National Transmission Planning Study

Chapter 1:

Introduction

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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 (this chapter)** 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** 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.

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List of Acronyms

AC	alternating current
ATB	Annual Technology Baseline
B2B	back-to-back
BPS	bulk power system
CAISO	California Independent System Operator
CEM	capacity expansion model
CONUS	contiguous United States
C-PAGE	Chronological AC Power Flow Automated Generation
DC	direct current
DOE	U.S. Department of Energy
EIA	Energy Information Administration
EIPC	Eastern Interconnection Planning Collaborative
ENTSO-E	European Network of Transmission System Operators for Electricity
ERCOT	Electric Reliability Council of Texas
EUE	expected unserved energy
FERC	Federal Energy Regulatory Commission
FACTS	flexible alternating current system
FRCC	Florida Reliability Coordinating Council
GDO	Grid Deployment Office
GW	gigawatt
HVDC	high-voltage direct current
HOT	High Opportunity Transmission
IEA	International Energy Agency
IRA	Inflation Reduction Act

ISO	independent system operator
ISONE	Independent System Operator of New England
ITCS	Interregional Transfer Capability Study
km	kilometer
kV	kilovolt
LCC	line-commutated converter
LOLE	loss of load expectations
LOLP	loss of load probability
MISO	Midcontinent Independent System Operator
MT	multiterminal
NARUC	National Association of Regulatory Utility Commissioners
NASEO	National Association of State Energy Officials
NGA	National Governor's Association
NERC	North American Electric Reliability Council
NEUE	normalized expected unserved energy
NIETC	National Interest Electric Transmission Corridors
NOPR	notice of proposed rulemaking
NREL	National Renewable Energy Laboratory
NTP Study	National Transmission Planning Study
NYISO	New York Independent System Operator
P2P	point-to-point
PNNL	Pacific Northwest National Laboratory
PRAS	Probabilistic Resource Adequacy Suite
ReEDS	Regional Energy Deployment System (model)
reV	Renewable Energy Potential (model)

RTO	regional transmission operator
SCRTP	South Carolina Regional Transmission Planning
SERTP	Southeastern Regional Transmission Planning
SME	subject matter expert
SPP	Southwest Power Pool
TW	terawatt
TRC	technical review committee
VSC	voltage source converter
WECC	Western Electricity Coordinating Council

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1 Introduction

In recent years, the transmission component of the U.S. electricity system has garnered increased attention, driven by a convergence of factors shaping the energy landscape. These include notable shifts in the generation resource mix toward low-carbon technologies located remotely from urban centers, a stagnation in new transmission projects over the past decade, heightened occurrences of extreme weather events prompting reevaluations of regional resource sharing, and evolving electricity demand patterns introducing new planning uncertainties for the future. These developments have underscored deficiencies in the current approach to transmission planning and development across the nation. Consequently, there have been concerted efforts at various levels—both regional and federal—to catalyze a more comprehensive and expedited consideration of transmission infrastructure within the United States. For instance, the Federal Energy Regulatory Commission (FERC) has been taking steps to improve processing times in interconnection queues, bolster transmission planning requirements, and increase the level at which electricity is transferred across regions (Federal Energy Regulatory Commission 2024; 2023). These endeavors reflect a growing collective recognition of the imperative to modernize and fortify the nation's transmission network to meet the evolving demands of a dynamic energy landscape.

To understand the transformation needed for the U.S. grid and how that future buildout might serve the nation's electric customers, the U.S. Department of Energy (DOE) Grid Deployment Office (GDO) partnered with the National Renewable Energy Laboratory (NREL) and the Pacific Northwest National Laboratory (PNNL) on the multiyear National Transmission Planning Study (NTP Study). The study sought to:

- Develop new national-grid-scale planning tools and methods that can be used by industry, especially when planning for interregional transmission capacity needs
- Identify potential transmission solutions that will provide broad-scale benefits to electric customers under a wide range of potential futures
- Inform planning processes for regional and interregional transmission
- Identify interregional and national strategies to maintain grid reliability as the grid transitions, including to a reliance on low- and zero-carbon energy resources.

The NTP Study combines innovative methods with state-of-the-art industry practices demonstrating a forward-thinking approach to understanding the role and value of transmission in future power systems. The national perspective of the study, which incorporates system-wide optimization, enables a holistic examination of transmission, assuming regulatory and institutional barriers are overcome. The study used a combination of tools—all under the principles of least-cost planning and maintaining power system reliability—to analyze multiple facets of transformative transmission expansion for the power system in the contiguous United States.

In preparing this report, DOE and the laboratories sought input from a wide variety of public participants and governments, including Tribes, state and local government officials, and utilities. The study's engagement approach included public meetings, a laboratory-managed technical review committee, coordination with existing convener groups, and Tribal outreach.

How can this study be used?

The NTP Study results are not intended to replace regional or interregional planning processes or develop plans of service. DOE's intent is this study will provide insights for a broad set of parties about the role that transmission can play in regions across the country and tools and analysis that can be used in transmission planning processes, while in particular highlighting potential uses of interregional transmission. Table 1 outlines the boundaries of the study in relation to the many transmission planning activities around the country.

Table 1. Boundaries of NTP Study

What the Study Does	What the Study Does Not Do
Link several long-term and short-term power system models to test multiple transmission buildout scenarios	Replace existing regional and utility planning processes
Develop and use innovative analytical approaches to evaluate resource adequacy, reliability, economics, and resilience to extreme events	Recommend specific locations or approvals for individual transmission lines or address detailed environmental or other land use issues, or cost allocation questions, that may be associated with future transmission lines
Provide information that can be used in existing planning processes by evaluating the impact to transmission of various scenarios	Evaluate specific transmission policies or proposed legislation
Test transmission options that may not be considered in current planning processes within utilities or regional planning organizations	Develop detailed plans of service or provide results that are as granular as planning done by utilities
Assess a range of economic, reliability, and resilience indicators for each transmission scenario considered	Evaluate industry proposed transmission projects
Provide companion reports describing opportunities and challenges to realizing potential transmission benefits identified by the study	Provide a roadmap for developing specific projects

1.1 Background

Transmission planning is evolving in the United States and around the world as electric power systems integrate new technologies and respond to decarbonization demands and reliability needs, and as new loads are added, such as data centers or domestic manufacturing and electrified heating and transportation. Local and regional transmission planning processes play a crucial role in transmission deployment in the

United States and typically involve collaboration among utilities, grid operators, regulators, Tribal representatives, and stakeholders to assess future needs for transmission infrastructure. These processes vary greatly across the United States, driven by diverse regulatory and market structures, historical precedents, generation mix, and other geopolitical influences and technical approaches. These processes and the resulting regional transmission plans (see Appendix A for recent regional plans) provided a foundation for the NTP Study.

In addition to local and regional planning, recent national-scale studies have contributed to transmission planning in the United States by providing insights about broad geographic trends and the potential benefits of interconnecting regional power systems. The following section gives an overview of recently completed national-scale studies.

1.1.1 U.S. national-scale transmission studies and activities

Several recent national-scale power system studies have highlighted the relationship between a decarbonizing energy sector and the cost-effectiveness of transmission to deliver low-cost energy around the country. Given there is currently no formal central planning process for the U.S. grid, these studies have been conducted primarily by the national laboratories and by academic institutions. This section summarizes some of the essential findings and the relevant methods from those studies, starting with the DOE National Transmission Needs Study ("Needs Study" hereafter) (U.S. Department of Energy 2023), which itself summarizes many recent reports. In aggregate, these studies have helped motivate the discussion of the role and value of transmission within the power sector, which is undergoing significant changes. In addition, the national scope of these studies fills a gap in holistically analyzing the value of interregional transmission options.

DOE's Needs Study examines many public sources and studies that assess current and future needs for additional transmission infrastructure and evaluates several recent national-scale studies that considered the development of the transmission system.[2] These studies consistently indicate significant transmission growth is needed in many parts of the country, especially in scenarios with "high clean energy growth." The study notes high clean energy scenarios are most closely aligned with current state and federal laws including the Inflation Reduction Act (U.S. Congress 2022). Focusing on the "high clean energy growth" scenarios for 2035, regional needs ranged from a median of 64% (moderate demand) to 128% (high demand) increase in transmission capacity compared to 2020 transmission capacity. Interregional needs were even more significant than regional, relative to current capacity. Between the moderate-demand

[2] The studies referred to in this section are summarized in Table VI-1 of the DOE Needs Study (U.S. Department of Energy 2023): *The Value of Inter-Regional Coordination and Transmission in Decarbonizing the U.S. Electricity System* (Brown and Botterud 2021), *North American Renewable Integration Study* (Brinkman et al. 2021), *Standard Scenarios* (Cole et al. 2021), *Solar Futures Study* (DOE 2021), *Net Zero America* (Larson et al. 2021), and *Supply-Side Options To Achieve 100% Clean Electricity by 2035* (Denholm et al. 2022).

and high-demand scenarios, the median growth envisioned is an increase of 114%–412%.[3]

One of the central modeling tools used in the six studies outlined by the DOE Needs Study is a capacity expansion model, which finds the optimal mix of generation, storage, and transmission at least cost for the entire contiguous United States (CONUS) model (see Section 3.3.1 for further explanation of these models). One important advantage of these models is they can make trade-offs between building generation, storage, or transmission within a single optimization. A key disadvantage, from the perspective of evaluating transmission, is they are typically not able to consider the entire transmission network or the detailed physics that govern power flow, which limits their direct application to industry transmission planning—which relies heavily on power flow models that incorporate the detailed physics of the electric power system. Several national-scale studies seek to improve the representation of power flow and other temporal or spatial considerations by running a production cost model or a power flow model as a companion tool in the analysis of a future year or snapshot in time. For example, the North American Renewable Integration Study used a production cost model at 5-minute resolution with much of the network represented with direct current (DC) power flow.[4] But managing and running production cost and power flow models of CONUS with network details stretches computational abilities, easily reaching solver limits for memory and other parameters if all physical constraints were represented. Continuing to advance national-scale power system studies to be more applicable for industry is an active area of research, including in the contributions from the NTP Study and follow-on activities.

1.2 Objectives and Design of the Project

In addition to the primary objectives of the NTP Study stated previously, several related objectives were identified by stakeholders, Tribal representatives, and the study team[5] as important outcomes that will strengthen the impact of the study:

- Advancing the methodologies on multivalue transmission planning
- Integrating uncertainty on decarbonization efforts, electrical demand, and technology development
- Producing multimodel approaches that industry can use to improve its own planning processes

[3] A recent evaluation of industry load growth assumptions has seen large and rapid increases in future projections. Grid Strategies evaluated the load projections from recent FERC filings and found between 2022 and 2023, the summer peak demand growth forecast for the United States for the next 5 years grew from 2.6% to 4.7% (835 to 852 GW), driven largely by new industrial and data center loads not foreseen in many load forecasts prior to 2022 (Wilson and Zimmerman 2023).
[4] Other examples of nodal or approximately nodal representation of CONUS in transmission studies include (Bloom et al. 2020; Overbye et al. 2022).
[5] The “study team” refers to NREL, PNNL researchers, and GDO who contributed to the study. The “laboratory team” refers only to NREL and PNNL.

- Creation and expansion of datasets that support industry transmission planning.

The design of the study reflects a balance in advancing the methods of transmission planning while remaining grounded in the real-world challenges faced by industry today. The following sections describe how external engagement (Section 1.2.1) and the technical design of the study (Section 1.2.2) contributed to meeting those objectives.

1.2.1 External engagement

The NTP Study's external engagement efforts were designed to leverage the expertise of a broad set of entities and individuals around the country interested in the power system and to provide smaller venues where the study team could obtain feedback on study assumptions, methods, and objectives. External engagement included the following four aspects:

- **Public engagement** through public meetings and an online comment form
- Engagement with **existing convener groups**
- **Technical review committee (TRC)**, inclusive of three subcommittees
- **Outreach to Tribal Nations and Native Communities**

DOE hosted three virtual public webinars during the study to provide an overview of the study, provide updates, share results, highlight ongoing activities and developments of the analysis, and receive questions and feedback to improve the study design and communications. At the public meetings, the study team responded to questions and collected comments. Comments and questions were also collected via a public comment form on the NTP Study website and a project email address. The project team reviewed all questions and comments and considered them as the study progressed.

The NTP Study team also engaged with existing convener groups such as the Eastern Interconnection Planning Collaborative (EIPC), Western Electricity Coordinating Council (WECC), the National Association of Regulatory Utility Commissioners (NARUC), the National Association of State Energy Offices (NASEO), and the National Governor's Association (NGA). In the case of NARUC, NASEO, and NGA, the study team received suggestions for members to join the TRC. With EIPC and WECC, the study team shared technical approaches and received feedback. In addition, the study team worked with NARUC and NASEO to vet load forecast and policy assumptions with states.

Technical Review Committee

The laboratory team convened a TRC to receive input from individual participants with diverse viewpoints. This process was a key part of the public outreach for the project. Table 2 shows the makeup of the three subcommittees that compose the TRC.

The TRC for this project comprised a Modeling Subcommittee, a Government Subcommittee, and a Land Use and Environmental Exclusions Subcommittee. The Modeling Subcommittee brought together experts who could provide individual input on data, assumptions, and modeling frameworks and provide a reference for how industry is using power system modeling. The Government Subcommittee enabled DOE to collect input from individuals at state and federal agencies who could provide feedback on how they view federal and state policy and regulatory issues in the analysis and give input on scenarios and assumptions. The Land Use and Environmental Exclusions Subcommittee included federal, state, and local wildlife, transportation, environmental, and legal experts who understood the multiple dimensions of transmission, renewable energy, and energy infrastructure development. Members of this subcommittee provided their individual views on generalized issues related to constraints on locating new transmission and generation. Tribal representatives were invited to participate in both the TRC plenary meetings and relevant subcommittee meetings. Additional specific Tribal engagement occurred as described in greater detail in Section 1.2.1.2.

Table 2. Overview of NTP Study Technical Review Committee and Subcommittees

Modeling Subcommittee	Government Subcommittee	Land Use and Environmental Exclusions
• Clean energy professionals, including representatives of nongovernmental organizations (NGOs) • Transmission owners/operators/developers • Load-serving entities • Regional transmission operators/independent system operators (RTOs/ISOs) • Government and NGO clean energy organizations • Academic modeling experts	• State public utility commissions • State energy offices • State governors' offices • Regulatory experts • Federal agencies	• State wildlife offices • Federal land, water, and wildlife management agencies • Local planners and siting offices • Legal scholars

Table 3 lists meetings of the TRC and its subcommittees. The Plenary TRC meetings were open to the public, although active participation in the meeting was reserved for TRC members.

Table 3. Summary of NTP Study External Engagement Events

Meeting Date	Meeting Type
05/20/2022	Plenary TRC
06/07/2022	Modeling Subcommittee
06/10/2022	Government Subcommittee
06/24/2022	Land Use and Environmental Exclusions Subcommittee
07/29/2022	Modeling Subcommittee
09/13/2022–09/20/2022	Regional Meetings
10/14/2022	Plenary TRC
10/28/2022	Modeling Subcommittee
11/04/2022	Government Subcommittee
12/02/2022	Land Use and Environmental Exclusions Subcommittee
12/07/2022–12/13/2022	Regional Meetings
02/10/2023	Modeling Subcommittee
03/24/2023	Modeling Subcommittee
04/21/2023	Government Subcommittee
05/01/2023–05/12/2023	Regional Meetings
10/17/2023	Plenary TRC
11/17/2023	Government Subcommittee
12/15/2023	Modeling Subcommittee
08/08/2024–08/22/204	Regional Meetings

For a more comprehensive list including topics covered in each meeting, see Appendix B.

The TRC engagement was not intended to build consensus or obtain approval, but rather solicited the viewpoints of individual attendees. The meetings for the TRC allowed the laboratory team to give updates on the progress of the study—typically around methodology decisions and interim results—and receive feedback in real time through surveys and during follow-up discussions (e.g., office hours and/or regional meetings). Subcommittees acted as an extension of the TRC, in which meetings were typically smaller and oriented around detailed discussions of analysis.

Outreach to Tribal Nations and Native Communities

The NTP Study scenarios have potential implications for many Tribal Nations, Native Communities, and lands under Tribal governance. Though, as noted above, the study does not consider specific siting considerations, a Tribe might encourage clean energy development on its land, or it might prohibit development in culturally or environmentally sensitive areas.

The laboratory team conducted broad outreach to Tribes with the assistance of DOE's Office of Indian Energy Policy and Programs primarily through its Energy News Newsletter. The aim was to inform Tribes of the study objectives, ask about their interest in transmission issues, and invite feedback. A Tribe could do the following:

- Identify Tribal enterprises engaged in utility-scale energy development or regional transmission planning
- Describe any Tribal policies pertaining to utility-scale energy development
- Identify ways to enhance Tribal engagement in transmission planning
- Express other interests or concerns related to national or regional transmission planning.

The laboratory team engaged directly with Tribes that responded to the initial solicitation of interest and provided information about how the benefits of the NTP Study findings may inform a Tribe's energy policies.

The laboratory team did not incorporate assumptions about Tribal policy within the NTP Study scenarios and therefore did not exclude any area simply by virtue of it being Tribal land. Consequently, if a scenario indicated a need for additional wind or solar generation in a particular state or region, the new capacity presumably may be on Tribal or non-Tribal sites.

1.2.2 Technical design and study advancements

The NTP Study team built the modeling workflow with two key principles: least-cost planning and power system reliability. These two principles are intertwined throughout the study with a multimodel approach that enables an understanding of transmission from both a long-term planning perspective and a detailed engineering perspective.

Several advances in the NTP Study make its technical approach unique among other studies and typical regional planning. Notably, the study links 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, studies 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 and other resources. This approach enables the identification of more value streams and reliability benefits of transmission than are typically considered in transmission planning.

The technical chapters of this report provide details on the methods employed and datasets created—most of which will be available for industry as a product of this study.

1.2.3 Reliability, resilience, and resource adequacy in the NTP Study

Bulk power system (BPS) reliability consists of resource adequacy, operational reliability, and resilience. Figure 1 shows the elements of BPS reliability and the subcategories that fit into each, with yellow boxes around those that the NTP Study was able to consider (adapted from (NREL 2024a)). Within industry planning studies, these components can be stretched across many studies and are often siloed and narrow in scope, considering, for example, only resource adequacy from a comparison of supply and projected demand without detailed modeling of transmission flows. The technical design of the NTP Study is meant to provide a more holistic perspective on reliability than in many industry planning processes by ensuring transmission constraints are considered in all aspects of the study—from long-range planning through power flow—and models with differing spatial and temporal detail are closely coupled in data and constraints.

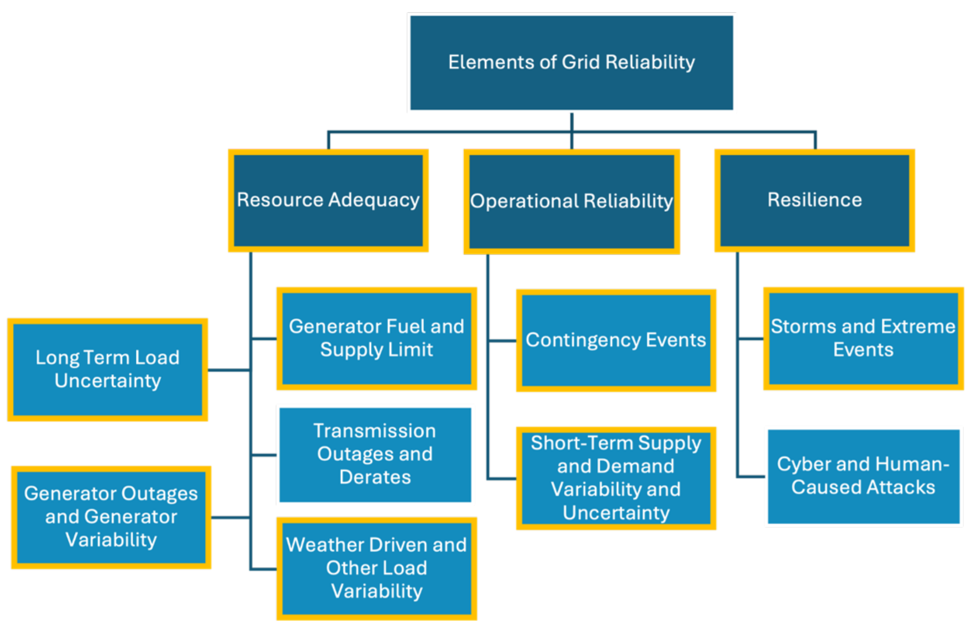

Figure 1. Elements of grid reliability

Yellow boxes indicate the NTP Study included an evaluation of these elements.

More detailed explanations of how the study team addressed reliability are provided in Chapters 2–5.

2 Study Approach

The NTP Study analysis used a combination of models and analytic tools (Figure 2) to meet the objectives outlined in the Introduction. The tools and methods are designed to reflect state-of-the-art industry practices and rigor in the level of detail and model formulations. However, the study team also made several advancements in this study to better capture and understand the role and value of transmission in future power systems. In addition, a fundamental challenge of a study that covers the entire CONUS is the scale of data that must be gathered and verified to provide meaningful results. To tackle this problem, the study team developed several techniques and datasets that will be made available to industry where possible at the conclusion of the study.

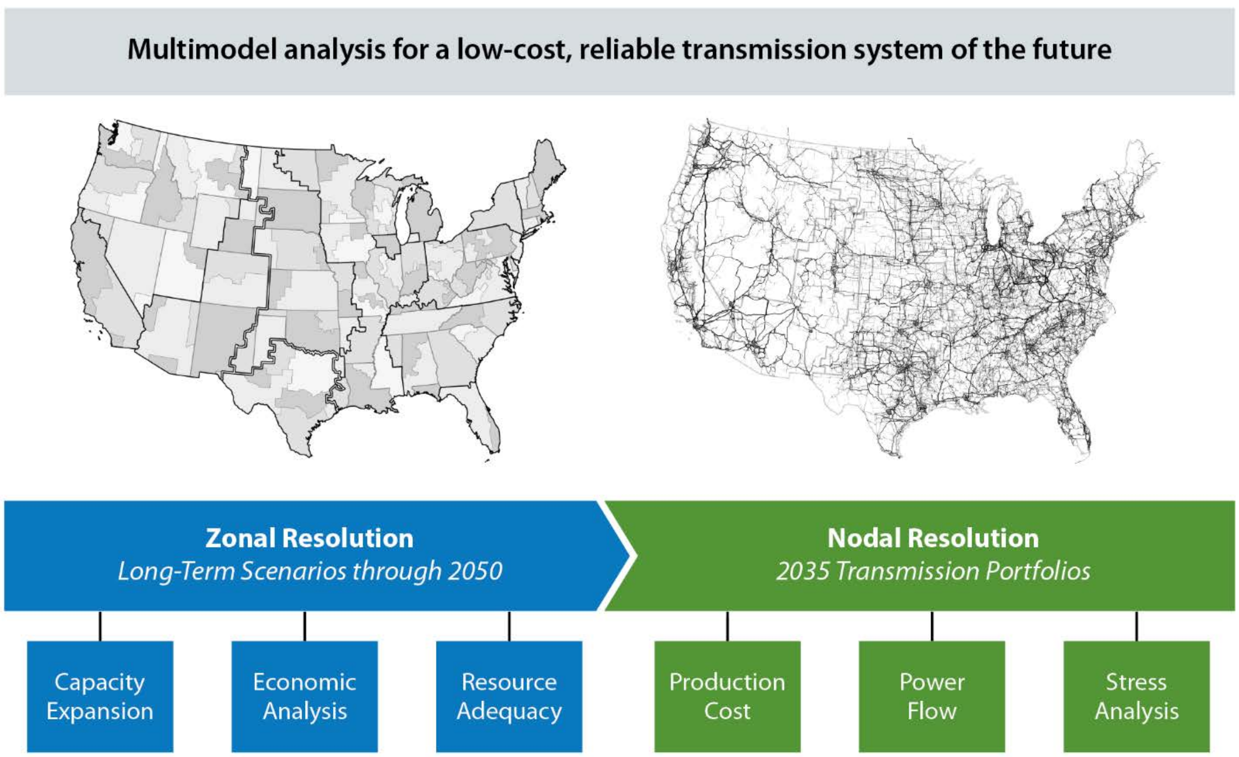

Figure 2. Modeling tools and workflow for the NTP Study

2.1 Capacity Expansion Model

The central tool in the NTP Study is the capacity expansion model, which the study team used to create future power system scenarios. The study team employed NREL's Regional Energy Deployment System (ReEDS) model, which chooses from a large set of new generation, storage, and transmission options to identify the systemwide least-cost portfolio that meets future demand, grid reliability, and policy requirements. For the study, the model finds the least-cost portfolio between 2020 and 2050. ReEDS applies a centralized planning approach but subdivides CONUS into 134 zones (Figure 3) to represent the grid network and reflect region-specific characteristics of generation, demand, and policies. For investment and dispatch modeling, each solve year is represented using 33 representative days with 4-hour resolution (Brown et al. 2023). Resource adequacy is enforced in the model by including up to 30 additional "stress periods" identified by the Probabilistic Resource Adequacy Suite (PRAS), as described in Section 2.2. The ReEDS documentation (Ho et al. 2021) and 2023 Standard Scenarios report (Gagnon et al. 2024) describe the model in greater detail. Chapter 2 provides details on how ReEDS was used for this study.

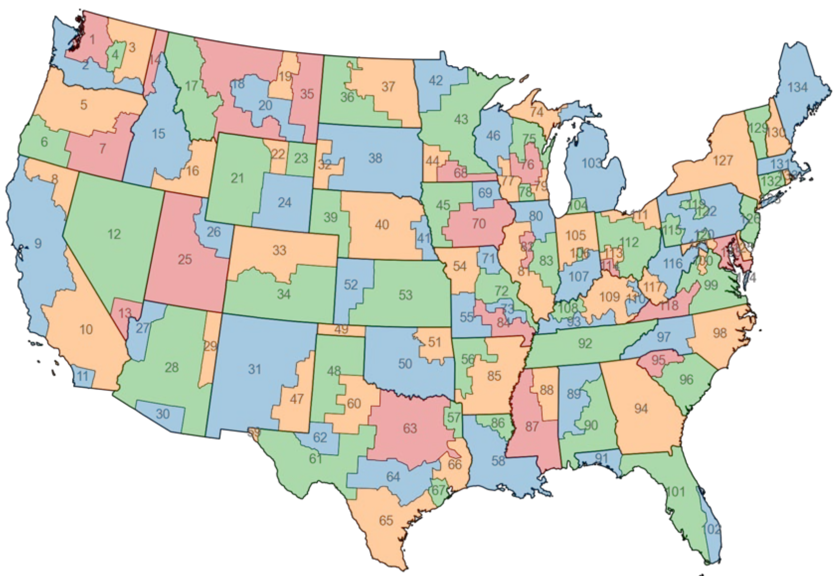

Figure 3. ReEDS 134-zone representation

2.1.1 Resource adequacy

The resource adequacy of the zonal scenarios (further described in Section 3) is evaluated using NREL's Probabilistic Resource Adequacy Suite (PRAS).[6] PRAS measures adequacy by performing Monte Carlo analysis of thermal generator outages[7,8] and simplified hourly dispatch over 7 weather years (2007–2013) of renewable energy availability. Reliability metrics estimated by PRAS include loss of load probability (LOLP), loss of load expectation (LOLE), and expected unserved energy. This study focuses on the normalized expected unserved energy—expected unserved

[6] North American Electric Reliability Council (NERC) defines resource adequacy as "[t]he ability of the electric system to supply the aggregate electrical demand and energy requirements of the end-use customers at all times, taking into account scheduled and reasonably expected unscheduled outages of system elements" (NERC 2020).

[7] Monte Carlo analysis refers to the repeated random sampling of generator outages to represent the probability of different outcomes.

[8] Transmission outages are not modeled; however, interregional transfer capacity assumed in PRAS and ReEDS partially accounts for transmission contingencies. See Chapter 2 for more details.

energy divided by total annual load—for each modeled year for CONUS.[9] PRAS has the same CONUS scope and 134-zone resolution as ReEDS; however, thermal generator capacity within each zone is further subdivided into individual units to appropriately simulate generator outages. Chapter 2 provides additional details about PRAS.

Several advancements were achieved in this study to integrate PRAS into ReEDS, which allows for a probabilistic approach to assessing resource adequacy within the planning model. This allows for an improved assessment of resource adequacy challenges in the future systems by exposing the planning model to "higher-stress" periods. More details of this approach are provided in Chapter 2.[10]

2.1.2 Economic analysis

The economic analysis, which is a complement to the detailed power systems modeling, intends to answer two key questions: What are the economic benefits of transmission and who are the beneficiaries?

To identify and quantify the economic benefits of transmission, the study team used outputs from ReEDS to evaluate changes in system investment and operating costs across transmission development frameworks. The results, presented in Chapter 2, provide insights on the total systemwide benefits of transmission, the types of benefits that provide the greatest value, and how the value of transmission changes over the planning horizon.

The beneficiary analysis provides details on the distribution of transmission benefits among planning regions and different types of network users. The national ReEDS modeling is used to disaggregate benefits among transmission planning regions to identify how each region benefits from transmission and how benefits change over time and across study sensitivities (Chapter 2).

2.2 Production Cost Models

The study team employed production cost models in this study to verify a select set of scenarios by representing the capabilities of all individual generators, storage units, and transmission lines in an operational model run for all hours of a year. Given the increased data and computational requirements of production cost models—especially those that represent the full nodal systems for the CONUS model—the study team selected a subset of scenarios from the capacity expansion model to convert to production cost

[9] Normalized expected unserved energy is used in this study because of its effectiveness for long-term planning because it measures the broader impact of an event by incorporating the total amount of unserved energy, as opposed to only the frequency of events.

[10] Another way in which PRAS is used is by assessing the resource adequacy of systems after the full system is planned using exogenous planning reserve margins. Earlier scenarios, which were completed as an interim step within the study, used only the post-examination step with PRAS. The internal ReEDS-PRAS linkage was developed as a task within the NTP Study and applied to the final scenarios. Earlier scenarios are used for certain analyses and are called out where appropriate. Mai et al. (Brown et al. 2023) compare the approaches.

modeling datasets. The process of conversion from zonal to nodal databases required extensive methods and data development and is detailed in Chapter 3.

The production cost model used for nodal analysis of the final set of scenarios for model year 2035 is NREL's Sienna model (NREL 2024b). Sienna is used to model unit commitment and dispatch using DC power flow for the full nodal network of CONUS, with a subset of transmission line flow limits enforced based on existing known flow gates, interfaces across regional seams, and transmission buildouts adapted from the capacity expansion model scenario. More details on the construct of the Sienna nodal model, the data inputs, and the nodal scenarios are provided in Chapter 3.

In addition to Sienna, the study team also uses a commercial production cost model, Hitachi GridView, to model the Western and Eastern Interconnections for a subset of scenarios. GridView is a chronological unit commitment and economic dispatch model designed to minimize power systems' operating costs by meeting electricity demand and reserve requirements while satisfying a range of operational constraints. Scenarios modeled with GridView are presented in Chapters 3 (Section 4 only), 4, and 5.

2.2.1 Economic analysis using nodal transmission topologies

Within the set of scenarios selected for production cost modeling, Chapter 3 presents an analysis to evaluate economic benefits associated with system operations using GridView simulations. The analysis estimates the systemwide benefits in WECC and disaggregates them according to different network users such as generators, transmission owners, and power purchasers.

2.3 Power Flow

The power flow analysis explored different future network topologies for the power system by modeling alternative generation and transmission expansion options and running contingency analyses to evaluate system reliability. The study team generated the Western Interconnection power flow cases using the PNNL Chronological Alternating Current (AC) Power Flow Automated Generation (C-PAGE) tool (Vyakaranam et al. 2021).The study team identified different grid conditions using results of the production cost modeling for each scenario to test reliable operations under different loading, wind, and solar conditions that the grid will undergo throughout the year using steady-state AC power flow techniques. The study team ran tests of credible contingencies on a select set of scenarios for model year 2035.

The study team used either simple queries, such as the hour with highest flow in one of the new lines, or intelligent sampling methods to select representative hours from the production cost model for the power flow analysis. The intelligent sampling method identifies a small percentage of hourly cases that are statistically representative of the whole year and appropriate for power flow analysis. Sampling a representative number of hours allowed the study team to examine how the same contingency may have a different reliability impact on the grid based on different grid conditions while reducing the computational burden required to perform this analysis. Chapter 4 provides more details on the power flow methods.

2.4 Stress Analysis

To understand the impacts of grid stress conditions, the study team used the GridView production cost model to apply extreme events to the Western Interconnection. This analysis evaluates how extreme events impact the grid by simultaneously increasing demand while diminishing supply. The study team adapted several modeling tools to simulate hourly load, wind, and solar time series under varying weather conditions as well as hydropower availability during droughts for two grid stress conditions: 1) heat waves and 2) combined heat waves and drought conditions. The study team conducted economic analysis of the stress events by using value of lost load estimates to determine the cost of unserved load to end customers of the power.

2.5 Multimodel Datasets

Many datasets are created and used as inputs to the power system models for the NTP Study. These datasets—including electricity demand, renewable resource data, and technology and cost assumptions—are documented in greater detail in Chapters 2—5, but the following paragraph describes the core power system datasets that feed through to all the models.

The power system networks are sourced from industry power flow planning cases for the Eastern Interconnection and Western Interconnection. For the Electric Reliability Council of Texas (ERCOT), the study team compiled the data from several sources because they could not obtain a recent power flow case (see Chapter 3 for more details of the ERCOT dataset). Power flow cases are created for reliability planning and coordination within the interconnections and form the starting point for the networks developed in the production cost and power flow models developed for this study. Chapters 3 and 4 of this report provide further detail about how these datasets are used for this study. Typically, the datasets require substantial additional data about generation operations to be usable in a production cost model, which is also detailed in the technical chapters. In addition, the ReEDS model uses these data to build the zonal-level transmission network, which is presented in (Brown et al. 2023). The study team also heavily rely on data from the U.S. Energy Information Administration (EIA) (see Chapter 2 for details).

3 Scenarios

The power system models described previously are used to generate and assess different scenarios of the U.S. electricity system. Specifically, the ReEDS capacity expansion model is used to analyze how the system might evolve from today through 2050, based on a certain set of assumptions, whereas most of the other models are used to analyze future portfolios identified by ReEDS. The production cost modeling, power flow, and stress case analyses focus on particular 2035 portfolios.

3.1 Transmission Frameworks

The scenarios are designed to assess the impacts of greater transmission expansion on the future resource mix, cost and economic metrics, and reliability. These impacts are measured against a reference scenario with more limited transmission expansion that approximately reflects a continuation of the current pace of transmission development over the next several decades. The counterfactual is referred to as the Limited (Lim) transmission framework, which includes two constraints on future transmission expansion: 1) no new interregional transmission and 2) an annual limit on total transmission builds.

Interregional transmission refers to transmission between the 11 planning regions, which are based approximately on the FERC Order No. 1000 regions[11] and ERCOT, as shown by Figure 4. In the Limited framework, transmission expansion is allowed *within* each planning region, including between different zones in a planning region or for spur lines or other network upgrades for new generation interconnections. However, the annual limit constrains total transmission—of all types—based on the maximum annual builds over the past decade, estimated to be 1.83 terawatt (TW)-mile/year.

[11] The South Carolina Regional Transmission Planning (SCRTP) region from FERC Order No. 1000 is included in the Southeastern Regional Transmission Planning (SERTP) in the analysis. Nonenrolled members of FERC planning regions and regions that are not part of FERC Order No. 1000 are included within the geographic boundaries shown in the figure. The models in this study reflected the Florida panhandle as part of SERTP, though it is now part of Florida Reliability Coordinating Council.

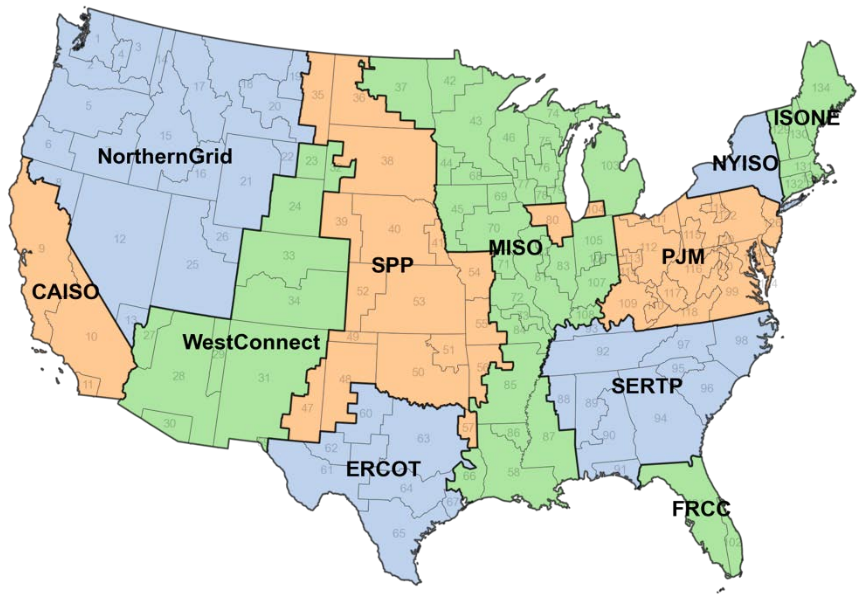

Figure 4. Planning regions

Regional acronyms: California Independent System Operator (CAISO), Southwest Power Pool (SPP), Midcontinent Independent System Operator (MISO), New York Independent System Operator (NYISO), Independent System Operator of New England (ISONE), Southeastern Regional Transmission Planning (SERTP), Florida Reliability Coordinating Council (FRCC).

Additional scenarios are created with alternative transmission frameworks that relax the constraints to transmission development applied in the Limited framework. In these transmission frameworks, interregional transmission expansion is allowed and no annual limit on transmission builds is applied. However, given uncertainties about future transmission technologies, transmission cost, and degree of coordination, three distinct frameworks (AC, Point-to-Point, and Multiterminal) are used in addition to the Limited framework.

The AC framework allows transmission expansion between all adjacent zones that are within the same interconnection. Transmission costs and losses are based on AC technologies. The Point-to-Point (P2P) and Multiterminal (MT) frameworks allow the same transmission expansion options as in the AC framework but include additional HVDC options and allow interconnection seam-crossing transmission. The P2P framework includes 195 candidate connections between nonadjacent zones that are within 1,000 miles. The MT framework does not include such long-distance high-voltage direct current (HVDC) options but enables more flexibly sized multiterminal converters. Figure 5 illustrates how the four transmission frameworks are represented in ReEDS; Chapter 2 (Section 2) discusses additional assumptions and other implementation details. How these various transmission frameworks and scenarios are represented in other models differs—including choice of transmission technology (AC vs. DC) options—from what is reflected in ReEDS. This includes using a detailed transmission planning method to translate the zonal ReEDS results into individual transmission elements as described in Chapter 3 of this report.

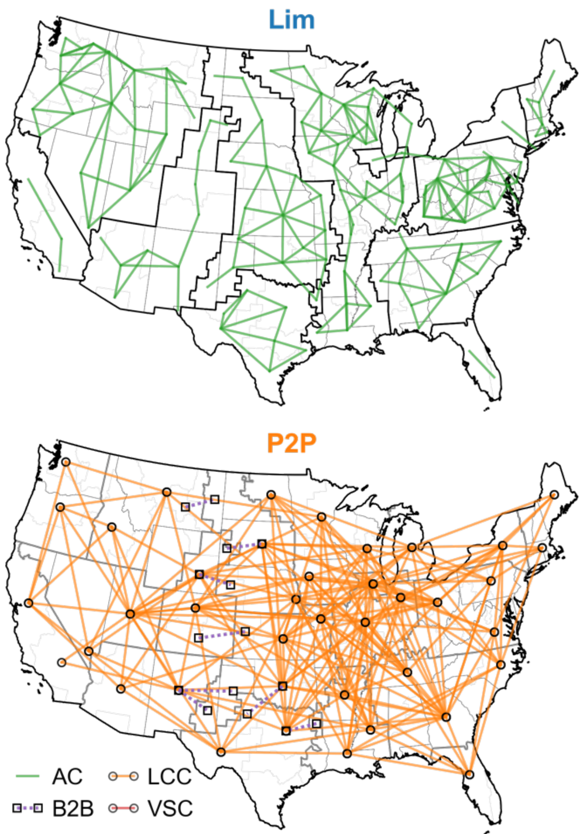

Figure 5. Transmission frameworks

Maps show interfaces where transmission capacity can be expanded under the corresponding transmission framework. AC interfaces in the AC framework are also allowed to be expanded in the P2P and MT frameworks but are not shown for clarity. Existing transmission interfaces are not shown. Allowable transmission types are AC (green), HVDC with line-commutated converters (LCC, orange), HVDC with voltage source converter (VSC, red), and back-to-back interties (B2B, purple dashed).

3.2 Scenario Design

Comparing results from scenarios under the accelerated transmission frameworks (AC, P2P, MT) with the Limited framework reveals the impact of greater transmission expansion. However, these impacts can depend on other factors, such as level of decarbonization, demand growth, and other technology and market conditions. The scenario design includes 36 “core” scenarios, which include all combinations of four transmission frameworks (Figure 5), three demand growth projections, and three levels of power sector emissions (Figure 6).

Demand growth →

Emissions constraint ↓	Low demand	Mid demand	High demand
	Low demand Current policies	Mid demand Current policies	High demand Current policies
	Low demand 90 by 2035, 100 by 2045	Mid demand 90 by 2035, 100 by 2045	High demand 90 by 2035, 100 by 2045
	Low demand 100 by 2035	Mid demand 100 by 2035	High demand 100 by 2035

Figure 6. Core demand and emissions scenarios

The central demand and emissions scenario is highlighted in yellow. "Current policies," "90 by 2035, 100 by 2045," and "100 by 2035" refer to emission constraints.

Demand growth assumptions include the Low-Demand case where U.S. load grows by 0.9% per year on a compound annual basis from 2021 to 2050. The Mid- and High-Demand cases have much greater load growth (2.0% per year and 2.7% per year, respectively) because of more significant electrification projections. This electrification—driven largely by electric vehicle adoption and electrified heating in buildings—also yields changes to demand profiles with more pronounced increases in winter peaks in many regions. The three demand cases span a wide range to capture the significant uncertainties with future load growth and diversity of expectations from regional planners.

All scenarios model enacted policies as of June 2023. These policies include state clean and renewable energy standards and federal clean energy tax incentives from the Inflation Reduction Act (IRA). Under the Current Policies scenarios, no other constraints on power sector emissions or incentives for clean electricity are assumed. In contrast, the study team included decarbonization scenarios that apply a national emissions constraint. In the central decarbonization scenarios, national power sector CO_2 emissions are required to reduce by 90% (from 2005 levels) by 2035 and fully (100%) by 2045 and assumes Mid-Demand growth. In the most ambitious decarbonization scenarios (100% by 2035), it is assumed grid emissions are fully eliminated by 2035.

In addition to the core scenarios, there are 15 sensitivities included, each modeled for all four transmission frameworks. All the sensitivities assume central decarbonization conditions (90% by 2035 power sector emissions trajectory and Mid-Demand growth). The dimensions considered by the sensitivities include technology costs, availability of nascent technologies, renewable energy siting, costs and challenges with (transmission and pipeline) infrastructure development, and climate change impacts. Chapter 2 (Section 2) describes these sensitivities in greater detail along with a description of the other assumptions used by default. The capacity expansion analysis models a total of 96 scenarios.

3.3 Scenario Design Process for Multifidelity Modeling

The above-described scenario framework was developed through an iterative process with feedback from the NTP Study TRC and other stakeholders throughout the multiyear study (Section 1.3.1). This feedback included current system plans and the associated assumptions used by regional electric system planners, interpretations of enacted state policies, and expectations of key drivers and uncertainties with future system evolution. Data availability along with computational and analytic tractability constrained the incorporation of all feedback; however, the scenario design is intended to address many of the topics of interest to NTP Study stakeholders. Although none of the scenarios represents a prediction of the future state of the U.S. electric system nor aligns perfectly with any individual stakeholder's expectations, the full suite of scenarios encompasses a broad range of possibilities. The ultimate scenario framework, described previously, is designed to inform key drivers related to transmission expansion and how robust they may be to future conditions.

The study team analyzed the entire set of 96 scenarios with the capacity expansion and resource adequacy models used in the NTP Study; however, only a limited number of scenarios were evaluated with the full suite of tools described in Section 2 because of their large number, complexities with model translations, and difficulties in setting up higher-fidelity models. For the most resource-intensive modeling components of the study, such as the AC power flow modeling (Chapter 4) and the stress analysis (Chapter 5), the scenarios analyzed relied on earlier rounds of the iterative scenario design process to enable sufficient time to build those models. The following clarifies the scenarios evaluated for each class of analyses conducted within the NTP Study.

3.3.1 Zonal capacity expansion and resource adequacy

The capacity expansion modeling analysis and results using the ReEDS model provides the starting point for the NTP Study analysis. ReEDS is a zonal model, representing CONUS using 134 zones, that finds the optimal resource mix over time through 2050. ReEDS and PRAS—the resource adequacy model—are integrated and share the same zonal structure (Chapter 2, Section 2.2). These two models are used to examine all the scenarios and their associated assumptions presented previously. The key findings from this analysis are presented in Chapter 2. Chapter 2 also presents an analysis of subregional High Opportunity Transmission (HOT) interfaces, which is based on the same zonal analysis from ReEDS. Specifically, this analysis relies on the full suite of sensitivities.

3.3.2 Nodal production cost modeling

A subset of the future scenarios developed by the zonal ReEDS model is further evaluated at nodal resolution with higher-fidelity modeling of system operations. This translation to nodal resolution relies on the disaggregation of generators and storage to individual units as well as the completion of a complex transmission planning analysis (Chapter 3). The study team completed the translation for three of the core scenarios, all using the central 90% by 2035 and Mid-Demand assumptions (Figure 6). The three scenarios include the Limited, AC, and MT transmission frameworks; only the projected

2035 portfolios from those are translated. The translations enabled CONUS-wide production cost modeling using the Sienna model. Key findings from this analysis are presented in Chapter 3.

Chapter 3 also includes additional production cost modeling, using the GridView model, that supplements the CONUS-wide modeling. This modeling includes an earlier version of the scenarios similar to those described in Section 3.2.

3.3.3 Nodal system security and resiliency analysis

The study team conducted additional modeling at nodal resolution to examine issues regarding system security and resiliency. This analysis required the completion of a similar zonal-to-nodal translation process—as for the production cost modeling—but also required computationally intensive processing to set up the analyses. Chapters 4 and 5 describe these processes for the power flow and stress tests, respectively. As a result of these additional processing requirements, these analyses started before the completion of the final capacity expansion scenarios described previously. Instead, they relied on earlier versions of the scenarios. The main differences between these earlier scenarios and the ones presented previously (and used in Chapter 2) are summarized in Appendix C.

Overall, the final scenarios use more up-to-date assumptions and improved model advancements; however, the same broad trends observed —including renewable and carbon-free electricity share—are similar between the scenario versions. Chapters 3–5 present results from the earlier scenarios, including their resulting portfolios, used for the analyses in these chapters.

4 Report Structure

The NTP Study modeling and analysis report contains six chapters. These chapters together represent the entirety of the multimodel framework discussed in Section 3 and should be considered as a single NTP Study. Though the chapters are distinct, the teams and individuals contributing to the report had consistent touchpoints and shared resources, data inputs, and feedback across multiple levels of modeling.

The chapters are arranged in succession similar to how the models are linked and data flow through the project—from Chapter 2, Long-Term U.S. Transmission Planning Scenarios, to Chapter 3, Transmission Portfolios and Operations for 2035 Scenarios, to Chapter 4, AC Power Flow Analysis for 2035 Scenarios, and finally to Chapter 5, Stress Analysis for 2035 Scenarios. Each chapter has a substantial amount of technical detail and findings specific to the modeling and analysis done within that chapter. Table 4 summarizes the contents of the chapters.

Table 4. Chapter Contents

Chapter	Summary of Contents
1: Introduction	• Background and context • Technical design of study and modeling framework • Introduction to scenario framework
2: Long-Term U.S. Transmission Planning Scenarios	• Methods for capacity expansion and resource adequacy • Key findings from scenario analysis, including findings on resource adequacy • Key findings from long-term regional economic analysis • Subregional High Opportunity Transmission interface analysis
3: Transmission Portfolios and Operations for 2035 Scenarios	• Methods for translation from zonal scenarios to nodal network-level transmission portfolios • Network transmission portfolios for a subset of scenarios • Key findings from transmission portfolio design and production cost modeling for CONUS • Western Interconnection deep dive analysis of earlier scenarios
4: AC Power Flow Analysis for 2035 Scenarios	• Methods for translating from zonal and nodal production cost models to AC power flow models • Contingency analysis for a subset of scenarios
5: Stress Analysis for 2035 Scenarios	• Methodology for developing stress scenario using the nodal transmission portfolios • Key findings from stress test production cost analysis • Economic analysis to compare between different stress cases
6: Conclusions	• Discussion of findings and lessons learned

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Appendix A. Regional Transmission Planning in the United States

There are several planning exercises within regions that may contribute to the overall transmission plan of a region. Utilities carry out planning for their local areas based primarily on reliability needs. Local transmission plans are then incorporated into the regional plans. Regional planners use the local plans as a starting point to evaluate the needs for the region. Typically, regional planning is carried out on a 1- to 3-year cycle that assesses near- to mid-term needs (ACEG 2023; Eto 2017).[12] Reliability is the foremost priority in local and regional planning, although varying degrees of consideration are also given to economic and policy-related benefits across different regions. In addition, several regional planners also perform longer-term planning studies that evaluate different scenarios of load and resource mix, although these are less common among the regional planners (ACEG 2023).

In a review of recent regional plans, the study team found that every region uses power flow (or load flow) tools for planning. Most also use some form of production cost or market modeling software. Almost all regions use at least a 10-year planning horizon, with a few looking out further to 15 or 20 years; with Independent System Operator New England (ISO-NE) also recently publishing a 2050 study (ISO-NE 2024). Table A-1 provides a list of recent regional transmission plans.

[12] Typical regional planning follows principles from Order Nos 890 and 1000 (Eto and Gallo 2017).

Table A-1. Recent Regional Transmission Planning Documents

Federal Energy Regulatory Commission (FERC) 1000 and Electric Reliability Council of Texas (ERCOT)	**Latest Regional Plan Accessed**	**URLs to Regional Plans (accessed May 2024)**
California ISO (CAISO)	2023	https://www.caiso.com/Documents/ISO-Board-Approved-2022-2023-Transmission-Plan.pdf
ERCOT	2023	https://www.ercot.com/gridinfo/planning
Florida Reliability Coordinating Council (FRCC)	2022	FRCC-MS-PL-018_FRCC_Regional_Transmission_Planning_Process.pdf
ISONE	2023	https://www.iso-ne.com/system-planning/system-plans-studies/rsp
Midcontinent ISO (MISO)	2024	https://www.misoenergy.org/planning/long-range-transmission-planning/
NorthernGrid	2023	https://www.northerngrid.net/private-media/documents/2022-23_Regional_Transmission_Plan.pdf
New York ISO (NYISO)	2023	https://www.nyiso.com/cspp
PJM	2022	https://www.pjm.com/-/media/library/reports-notices/2022-rtep/2022-rtep-report.ashx
Southeastern Regional Transmission Planning (SERTP)	2023	http://www.southeasternrtp.com/docs/general/2022/2022_Regional_Transmission_Plan_and_Input_Assumptions_Final_Non-CEII.pdf
South Carolina Regional Transmission Planning (SCRTP)	N/A	https://www.scrtp.com/assets/pdfs/document-library/attachment-k-to-stakeholders.pdf
Southwest Power Pool (SPP)	2023	https://www.spp.org/documents/70584/2023%20itp%20assessment%20report%20v1.0.pdf
WestConnect	2023	https://doc.westconnect.com/Documents.aspx?NID=20635&dl=1

Appendix B. Stakeholder Meetings

Table B-1. Stakeholder Engagement Meetings During the NTP Study

Date	Meeting Type	Meeting Purpose
3/15/2022	Public Meeting	Officially kick off the National Transmission Planning Study
05/20/2022	Plenary Technical Review Committee (TRC)	Provide project overview and details on modeling activities.
06/07/2022	Modeling Subcommittee	Discuss methodology in developing baseline cases.
06/10/2022	Government Subcommittee	Discuss methodology in developing baseline cases and request feedback on state policy assumptions for the study.
06/24/2022	Land Use and Environmental Exclusions Subcommittee	Discuss baseline assessment and scenario tasks as well as an introduction to the Interregional Regional Energy Zones (IREZ) methodology. Subcommittee requested to provide preferences through an online survey.
07/29/2022	Modeling Subcommittee	Provide updates on baseline analysis, overview of scenario task and content, presentation of capacity expansion model draft candidate scenarios, and zonal analysis of test scenarios.
08/26/2022	Office Hours	Open to all TRC members and subject matter experts (SMEs) for the project team to answer any clarifying questions.
09/13/2022	West Regional Meeting	Regional meetings were open to TRC members and SMEs within the specific region or to multiple regions if overlap occurred. These meetings included regionally focused project updates and results.
09/16/2022	Central Regional Meeting	
09/19/2022	Southeast Regional Meeting	
09/20/2022	Northeast Regional Meeting	
10/14/2022	Plenary TRC	Provide updates on modeling framework overview and upcoming plans for federal and state policies; key findings and supporting evidence of initial candidate scenarios; Western Interconnect baseline results and power flow analysis introduction; brief updates on zonal-to-nodal analysis, IREZ, and the economic analysis tasks.

Date	Meeting Type	Meeting Purpose
10/21/2022	Public Update Meeting	Provide updates on the scenario analysis, receive questions, and point the public to the comment form on the project website. Questions asked during the webinar were used to inform the Frequently Asked Questions section of the project website.
10/28/2022	Modeling Subcommittee	Provide overview of the Renewable Energy Potential (reV) model and the IREZ task; update on zonal-to-nodal analysis.
11/04/2022	Government Subcommittee	Provide overall project updates; capacity expansion scenarios down-selection for nodal modeling; deeper dive into IREZ analysis; introduction to cost-benefit approach.
12/02/2022	Land Use and Environmental Exclusions Subcommittee	Provide overall project updates; capacity expansion scenarios down-selection for nodal modeling; zonal-to-nodal deep dive; introduction to resource adequacy task.
12/07/2022	Northeast Regional Meeting	Regional meetings were open to TRC members and SMEs within the specific region or to multiple regions if overlap occurred. Provide regionally focused project updates and results.
12/08/2022	West Regional Meeting	
12/09/2022	Central Regional Meeting	
12/13/2022	Southeast Regional Meeting	
02/10/2023	Modeling Subcommittee Meeting	Share project status updates (e.g., round 2 of capacity expansion model [CEM] analysis); overview of the zonal-to-nodal workflow and methodology; review of selected zonal-to-nodal results.
03/03/2023	Office Hours	Open to all TRC members and SMEs for the project team to answer any clarifying questions.
03/24/2023	Modeling Subcommittee	Provide overview of the zonal-to-nodal results broken down by region (i.e., East and West presentations); review of stress cases.
04/21/2023	Government Subcommittee	Provide modeling and process updates; overview of *Regulatory Pathways Paper* concept; overview of economic analysis.

Date	Meeting Type	Meeting Purpose
05/01/2023	Southeast Regional Meeting	Regional meetings were open to TRC members and SMEs within the specific region or to multiple regions if overlap occurred. Provide regionally focused project updates and results.
05/03/2023	Central Regional Meeting	
05/11/2023	Northeast Regional Meeting	
05/12/2023	West Regional Meeting	
8/1/2023	Public Meeting	Provide a progress update on the study, solicit and answer questions from participants, and direct participants to the comment form in the project website.
10/17/2023	Plenary TRC	Provide general project updates; modeling framework review; capacity expansion modeling updates; stress cases and economic analysis.
11/17/2023	Government Subcommittee	Provide modeling and project timeline updates; review of *Regulatory Pathways Paper* concept and task updates; updates on the following analyses tasks: resource adequacy, extreme events, and economics.
12/15/2023	Modeling Subcommittee	Review *High Opportunity Transmission Analysis*; provide updates on zonal-to-nodal production cost modeling; provide updates on power flow analysis.
08/08/2024	Central Regional Meeting	Regional meetings were open to TRC members and SMEs within the specific region or to multiple regions if overlap occurred. Provide a preview of final results.
08/13/2024	Northeast Regional Meeting	
08/15/2024	West Regional Meeting	
08/22/2024	Southeast Regional Meeting	

Appendix C. Scenario Versions

Table C-1 summarizes the major differences between the final scenarios (described in Sections 2.1–2.2, used in the scenario analysis from Chapter 2, and used for the contiguous United Stated (CONUS)-wide production cost modeling in Chapter 3) and earlier scenarios (used in the GridView modeling from Chapter 3, Section 4, and the analyses in Chapters 4–5).

Other differences not listed here are summarized in the National Renewable Energy Laboratory (NREL) 2023 Standard Scenarios (Gagnon et al. 2024), where the final scenarios are largely based on the Regional Energy Deployment System (ReEDS) model version and assumptions used in the 2023 Standard Scenarios Mid-Demand case; earlier scenarios are largely based on the 2022 version (Gagnon et al. 2022).

Table C-1. Differences Between Scenario Versions

Topic	**Earlier (round 1) Scenarios** Used in Chapters 4 and 5; Chapter 3 (Section 4 only)	**Final (round 2) Scenarios** Used in Chapters 2 and 3	**Notes**
Time resolution	17 seasonal-diurnal time slices	33 representative days at 4-hour resolution	(Brown, Cole, and Mai forthcoming)
Resource adequacy	Seasonal planning reserves and capacity credit	Combined ReEDS-Probabilistic Resource Adequacy Suite (ReEDS-PRAS) modeling with up to 30 stress periods	(Brown, Cole, and Mai forthcoming)
Hydrogen modeling	Exogenous fuel costs ($20/MMBtu) for zero-carbon renewable energy combustion turbines	Endogenous modeling of electrolytic hydrogen production, storage, and use in combustion turbines	
Policies	State and federal policies as of May 2022, which did not include the IRA tax incentives	State and federal policies as of June 2023, including the tax credits from the Inflation Reduction Act (IRA)	
Demand growth	Two demand scenarios with load growth of 0.9%/year and 2.4%/year	Three demand scenarios (Section 3.3) with load growth of 0.9%/year, 2.0%/year, and 2.7%/year	Additional state-level calibration was applied to the final demand scenarios using 2021 Energy Information Administration (EIA) data; the Mid-Demand assumptions from the final scenarios included the impacts of the IRA (see Chapter 2 for details)
Technology projections	ATB 2022 Moderate case	Annual Technology Baseline (ATB) 2023 Moderate case, with sensitivities using the Advanced case	(National Renewable Energy Laboratory 2022; 2023)
Limited transmission framework	No interregional transmission expansion and no annual cap on new transmission expansion	No interregional transmission expansion and an annual cap on total new transmission expansion	The final scenarios result in greater differences between the Limited and other transmission frameworks

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