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Commentary

What can we learn from US national transmission studies?

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Multiple US regions have announced new electricity transmission plans, are actively revisiting the future role of transmission, and could benefit from findings from recent national-scale transmission studies. A review of seven national studies shows that significant transmission expansion is cost-optimal for serving new demand, integrating additional resources, and supporting grid reliability. A majority of the reviewed scenarios, which span a range of policy and technology assumptions, include at least a doubling of the transmission system by 2050. The national studies find substantial net system cost savings from transmission expansion and high benefit-cost ratios for transmission investments. The results are derived through multi-value, nationally coordinated, co-optimized, multi-scenario modeling, which is an approach that could yield lower-cost pathways compared to current industry planning practices.

Expanding electric transmission infrastructure can unlock cost-effective ways to maintain grid reliability and access new resources to meet electricity needs of the future. Recognizing the growing importance of transmission, US states and grid operators have taken major steps to develop new transmission projects within their regions. Recent examples include California Independent System Operator's (CAISO's) first 20-year transmission outlook, Midcontinent Independent System Operator's (MISO's) Multi-Value Projects and Long-Range Transmission Planning efforts, Southwest Power Pool's (SPP's) Integrated Transmission Plans, the Joint Targeted Interconnection Queue interregional study from MISO and SPP, and others.[1] At the national level, the Federal Energy Regulatory Commission (FERC) issued Order 1920 to reform regional transmission planning, the US Department of Energy (DOE) announced an updated set of National Interest Electric Transmission Corridors, the North American Electric Reliability Corporation (NERC) completed the Interregional Transfer Capability Study,[2] and several bills supporting transmission development have recently been proposed in the US Congress.[1]

These efforts are occurring alongside a considerable slowdown in additions of high- and extra-high-voltage transmission, a growing backlog of generation and storage capacity waiting in interconnection queues,[3] and rising electricity demand; the near-term value of transmission expansion under these conditions is evidenced by substantial interregional congestion.[4] Relieving the interconnection bottleneck would enable the integration of new resources to replace old and retiring generation capacity and meet growing power demand from data centers and electrification. Equally important, though less often appreciated, is transmission's vital role in supporting system resource adequacy—the ability to meet demand even under the most stressful grid conditions—especially with increasing adoption of weather-dependent generation resources, which makes diversification over larger footprints increasingly valuable.[5]

Here, we discuss the significant expansion of transmission modeled by recent studies of the future US grid, describe why these studies include beneficial transmission expansion, and discuss learnings from the national studies that could be translated into industry practice.

Robust transmission expansion is found in many future scenarios

We examine seven recent national studies of power system transformation published by federal government agencies, national laboratories, academic institutions, and other research organizations[6–12] to assess the extent of transmission expansion under 23 optimized US power system scenarios. Recent studies (published between 2021 and 2024) that modeled the entire contiguous US considered scenarios with diverse policies and resource mixes and reported relevant data were chosen for this review; authors of this commentary are contributors for five of the seven studies. The scenarios show that substantial transmission expansion is used to meet high demand growth, demonstrated by the relationship between transmission growth and total generation (Figure 1A). They also show the connection between transmission and variable renewable energy (VRE)—wind and solar—resources (Figure 1B). These strong relationships exist across all studies reviewed despite differences in modeling methods and assumptions, transmission options modeled, and policies considered (see supplemental information for scenario details). The five

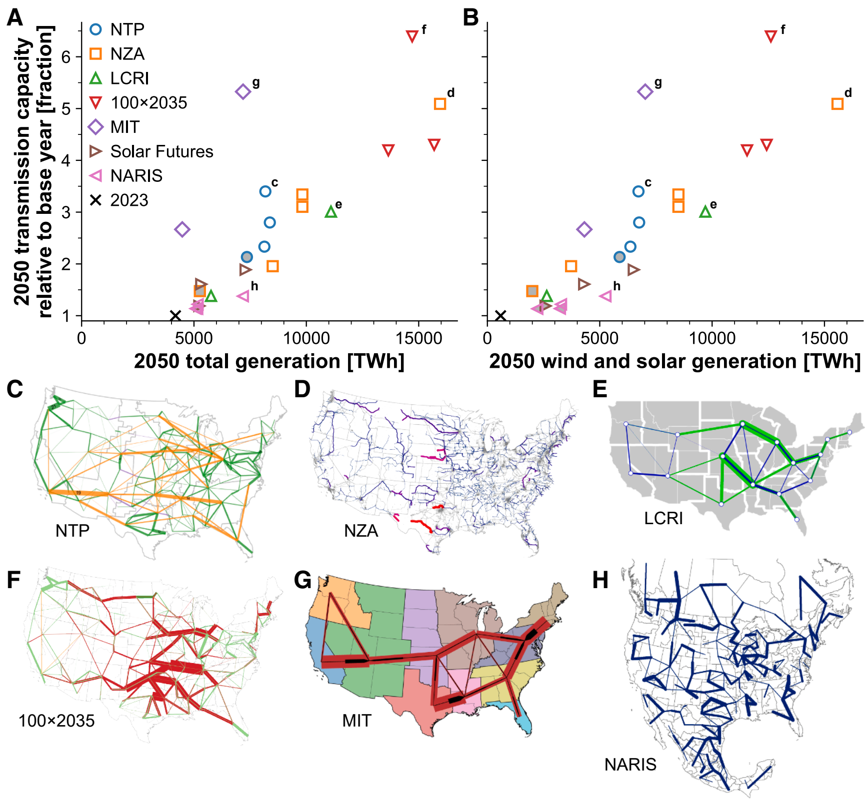

Figure 1. Relationships between transmission expansion with total generation and renewable energy
The figure shows results from the main scenarios (23 total) from seven studies: the National Transmission Planning (NTP) Study,[6] Net-Zero America (NZA),[8] Low-Carbon Resources Initiative (LCRI),[9] 100% clean by 2035 (100×2035),[10] Brown and Botterud from the Massachusetts Institute of Technology (MIT),[11] Solar Futures study,[12] and the North American Renewable Integration Study (NARIS).[7] Panels show 2050 transmission relative to a base year versus total generation (load) growth (A) and wind and solar generation (B). Transmission is measured as power times distance (GW-kilometers). Nonshaded markers show scenarios with a national emissions constraint; shaded gray markers show scenarios without. All studies except NARIS use 2020 as the base year for the transmission system; NARIS uses 2016 as the base year. (C–H) show modeled transmission maps from the six studies that include spatial transmission results, with data points labeled in (A) and (B). The relative thickness of the lines (within each panel) indicates transmission capacity, but the scales between maps are not harmonized. (C) is reprinted with permission,[6] copyright 2024, US Department of Energy. (D) is adapted from slide 133 of Larson et al. with permission,[8] copyright 2021, Princeton University. (E) is reprinted with permission,[9] copyright 2022, the Electric Power Research Institute. (F) and (H) are reprinted with permission,[7,10] copyright 2022 and 2021, the National Renewable Energy Laboratory. (G) is reprinted with permission from Brown and Botterud,[11] copyright 2021, Elsevier.

scenarios without an explicit constraint on national CO_2 emissions (gray shaded markers in the figure) result in less transmission, whereas optimal transmission expansion is greater in the 18 scenarios with 80%–100% power sector CO_2 emission reductions (nonshaded markers). In 13 of the 23 scenarios, the optimal amount of US transmission capacity at least doubles by 2050. Transmission capacity at least quadruples in five scenarios.

In many scenarios, transmission expansion is geographically widespread within and across regions (Figures 1C–1H), with some even including new high-voltage direct current (HVDC) connections across the seams between the three asynchronous grids in the contiguous US: the Western Interconnection, the Eastern Interconnection, and the Texas Interconnection. The National Transmission Planning (NTP) study[6] and the 100% by 2035 (100×2035) study[10] find that HVDC, which facilitates long-distance transmission, reduces cost and is widely deployed when available. HVDC deployment is growing globally, but US experience with HVDC is limited, with only a few operating HVDC lines and about 2 GW of connections across the three interconnection seams.

Transmission offers multiple benefits

The reviewed studies all use optimization-based planning models, which means projected transmission expansions are part of the lowest-cost—including capital, fuel, and operations and maintenance costs for generation, storage, and transmission—power system portfolios. This raises the following question: how does investing in transmission result in lower system costs?

One reason is that transmission unlocks low-cost generation by helping relieve bottlenecks and enabling access to resources in locations that lack existing transmission infrastructure. NTP[6] finds that transmission expansion and upgrades for supporting generation interconnection play a critical role; local interconnection capacity accounts for at least 30% of total transmission expansion in the main scenarios. Similarly, the substantial transmission expansion estimated from Net-Zero America (NZA)[8] is used to support transmission necessary to deliver electricity to major metropolitan areas.

Beyond local transmission for generator interconnection, the studies also deploy long-distance transmission to access low-cost generation in the central parts of the country and deliver it to distant load centers. Such need for transmission to reduce congestion is already evident through VRE curtailments, when power production must be reduced because of grid limitations. Wind curtailment in SPP and Electric Reliability Council of Texas (ERCOT), which respectively had 38% and 20% of their 2024 generation from wind energy, has been rising (reaching 8%–9% and 4%–5% in recent years). In the reviewed studies, about 40% to nearly 100% of total 2050 US generation is met by VRE (the US VRE generation share was about 17% in 2024). Absolute VRE generation grows even faster in high load growth scenarios (Figure 1).

Transmission also links geographically diverse regions to support resource adequacy—an important element of overall grid reliability. Although resource adequacy is a portfolio-wide characteristic, transmission offers unique reliability value for power systems with weather-dependent resources and loads by expanding the size of the portfolio. Isolated regions have greater risks from high-demand/low-supply periods, but greater network interconnectivity over large areas reduces these risks and enables a broader pool of resources to serve load. Transmission is used bidirectionally to enable such resource sharing, thus reducing the overall need for "peaking" generation within the connected regions.[6,7] Supply risks arise from both low VRE conditions (e.g., multiple cloudy days and/or low wind conditions) and thermal plant outages, which correlate with extreme temperature conditions. Interregional transmission is particularly valuable for reliability because it could support resource sharing across distances that are larger than weather systems. NTP finds that without resource adequacy coordination, the amount of transmission expansion found in the optimal portfolios decline by 40%–60% and overall system costs increase due to increased expenditures on local generation and storage capacity.[6] An empirical study[4] finds 50% of the total value of interregional transmission is captured during the top 5% of all hours, further indicating the high resource adequacy value of transmission. Another study[5] quantifies interregional transmission's capacity contributions during extreme events and discusses transmission's role for resource adequacy more broadly. This body of work suggests that excluding interregional transmission (and associated external resources) for resource adequacy planning in current practices is leaving a significant source of transmission value off the table.

Maintaining reliability and large-scale VRE integration are two common features in modeled scenarios, with transmission enabling cost-effective achievement of both. Building the new transmission identified in the studies would require substantial financial investments, but these investments in transmission are more than offset, in aggregate, by reduced costs from avoided fuel, operating, and capital expenditures on generation and storage. These net cost savings (relative to a case where transmission development is limited to historical levels) are estimated to range from \$270 to \$490 billion through 2050 (or, equivalently, 1.2–1.7 cents per kilowatt-hour in 2050) in the main scenarios from NTP.[6] NTP estimates that savings are greatest (up to about \$1 trillion) with higher demand growth and with widespread interregional and HVDC transmission development.[6] Similarly, the 100×2035 study's "Infrastructure Renaissance" scenario, which includes an HVDC macrogrid, has the lowest total cost among the four main scenarios modeled.[10] The Massachusetts Institute of Technology also finds scenarios with the greatest interregional transmission buildout to achieve the lowest total costs.[11]

Savings can be translated to benefit-cost ratios for the transmission portfolios studied (Figure 2). NTP estimates transmission benefit-cost ratios that range from 1.6 to 1.8 in the main scenarios and 1.5 to 2.3 across a range of sensitivities.[6] As with total cost savings, benefit-cost ratios are often greater when demand is higher. High benefit-cost ratios exist in scenarios where emerging technologies, such as hydrogen or carbon capture and storage, are not commercially viable, suggesting transmission offers a hedge against generation technology-related uncertainties. Even when transmission costs are higher, transmission benefit-cost ratios remain above 1.5, although less overall transmission expansion occurs with assumed higher costs. The other six national studies reviewed do not report transmission benefit-cost ratios, but recent subnational studies[13,14] find similar benefit-cost ratios for transmission. The Atlantic Study estimates benefit-cost ratios ranging from 2.3 to 2.9 for transmission off the US East Coast in the main scenarios and even higher benefits in some sensitivities.[13] The Seams Study finds benefit-cost ratios of 1.2–2.9 for transmission expansion between the Eastern and Western interconnections.[14]

Translating national-scale modeling into practice

The benefits of regional and interregional transmission expansion are clear from the national studies reviewed, but there is a large gap between the transmission expansion envisioned in these studies and current grid development. This gap exists partly because of the differences in perspectives between national models and the decision-making of electric industry planning organizations: national models use a centralized optimization framework whereas current grid planning is only regional in scope and is based on numerous (often uncoordinated) local and regional planners with diverse interests. Moreover, established planning paradigms in the US—focused largely on engineering studies to meet regional transmission reliability standards—are slow to add economic planning criteria and cost-benefit analyses. To date, the vast majority of US transmission investments, which total about \$30 billion annually, are used for meeting local and regional reliability criteria, not to minimize overall power system costs or other broader economic objectives. Furthermore, where economic multi-value analysis has already been used in transmission planning (e.g., MISO), its focus is limited to individual regions with significant gaps in and barriers to interregional planning. Broadening the use of multi-value analyses in regional transmission planning and expanding the scope of planning efforts to include interregional

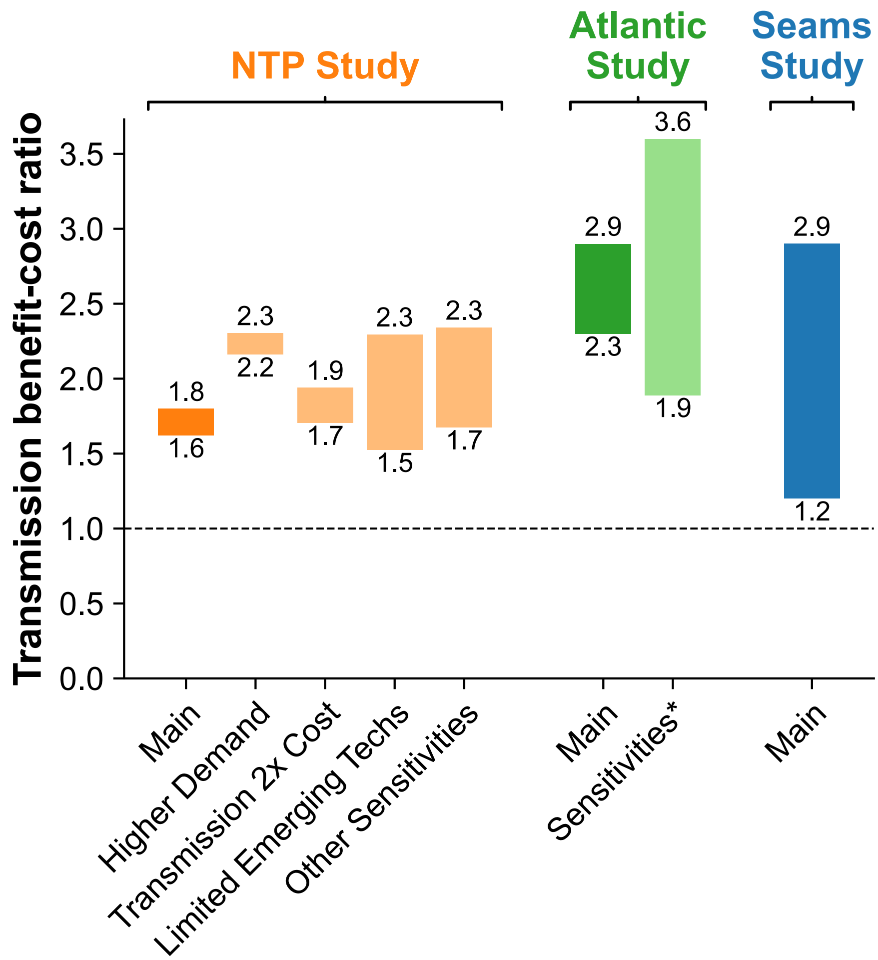

Figure 2. Transmission benefits outweigh costs across a range of scenarios, studies, and transmission types
The figure shows benefit-cost ratios for NTP,[6] the Atlantic Offshore Wind Transmission Study,[13] and Interconnection Seams Study.[14] Benefit-cost ratios estimated in NTP[6] and the Atlantic Study[13] are shown separately for each study's main scenarios as well as a selection of sensitivities. *Note: benefit-cost ratios for the Atlantic Study sensitivities exclude transmission's resource adequacy benefits.

transmission will require substantial adjustments to existing processes and addressing institutional barriers.

The national models and studies often assume the process and institutional barriers are overcome. Rather than dismissing the results of national models as unrealistic, we suggest learning from the holistic perspective of national planning models and adapting real-world practices accordingly. We identify four areas where the approaches from the national studies offer valuable lessons.

(1) Multi-value quantification. Long-term planning models apply a systemwide perspective in their decision making, thereby intrinsically using a "multi-value" approach. The net benefits of transmission estimated in the studies include operating and capital costs and consider both electricity cost and reliability benefits. Traditional evaluations of transmission have not always done so, and economic and resource adequacy benefits (and corresponding capital cost savings) are often omitted.[15] Similarly, wholesale power markets do not incentivize transmission development or attribute resource adequacy value to transmission—even though transmission smooths out variability in generation and demand, thereby lowering generation costs and reducing the need for peaking capacity. Some transmission planners have started to incorporate a wider range of benefits in their transmission valuation, and FERC Order 1920 calls for at least seven categories of project benefits to be evaluated in long-term planning processes.[1] These examples highlight the growing recognition of transmission's multiple sources of value. Increased adoption of multi-value planning would bring regional planning practices more in alignment with the total systemwide cost perspective used in national models.

(2) Multi-regional planning. National planning approaches differentiate regions by their resource options, demand profiles, and policies but find least-cost solutions for the larger multi-regional system. In contrast, with few exceptions,

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system planning in the US tends to be performed for regions in isolation, with limited interregional coordination. Even when interregional transmission options are explored, inconsistencies in value quantification approaches and differences in cost-allocation methods may prevent progress on potentially beneficial projects. To fully realize the value of transmission, interregional integration—through joint planning and operations between multiple regional transmission organizations (RTOs), expansion of RTO or system operator footprints, or a broader facilitated process—such as is conducted in the planning processes of the European Network of Transmission System Operators for Electricity (ENTSO-E)—would be needed.[1]

(3) Co-optimization. In the national studies reviewed, investment in all types of assets—generation, storage, and transmission—are co-optimized, whereas in practice, generation and transmission investments are often planned separately and sequentially. This approach can lead to suboptimal portfolios, undervaluation of transmission, and higher total costs. For example, when generation is planned first and resource adequacy targets are met through in-region generation-only solutions, the potential resource adequacy benefits of transmission are ignored, leading to less transmission and an overbuilt generation system. Although full co-optimization may be difficult to implement given separate transmission and generation planning processes, the development of renewable energy zones can provide a bridge by signaling strong co-development opportunities. The Texas Competitive Renewable Energy Zones (CREZ) is a successful example that led to the most significant US transmission development in recent decades.[1]

(4) Expanding options. The models and studies consider technologies and scenarios that break from current trends. For example, NTP shows the high upside benefits of widespread adoption of new multi-terminal HVDC infrastructure, which has yet to be deployed in the US.[6] The Atlantic Study offers transformative offshore interregional transmission systems.[13] Exploring a wider range of future scenarios and technologies could help planners address uncertainties and identify more-flexible transmission expansion options that are valuable under diverse conditions.

Of course, all planning models are imperfect representations of reality. Like most models used in industry planning today, the reviewed models and studies are limited or lacking in their representation of social acceptance, siting, and permitting considerations; cost-allocation challenges; supply chain and workforce factors; and regulatory or institutional barriers to coordinated planning and operations. The studies often also omit options that could increase transfer capacities with fewer obstacles and costs than greenfield transmission construction, such as grid enhancing technologies, reconductoring, and upsizing. National studies have also yet to fully recognize transmission's contribution to improving grid resilience, which could further bolster transmission development. For example, NERC identifies 35 GW of "prudent" interregional transmission additions by 2033 solely for addressing reliability and resiliency needs.[2] Adding resiliency value to the benefits examined in planning studies is expected to further strengthen the case for transmission. Finally, there are both institutional and technical challenges with translating national modeling for regional or local implementation that need to be overcome. Advancements in high-resolution models, data flows, and cost-allocation methods are needed for actionable planning to incorporate solutions from the national modeling efforts.

Nonetheless, the national studies and models reviewed here offer important lessons. They consistently find that transmission expansion is a cost-effective means to serve new demand, integrate new resources, and support grid reliability. The way these studies reach this conclusion is also instructive. The models' multi-value, nationally coordinated, co-optimized, multi-scenario approach identifies beneficial solutions that may be overlooked by the industry's current regionally and reliability-focused planning practices. Closer coordination—between multiple regions, developers and land users, and generation and transmission planning—could be a key step toward achieving transmission planning that facilitates implementing the lower-cost pathways consistently identified in these studies.

Data and materials availability

The data for Figures 1A, 1B, and 2 are available upon request. Figures 1C–1H are directly from the referenced studies.

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Conceptualization, T.M. and D.P.; visualization, P.B.; funding acquisition, D.P.; writing – original draft, T.M. and P.B.; writing – review & editing, D.P., G.B., A.B., P.D., R.G., J.H., D.L., J.K., J.O., J.P., A.R., C.S., and J.W.

DECLARATION OF INTERESTS

The authors declare no competing interests.

SUPPLEMENTAL INFORMATION

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