, with 16 GW of new storage. Transmission-plus-storage optimization provided a far cheaper solution (0.5 GW of storage), imposed the least curtailment of renewable generation, and enabled the storage to be utilized more fully. The transmission-only optimization was only marginally more expensive than the transmission-plus-storage solution.

The MIT study included a broad sensitivity analysis, showing that inexpensive, flexible nuclear reduced the amount of transmission required, while increased electrification or tightened renewable siting constraints increased the need for transmission. The combination of low-cost wind/PVs/batteries with nationally optimized transmission had the least cost of all the sensitivity cases considered.

ZeroByFifty examined hydrogen production and utilization as a long-duration storage mechanism and found that more transmission was needed with the hydrogen scenarios. Given the expenses associated with the transport of hydrogen (leakage, transport efficiency, and so on), the study found it cheaper to produce the hydrogen closer to its utilization

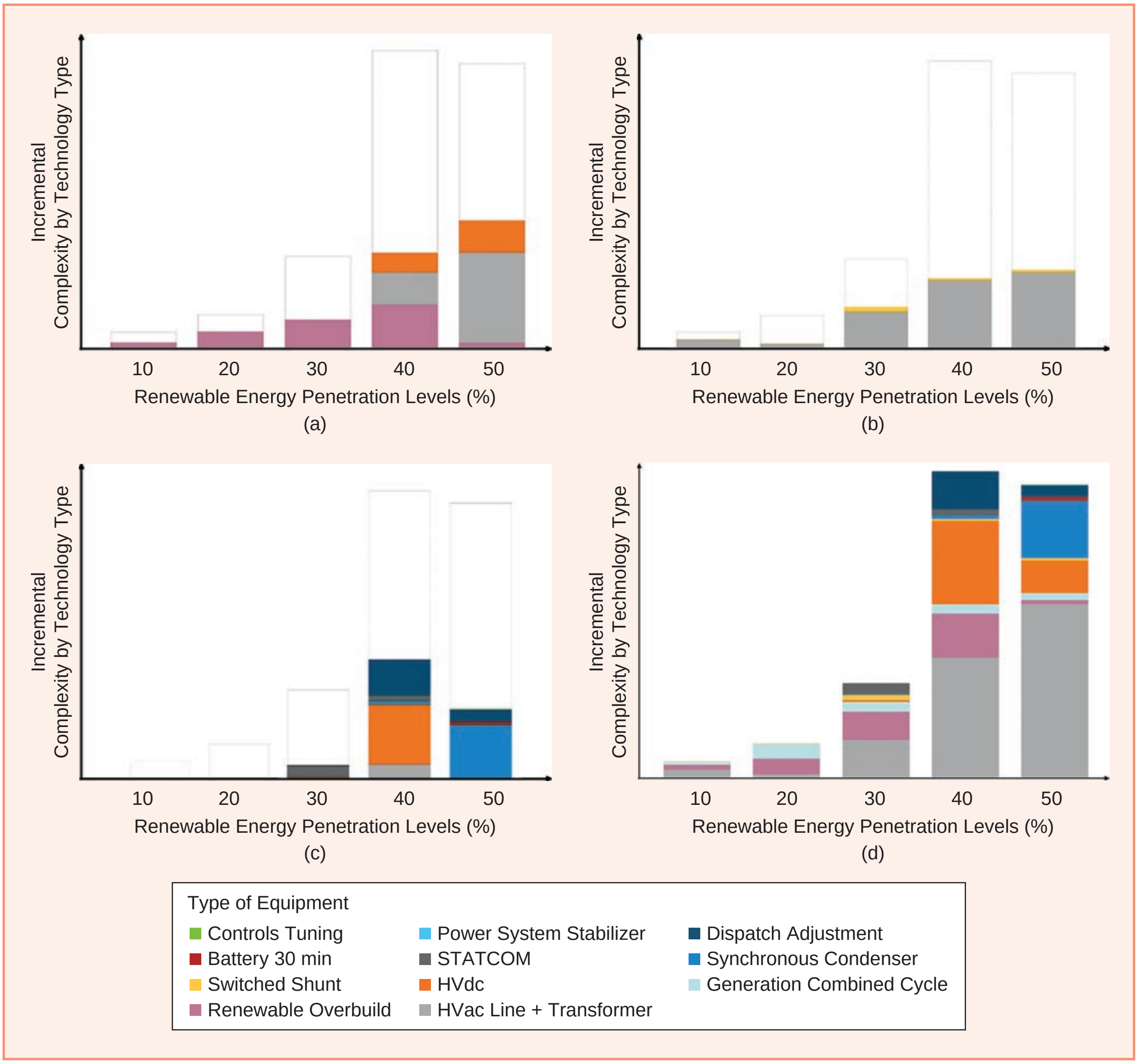


figure 5. The results from the RIIA, showing the mitigations needed for (a) system balancing; (b) steady-state stability; (c) dynamic stability; and (d) the sum of resource adequacy, system balancing, steady state, and dynamic stability. The *y*-axis of increased complexity is determined by the cost of mitigation options. STACOM: static synchronous compensation.

> The macrogrid concepts presented in this article for the United States and Europe cannot be planned, designed, or implemented without an entity that is responsible for executing transmission at that level.

centers. Transmitting electricity to the hydrogen production facilities was more cost-effective than producing hydrogen near electricity generation facilities and transporting the hydrogen to the utilization centers.

Does the Use of Local Resources or DERs Obviate the Need for Transmission?

Distributed solar, storage, and responsive demand will be critical to reach 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 demands. Transmission enhances the use of DERs: ZeroByFifty built 50% more DERs with the HVdc network. Distributed PVs and storage injected energy and balancing services into load centers. But during times of excess or insufficient generation, additional transmission infrastructure was needed to balance the system over all hours of the day.

Most of the capacity expansion studies model distributed PVs either by endogenously setting targets or by examining the economic tradeoff of utility-scale PVs plus transmission versus distributed PVs. To our knowledge, only Vibrant Clean Energy has co-optimized generation, transmission, and the distribution interface. In “Why Local Solar for All Costs Less: A New Roadmap for the Lowest Cost Grid,” they found that costs of upgrading distribution feeder infrastructure increase with the electrification of buildings, transportation, and industry. They found that by including these distribution infrastructure costs in the capacity expansion model, some storage and PV investments shifted from large utility-scale projects to distribution-level installations. This analysis found that the increased capacity of DERs did not reduce the need for bulk system transmission. Rather, the co-optimized clean energy scenarios built substantially more distributed solar and storage *and* required 10 million MW-mi more of transmission than the scenario, which did not co-optimize distribution. Because 100% clean electricity may be a step on the road to 100% clean energy, and because electrification has significant impacts on the distribution system, modelers will need to increasingly include the distribution interface when they study optimal decarbonization pathways.

A Path Forward for Transmission

The following steps may provide a path forward to support 100% clean electricity.

- ✔ *Establish a national or international transmission planning authority*: The macrogrid concepts presented in this article for the United States and Europe cannot be planned, designed, or implemented without an entity that is responsible for executing transmission at that level. This wide-scale geographical perspective on transmission planning requires at least a national-level perspective on current and long-term future resource locations, demand requirements, system optimization, and planning. A national transmission planning organization would work with regional planners and others to coordinate top-down and bottom-up needs and optimize solutions. ENTSO-E offers an example of an international solution.
- ✔ *Conduct a national or international transmission planning process*: Long-term, ongoing transmission planning processes are superior to “one-off” planning exercises, which can quickly become outdated. A successful decarbonization strategy will require the accelerated construction of clean energy resources and transmission as well as rapid technological innovation. All of these would be reflected in recurring, comprehensive planning cycles to capture the full range of the transmission’s benefits and evolving grid needs and opportunities. This approach must include reliability analyses, such as resource adequacy, capacity expansion, system balancing, steady-state stability, and dynamic stability. This effort will look like an integrated resource and transmission planning effort. Even though resource deployment is often left to developers, regulators, and utilities to plan and build, transmission availability determines where and how much generation is built. Local and regional transmission planning needs to integrate into and coordinate with a national plan. European law requests two-year cycles of joint scenario development from both the gas and electric ENTSOs. It also requests pan-European infrastructure plans for electricity and gas for a 10- to 20-year time horizon and annual adequacy assessments for a 10-year time horizon.
- ✔ *Renewable energy zones and proactive transmission development*: The best wind and solar resources are typically located in regions that are distant from large load centers. The interconnection of resources with individual generator tie lines can be inefficient, slow, and costly. A planned approach that identifies preferred renewable energy zones and proactively builds properly sized transmission to these zones will enable an expeditious, efficient growth of clean resources. As in the CREZ process, this can be combined with a fair and reasonable cost allocation (recognizing that

beneficiaries change over time) and expedited siting and permitting processes.

✔ *Principles for a macrogrid*: The integration of the macrogrid into the existing ac systems serving regional needs will require unprecedented regulatory and engineering coordination. Some principles to consider for designing a macrogrid include

- *Connecting regions with diverse load and generation profiles*: The macrogrid will connect regions that have different wind, solar, and load characteristics and connect renewable energy zones to load centers.
- *Having the smallest cost and footprint possible*: It is essential to maximize the use of existing transmission, highway, and railway rights of way to reduce lengthy siting and permitting challenges.
- *Taking advantage of existing surplus transmission capability*: Future interconnection points should take advantage of existing “brownfield sites” with surplus transmission capabilities when possible. That said, not all surplus transmission capacity links to high-quality clean energy resources, and it may not be sufficient for future generation needs. Some “greenfield sites” of entirely new lines and substation facilities may need to be constructed.
- *Having a network of transmission lines to maximize overall grid resiliency*: The macrogrid network should use looped (redundant) transmission where possible for layered defense in depth against multiple operational contingencies and extreme weather events. For example, an outage of a path on the macrogrid should not lead to overloads on the underlying ac network.
- *Being both tightly integrated and able to separate safely when necessary*: The transmission grid should be tightly integrated to share the resources that provide reliability services essential to maintaining a healthy system frequency. But at the same time, it should have the capability to separate or break apart quickly and safely to prevent a cascading collapse from affecting multiple regions. The integration of a macrogrid into the existing separation plans will require careful engineering coordination.
- *Being built out in several stages*: For effective execution and to maintain a balanced, reliable operation over time, the macrogrid network should be built out in multiple, planned stages over decades.

Many studies find that large-scale transmission is a key enabler to the affordable, reliable decarbonization of electricity or energy. Transmission can complement and facilitate a better utilization of storage and DERs. Because transmission planning and coordination need to occur at a national or even international scale, leadership at the highest levels of government is critical to realizing a clean energy future.

For Further Reading

P. R. Brown and A. Botterud, “The value of inter-regional coordination and transmission in decarbonizing the US electricity system,” *Joule*, vol. 5, no. 1, pp. 115–134, 2020. doi: 10.1016/j.joule.2020.11.013.

“TYNDP 2020 main report,” ENTSO-E, Jan. 2021. https://eepublicdownloads.blob.core.windows.net/public-cdn-container/tyndp-documents/TYNDP2020/Foropinion/TYNDP2020_Main_Report.pdf

A. L. Figueroa-Acevedo et al., “Design and valuation of high-capacity HVDC macrogrid transmission for the continental US,” *IEEE Trans. Power Syst.*, vol. 36, no. 4, pp. 2750–2760, July 2021. doi: 10.1109/TPWRS.2020.2970865.

“Renewable integration impact assessment,” Midcontinent Independent System Operator, Carmel, IN, 2017. [Online]. Available: https://www.misoenergy.org/planning/policy-studies/Renewable-integration-impact-assessment

J. Pfeifenberger, S. Newell, and W. Graf, “Offshore transmission in New England: Benefits of a bsetter planned grid,” Anbaric, Wakefield, MA, 2020. [Online]. Available: https://newengland.anbaric.com/wp-content/uploads/2020/07/Brattle_Group_Offshore_Tranmission_in_New-England_5.13.20-FULL-REPORT.pdf

C. T. M. Clack, A. Choukulkar, B. Coté, and S. McKee, “Transmission insights from ‘ZeroByFifty’,” presented at the Energy Systems Integration Group Transmission Workshop, Nov. 11, 2020. [Online]. Available: https://www.vibrantcleanenergy.com/wp-content/uploads/2020/11/ESIG_VCE_11112020.pdf

Biographies

Debra Lew is with Energy Systems Integration Group, Boulder, Colorado, 80305, USA.

Jordan Bakke is with the Midcontinent Independent System Operator, Minneapolis, Minnesota, 55121, USA.

Aaron Bloom is with Nextera Analytics, Minneapolis, Minnesota, 55107, USA.

Patrick Brown is with the MIT Energy Initiative, Cambridge, Massachusetts, 02139, USA.

Jay Caspary is with Grid Strategies LLC, Higden, Arkansas, 72067, USA.

Christopher Clack is with Vibrant Clean Energy, Boulder, Colorado, 80301, USA.

Nicholas Miller is with Hickory Ledge LLC, Delmar, New York, 12054, USA.

Antje Orths is with Energinet, Fredericia, 7000, Denmark.

Alison Silverstein is with Alison Silverstein Consulting LLC, Austin, Texas, 78660, USA.

John Simonelli is with Flashover LLC, New Hampshire, 06016, USA.

Robert Zavadil is with Enernex, Knoxville, Tennessee, 37932, USA.