National Transmission Planning Study

Chapter 6:

Conclusions

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Suggested citation
U.S. Department of Energy, Grid Deployment Office. 2024. *The National Transmission Planning Study*. Washington, D.C.: U.S. Department of Energy. https://www.energy.gov/gdo/national-transmission-planning-study.

Context

The National Transmission Planning Study (NTP Study) is presented as a collection of six chapters and an executive summary, each of which is listed next. The NTP Study was led by the U.S. Department of Energy's Grid Deployment Office, in partnership with the National Renewable Energy Laboratory and Pacific Northwest National Laboratory.

- The **Executive Summary** describes the high-level findings from across all six chapters and next steps for how to build on the analysis.
- **Chapter 1: Introduction** provides background and context about the technical design of the study and modeling framework, introduces the scenario framework, and acknowledges those who contributed to the study.
- **Chapter 2: Long-Term U.S. Transmission Planning Scenarios** discusses the methods for capacity expansion and resource adequacy, key findings from the scenario analysis and economic analysis, and High Opportunity Transmission interface analysis.
- **Chapter 3: Transmission Portfolios and Operations for 2035 Scenarios** summarizes the methods for translating zonal scenarios to nodal-network-level models, network transmission plans for a subset of the scenarios, and key findings from transmission planning and production cost modeling for the contiguous United States.
- **Chapter 4: AC Power Flow Analysis for 2035 Scenarios** identifies the methods for translating from zonal and nodal production cost models to alternating current (AC) power flow models and describes contingency analysis for a subset of scenarios.
- **Chapter 5: Stress Analysis for 2035 Scenarios** outlines how the future transmission expansions perform under stress tests.
- **Chapter 6: Conclusions (this chapter)** describes the high-level findings and study limitations across the six chapters.

As of publication, there are three additional reports under the NTP Study umbrella that explore related topics, each of which is listed next.[1] For more information on the NTP Study, visit https://www.energy.gov/gdo/national-transmission-planning-study.

- **Interregional Renewable Energy Zones** connects the NTP Study scenarios to ground-level regulatory and financial decision making—specifically focusing on the potential of interregional renewable energy zones.

[1] In addition to these three reports, the DOE and laboratories are exploring future analyses of the challenges within the existing interregional planning landscape and potential regulatory and industry solutions.

- **Barriers and Opportunities To Realize the System Value of Interregional Transmission** examines issues that prevent existing transmission facilities from delivering maximum potential value and offers a suite of options that power system stakeholders can pursue to overcome those challenges between nonmarket or a mix of market and nonmarket areas and between market areas.
- **Western Interconnection Baseline Study** uses production cost modeling to compare a 2030 industry planning case of the Western Interconnection to a high renewables case with additional planned future transmission projects based on best available data.

List of Acronyms

AC	alternating current
CO_2	carbon dioxide
CONUS	contiguous United States
DOE	U.S. Department of Energy
HOT	High Opportunity Transmission
HVDC	high-voltage direct current
NREL	National Renewable Energy Laboratory
NTP Study	National Transmission Planning Study
PNNL	Pacific Northwest National Laboratory
TRC	technical review committee

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1 Background

Transmission is a critical part of the U.S. electricity system that has attracted increased attention recently because of several emerging trends. The generation resource mix is shifting to more geographically distributed and lower-emissions technologies, extreme weather events are becoming more frequent and have led to a reevaluation of resource sharing across regions, and electricity demand will likely increase—all of which create planning uncertainties in the coming decades.

The National Transmission Planning Study (NTP Study) was initiated to better understand the role, value, and opportunities for transmission across the bulk power system in the contiguous United States (CONUS). The NTP Study aims to inform regional and interregional transmission planning processes and identify transmission opportunities that will provide broad-scale benefits to electricity customers. To do this, the NTP Study applied a novel framework for considering the U.S. transmission system from a holistic perspective.

Several advances in the NTP Study make its technical approach unique to those of other studies. Notably, the study linked models often used in disparate transmission planning processes within industry through an ambitious multimodel analytic framework. The NTP Study is distinct from other studies and planning activities in three primary ways:

- The NTP Study inherently included interregional transmission because it used a national perspective. Interregional transmission solutions are not often included in bottom-up planning actions taken by existing transmission planning organizations. However, without a national or multiregional perspective, stakeholders may miss viable transmission expansion opportunities that can lead to significant potential systemwide savings.
- The NTP Study considered business-as-usual and ambitious scenarios that push decarbonization beyond the current emissions policies for many regions around the country. By taking this approach, the study team explored a broader set of technologies and captured a combination of factors and opportunities than is typically considered in industry planning.
- By integrating multiple models and planning aspects, the NTP Study provides a comprehensive view of transmission alongside generation and storage technologies. This approach enables the identification of more value streams and reliability benefits of transmission than are typically considered in transmission planning.

To validate the NTP Study approach, the team conducted extensive and varied stakeholder engagement with a wide variety of stakeholders. This included public meetings; a technical review committee (TRC) comprising a modeling subcommittee, a government subcommittee, and a land use and environmental exclusions subcommittee; coordination with existing convener groups; and Tribal outreach. The study team's core premise was that a broad set of stakeholders should be involved throughout the study to shape objectives, provide technical feedback and advice, and ensure study outcomes answer the industry's most pressing questions.

2 Key Findings

The NTP Study demonstrates different transmission expansion frameworks offer an array of reliability and cost benefits—both under a current policies framework and as systems reach higher levels of decarbonization. When interregional and regional transmission are evaluated simultaneously, additional opportunities emerge that further increase the benefits of transmission by enabling access to a diverse set of resources, including more geographically dispersed low-cost clean energy.

Following is a summary of the key findings across the four technical chapters of the NTP Study (Chapters 2–5).

Under current policies…

The lowest-cost U.S. electricity system portfolios that meet future demand growth and reliability requirements include substantial expansion in transmission.

- The total transmission system of the contiguous United States expands 2.1 to 2.6 times the size of the 2020 system by 2050 and interregional transmission grows 1.9 to 3.5 times.
- Interregional coordination to meet resource adequacy, using both existing and new transmission, can save the U.S. electricity system hundreds of billions of dollars.
- Accelerating transmission deployment beyond historical rates reduces power system CO_2 emissions by 10 to 11 billion metric tons (43% to 48%) through 2050.
- The amount of transmission expansion and the emissions savings from transmission scale with the level of electricity demand.

Under a U.S. electricity system carbon target that achieves a 90% greenhouse gas emissions reduction by 2035 and 100% by 2050…

The study finds hundreds of billions of dollars of net benefits from large-scale transmission expansion compared to historic rates of transmission deployment.

- Accelerated transmission expansion leads to national electric system cost savings of $270–490 billion through 2050.
- Incremental investments in transmission are more than compensated for by reduced electric system costs for fuel, generation and storage capacity, and other costs. Approximately $1.60 to $1.80 is saved for every dollar spent on transmission.

- The benefits of transmission expansion to system costs scale with the level of electricity demand and rate of decarbonization.

A substantial expansion of the transmission system throughout the entire contiguous United States delivers the largest benefits across a wide variety of scenarios.

- The United States transmission system expands 2.4 to 3.5 times the size of the 2020 system by 2050.
- Transmission expansion occurs at all scales—including local, regional, and interregional—and for all regions of the country. Expansion of new long-distance transmission is concentrated in the central part of the country.
- The use of high-voltage direct current (HVDC) transmission technologies, including advanced multiterminal converters, results in the greatest benefits to consumers across the transmission options studied.
- The largest benefits of transmission are realized when interregional transmission is most substantial, including building across the interconnection seams. When U.S. electricity emissions are limited, future transfer capacities for many regions exceed 30% of the region's peak demand and total aggregate U.S. interregional transfer capacity increases to 2.6 to 4.6 times the 2020 capacity by 2050.
- Constraining transmission growth results in higher cost portfolios with more nuclear generation, hydrogen, and carbon capture capacity required especially when carbon emissions are limited.

Grid reliability can be maintained in future low-carbon grid scenarios with the lowest-cost solutions relying on coordinated transmission utilization between regions during periods of greatest stress.

- All 96 modeled future grid scenarios in the study—including those with about 90% of annual generation from variable resources—meet or exceed resource adequacy standards.
- When transmission regions coordinate to achieve resource adequacy, system costs through 2050 are lowered by $170–380 billion. In scenarios that allow coordination, transmission is used bidirectionally across many regional interfaces to support resource adequacy.
- High-resolution grid simulations demonstrate hourly demand and supply can be balanced in power systems with very high shares of renewable energy. In scenarios with larger transmission expansion, imports and exports between regions play a substantial role in helping grid operators balance supply and demand in all hours.

- Power flow analyses specific to the Western Interconnection demonstrate highly decarbonized systems can withstand selected typical contingencies on new-build transmission lines even when lines are highly loaded. Energy storage provides a substantial portion of the primary frequency response for the modeled large power plant contingencies.

- An analysis of four extreme event stress cases in the Western Interconnection, showed that in some cases the buildout of additional interregional transmission can support the power system during extreme weather events, decreasing the potential for and amounts of power shortages.

The NTP Study identifies several examples of transmission investment that could be promising candidates for more in-depth consideration by planners and developers.

- High Opportunity Transmission (HOT) interfaces represent transmission capacity expansion results between regions across many scenarios. Transmission projects that align with these HOT interfaces could be strong candidates for further study and serve as a starting point for accelerated transmission expansion.

- Transmission portfolios that deliver broad-scale benefits to consumers were developed using laboratory and industry tools. These transmission portfolios demonstrate new interregional transmission combined with intraregional transmission upgrades can help meet the flexibility requirements of high renewable energy power systems.

<u>Regardless of future policy, market, and technology conditions…</u>

Grid planning at the national or multiregional scale requires enhanced institutional coordination, accessible data, and new grid modeling approaches, which have advanced under the NTP Study in partnership with technical and planning experts.

- Advancing grid models—merging siloed planning processes, facilitating translations between models, and overcoming computational barriers—is critical to analyzing transmission comprehensively and capturing transmission's multifaceted impacts.

- Additional data on potential extreme events, technology advancements, and demand uncertainty will support robust transmission and reliability planning to identify the best expansion opportunities for consumers under changing conditions. Data access enables broader participation and collaboration.

The identified benefits and expansion opportunities assume coordinated planning and use of transmission that goes beyond current practices. Developing guidelines for planners or a framework for coordination between numerous stakeholders can help realize these benefits.

The findings in this study highlight many advantages of a more coordinated approach to planning and deployment of transmission in the United States. These findings can be used by industry in transmission planning efforts, by regulators to better understand different utility investment options to achieve policy objectives, or by researchers and consultants as a starting point for further study.

3 Limitations and Caveats

The NTP Study made several advancements to be able to model the CONUS grid under nearly 100 potential future scenarios and produce transmission portfolios tested with highly detailed power system modeling. However, there are several limitations and important caveats to this approach:

- Within the time, computational, and resource limitations of the NTP Study, the study team did not analyze all future scenarios with a mix of demand, technologies, or policies used by the entire comprehensive multimodel suite for the study. Detailed power system modeling of a broader range of scenarios will increase confidence in the results.
- The diversity of regulations, standards, and market rules that may impact the operations of the grid are not fully represented in the models, which may limit the total number of benefits quantified in the study that are realized. In general, the NTP Study scenarios assume greater institutional and policy coordination than currently exists in U.S. power system operations.
- The detailed planning that happens in utilities and regional transmission planning processes is beyond the scope of this study. Therefore, any solutions identified in the NTP Study may not be directly applicable to an area or region given the many additional details, such as transmission line siting and local physical constraints, that comprise regional and utility planning.
- Certain technologies, such as carbon capture and storage and hydrogen-fueled generation, which are abundant in modeling in the later years in the decarbonization scenarios (2040–2050), are not commercially widespread today. Though progress is being made in developing these technologies, uncertainty remains as to when they will be commercially available and at what cost.
- Given time constraints, the extreme event analysis conducted for this study considers only two different heatwaves and a drought in the Western Interconnection. It does not evaluate the full range of extreme events that could occur throughout the country, such as cold snaps in Texas and severe storms along the East Coast of the United States. The results presented here demonstrate the types of benefits that transmission can provide in extreme events, but conclusions cannot be drawn for all extreme events throughout the country. More work is needed in this area.

The study team evaluated reliability in several ways within the modeling framework, but they did not undertake NERC-level reliability assessments (North American Reliability Corporation n.d.). For this and other reasons, the solutions presented in this study are not prescriptive but rather indicative of the opportunities for transmission expansion in the U.S. grid. Follow-on studies could address some of these limitations, as could industry and other researchers applying NTP Study findings and data within their own planning and study frameworks.

4 Future Work

The NTP Study addresses a wide range of questions about the role of transmission in the bulk power system in CONUS, along with the reliability and cost benefits that can be gained through accelerated transmission expansion. However, a national-scale, interregional transmission planning effort of this scope is a significant undertaking—and there are several questions that either lie outside the scope of this analysis or require further investigation. The Grid Deployment Office intends to continue to lead national-scale grid planning efforts by developing enhanced institutional coordination, accessible data, and new grid modeling approaches in partnership with technical and planning experts. The Grid Deployment Office also intends to work with industry to put the findings and tools developed in the NTP Study into action in ongoing planning processes at the state, regional, and interregional levels. Future work could include the following:

- **Transmission siting.** Transmission network data available for the NTP Study are limited in that detailed rights-of-way information and other transmission infrastructure details (age of conductors, tower type, and so on) that could lead to more refined solutions for transmission expansion are not readily available. Additional analysis on the location and routing of transmission—and integration back into planning models—will build confidence in potential transmission solutions. Though not a focus of this study, future in-depth consideration of promising transmission options should include careful consideration of environmental, health, and community impacts and options.
- **Reliability and resilience.** The NTP Study team analyzed several aspects of reliability and resilience, including resource adequacy, contingency analysis, stress analysis, and system flexibility required for reliable operations. These elements of reliability should be further studied—particularly analysis of reactive power coordination, dynamic simulations and frequency response, and voltage ride-through during grid disturbances. In addition, though the NTP Study was able to evaluate discrete extreme weather events for the Western Interconnection, additional events should be studied to understand the role of transmission in mitigating risks from extreme weather. Future analysis should consider different areas of the country, including across multiple interconnections and different types of singular and compounded extreme events.
- **Markets and operations.** The NTP Study nodal scenarios envisioned complete coordination between transmission regions in the system’s operations. As highlighted by a companion report for the NTP Study, *Barriers and Opportunities To Realize the System Value of Interregional Transmission* (Simeone and Rose 2024), complete coordination is optimistic given the challenges with coordinating the use of existing interregional transmission. These challenges will likely be magnified if the amount of interregional transmission is substantially greater than it is today. Further work should take a closer look at how different levels of market and nonmarket and operational coordination can impact transmission’s use and value.

- **Distribution of impacts.** The NTP Study included limited analysis of regional disaggregation of cost savings from accelerated transmission and relative impacts between producers and consumers. Rather, the analysis of costs and savings described in this report primarily applies to the contiguous U.S. electric system as a whole. Additional analysis is needed to assess who would gain the most benefits and who might incur greater costs. Expanding the distributional impacts assessment between the diverse producers and consumers, such as between different socio-economic classes and between generators and transmission, could better inform impacts of transmission expansion to individual households, equity and energy justice issues, and market design and cost recovery to incentive new infrastructure development. Furthermore, expanding the impacts beyond costs and greenhouse gas emissions would provide a more comprehensive evaluation of transmission expansion.
- **Enabling technologies.** The NTP Study considered several transmission technologies and used advanced methods to capture multiple value streams for transmission. However, additional considerations about the best technology to increase capacity between regions, such as reconductoring or the use of grid-enhancing technologies (e.g., dynamic line ratings and power flow control devices), were not studied in detail. Because many transmission additions in the coming decades are likely to include a combination of new transmission and grid-enhancing technologies, better capturing these trade-offs could be an important step in planning studies going forward. In addition, experience with HVDC technologies in the United States is limited, so opportunities exist to better integrate HVDC technology capabilities into system planning and operations.
- **Grid edge solutions.** The NTP Study did not explore all alternatives to transmission, including distributed resources and nonwires solutions. Energy efficiency, demand response, coordinated electric vehicle charging, virtual power plants, and other demand-side flexibility programs can play important roles in the energy transition. They can reduce the need for transmission and supply-side resources by reducing electricity demand, avoid the need for assets with low use, and help support resource adequacy and reliability. However, the scale of transformation in the NTP Study scenarios—especially the high-demand or decarbonization scenarios—will likely still require large-scale transmission expansion even with the implementation of these nonwires solutions. These solutions may have large impacts on certain regional needs, and further study can improve estimates of these needs.
- **Supply chains**. The NTP Study did not explore the availability of materials and infrastructure to meet the transmission and generation needs in the scenarios. Further study on the supply chains of critical infrastructure is important. HVDC technologies are of particular importance.
- **Policy options and coordination.** The NTP Study included binding state policies in the modeled scenarios and invited comments and vetting of the policy representations and assumptions to TRC Government Subcommittee members and other state policymakers and experts. Future modeling work should further

explore options to achieve emerging federal and state policy goals and targets. Future U.S. Department of Energy modeling and analysis activities should include convenings, modeling, and data to support regional and interregional coordination efforts.

In addition, there are operational and administrative lessons to be learned from a study of this scale:

- **External engagement.** Outside experts were crucial for providing input on the scope of the project and providing data and feedback. Deep engagement with state, regional, Tribal, and national entities is important for national-scale transmission studies going forward. A process for future national-scale studies that builds on the engagement process established in the NTP Study could help leverage lessons learned.
- **Data management.** Data management across many different models, inclusive of all three interconnections, was a huge challenge in the NTP Study. The study team developed new methods to manage and visualize the data with an emphasis on transmission networks, but more can be done to expedite study outcomes and increase accuracy. Specifically, ongoing dataset development outside of a study objective will enable studies on faster timelines and with more consistent inputs. Such dataset development could include model working groups that update data and models at regular intervals and in coordination with a broader stakeholder team and systematic processes so stakeholders understand expectations, outcomes, and timelines for updated datasets. Another important element of working with U.S. power system data is some aspects of it may have restricted access. Understanding these elements and coordinating stakeholders accordingly is an important and necessary step.

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DOE/GO-102024-6262 | October 2024