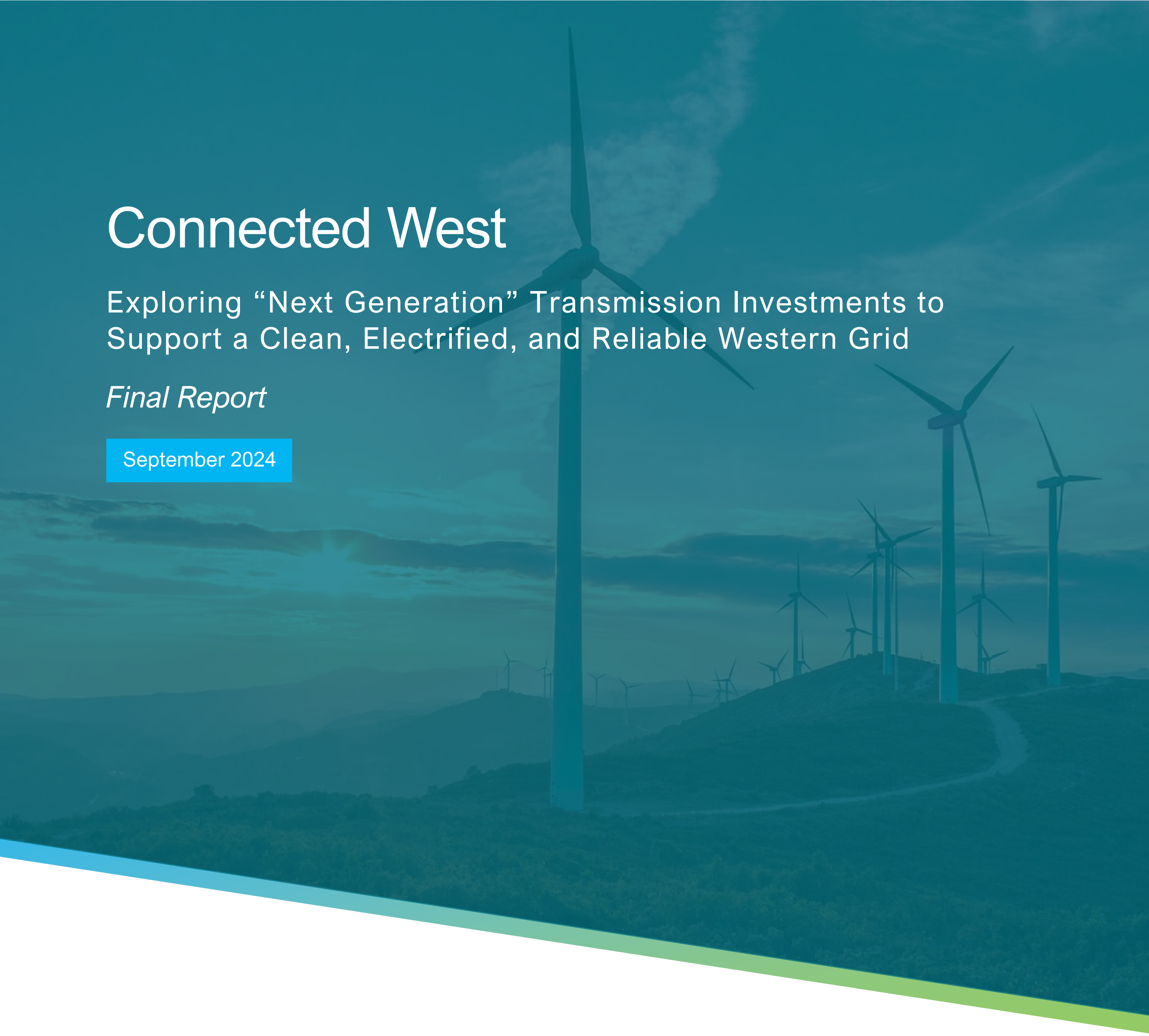
Connected West

Exploring "Next Generation" Transmission Investments to Support a Clean, Electrified, and Reliable Western Grid

Final Report

September 2024



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About the Connected West Study

Connected West is a 20-year transmission planning study aimed at forecasting long-range transmission infrastructure needs of the Western grid required to support a highly decarbonized and electrified economy. The study focuses on identifying “next generation” transmission investments, targeting the identification of portfolios of new transmission expansion projects that represent investment above and beyond upgrades that have been previously proposed by Western utilities and developers. With insights and recommendations based on these new transmission portfolios and their performance, the Connected West study serves as a new data point on scenario-driven long-term transmission deployment in the West.

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The findings and observations contained in this report are based on Energy Strategies’ independent analysis and do not represent the views of any of the Technical Review Committee organizations and cannot be attributed to any individual Technical Review Committee member.

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Executive Summary

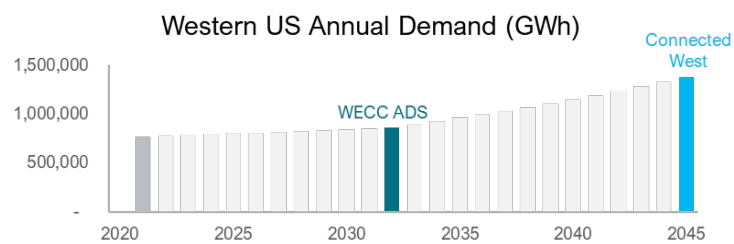
The Connected West study ("Connected West") is a 20-year transmission planning analysis that explores transmission portfolios that meet the evolving needs of the Western grid under an economy-wide decarbonization and high electrification future. The scenario-based study evaluates a range of transmission solutions and configurations, focusing on their benefits, costs, land usage, and development feasibility. By providing insights and recommendations based on these new transmission portfolios and their performance, Connected West serves as a new and innovative datapoint for Western planners and stakeholders. In addition to laying out conceptual transmission roadmaps for transmission infrastructure to support the decarbonization and electrification of the Western economy, it also introduces new and innovative study techniques that can be leveraged in future Western planning endeavors.

The *Power of Place: West* report, released in August 2022 by The Nature Conservancy, provides critical inputs on which Connected West relies. That study explores the land use requirements and conservation impacts of achieving net-zero greenhouse gas emissions across eleven Western states by 2050. It analyzes two scenarios using economy-wide models: a high electrification scenario employing various clean energy technologies and a renewables-only scenario. Connected West leverages the "High Electrification" scenario results from *Power of Place: West*, adopting load forecasts and resource buildouts as modeling inputs. Additionally, Connected West utilizes extensive databases on land use and development sensitivities to inform transmission routing and costing analyses. While *Power of Place: West* focused on the land use implications of economy-wide decarbonization pathways, it did not include detailed transmission analysis. Connected West fills this void by providing a more precise view of the transmission needs for the High Electrification scenario, leveraging optimal generation resource expansion plans, load forecasts, and environmental databases, while focusing on transmission, grid reliability, and transmission business case analysis.

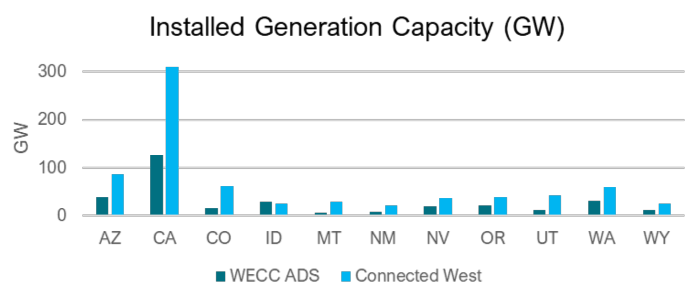
As a result, Connected West explores transmission portfolios that help the Western grid:

- **Accommodate load growth** consistent with a highly-electrified Western economy, with peak demand increasing

Figure 1: Key Forecasts for Connected West



Peak demand increases by approximately 100 GW by 2045, consistent with an electrified Western economy.



Generation fleet more than doubles to nearly 750 GW primarily through the addition of clean resources and storage.

by approximately 100 GW by 2045; and

- **Integrate a 2045 generation fleet** that is two times the size of the forecasted fleet in 2032, with the majority of the incremental capacity coming in the form of new wind, solar, geothermal and storage resources.

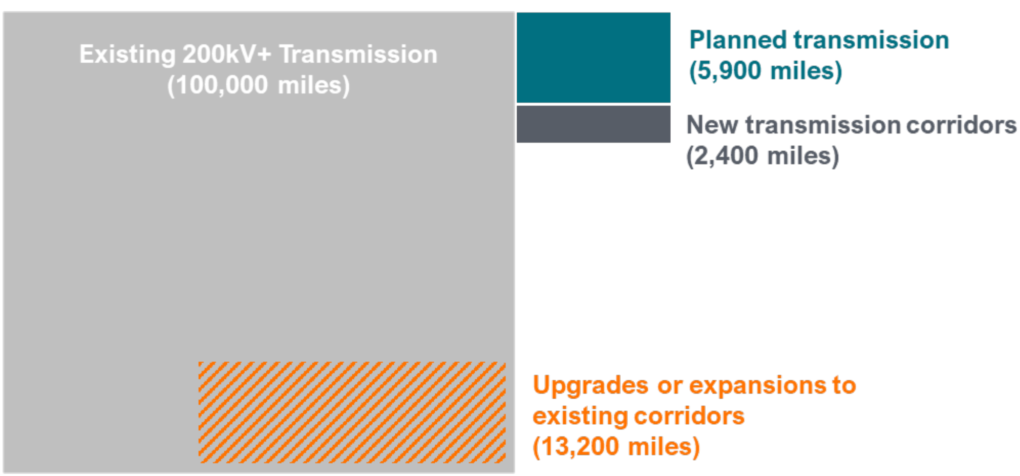
The nodal economic and reliability modeling performed in Connected West assumed that nearly all known planned and proposed transmission upgrades are constructed, representing over 5,900 line miles and nearly $30 billion of assumed grid investment. Therefore, the study's findings, below, stem from this exploration into the nature and scope of the "next generation" of transmission investments that could be needed by the West for this future scenario.

Figure 2: Planned Transmission Assumed in Study Insufficient

Transmission Expansion Needed Despite Assumed Upgrades

To support an electrified and deeply decarbonized Western grid in 2045, significant transmission expansion is required. The study identifies that gross new transmission needed by 2045 exceeds 20,000 line miles, with only about 25% of that total available from planned upgrades assumed in the study. For context, there is roughly 100,000 miles of existing transmission greater than 200-kV in-service in the West today.

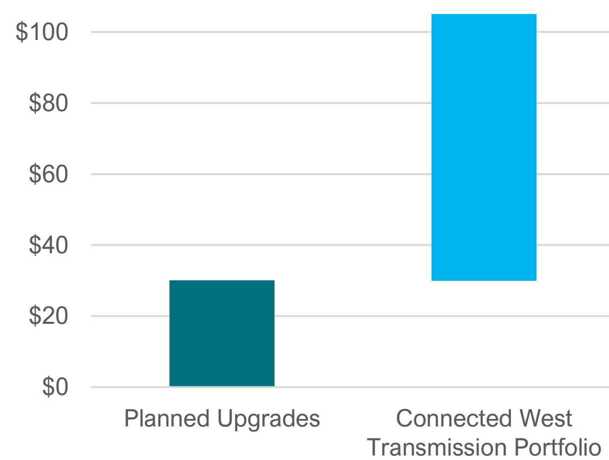
Figure 3: Connected West Transmission Gap Context (Transmission Line Miles >200kV only)



Note: Transmission solutions identified in Connected West portfolios focus on high-voltage and inter-regional transmission needs. Line-mile estimates do not capture all transmission necessary to facilitate the future envisioned in this study.

The high-voltage investment gap to support reliability and efficiency of the grid, representing the next tranche of regional-scale transmission investments *not currently planned for*, is on the order of at least $75 billion. This investment, at a minimum, is necessary to address the transmission constraints identified in the Connected West scenario. This transmission investment gap should be considered a "floor" not a "ceiling" of future transmission need, given the neccsary limitations in technical approach and scope.

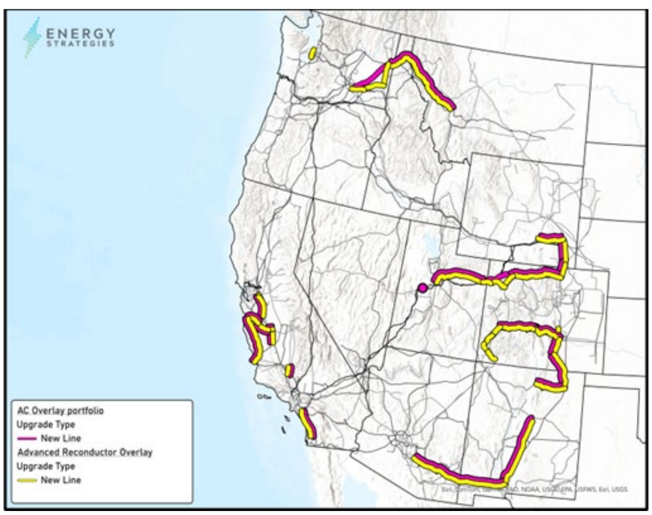
Figure 4: Transmission Investment Gap ($B)



Significant Portion of New Transmission Capacity Achievable with Enhancements to Existing Infrastructure

Results indicate that a significant portion of new transmission capacity across the West can be met with reconductoring upgrades, co-locating new lines, and advanced grid technologies such as high-capacity conductors. In some portfolios, reconductoring projects and co-locating new lines accounted for approximately 85% of the required line miles, minimizing the need for new greenfield transmission corridors.

Figure 5: Commonality in Corridors for Two of the Transmission Portfolios



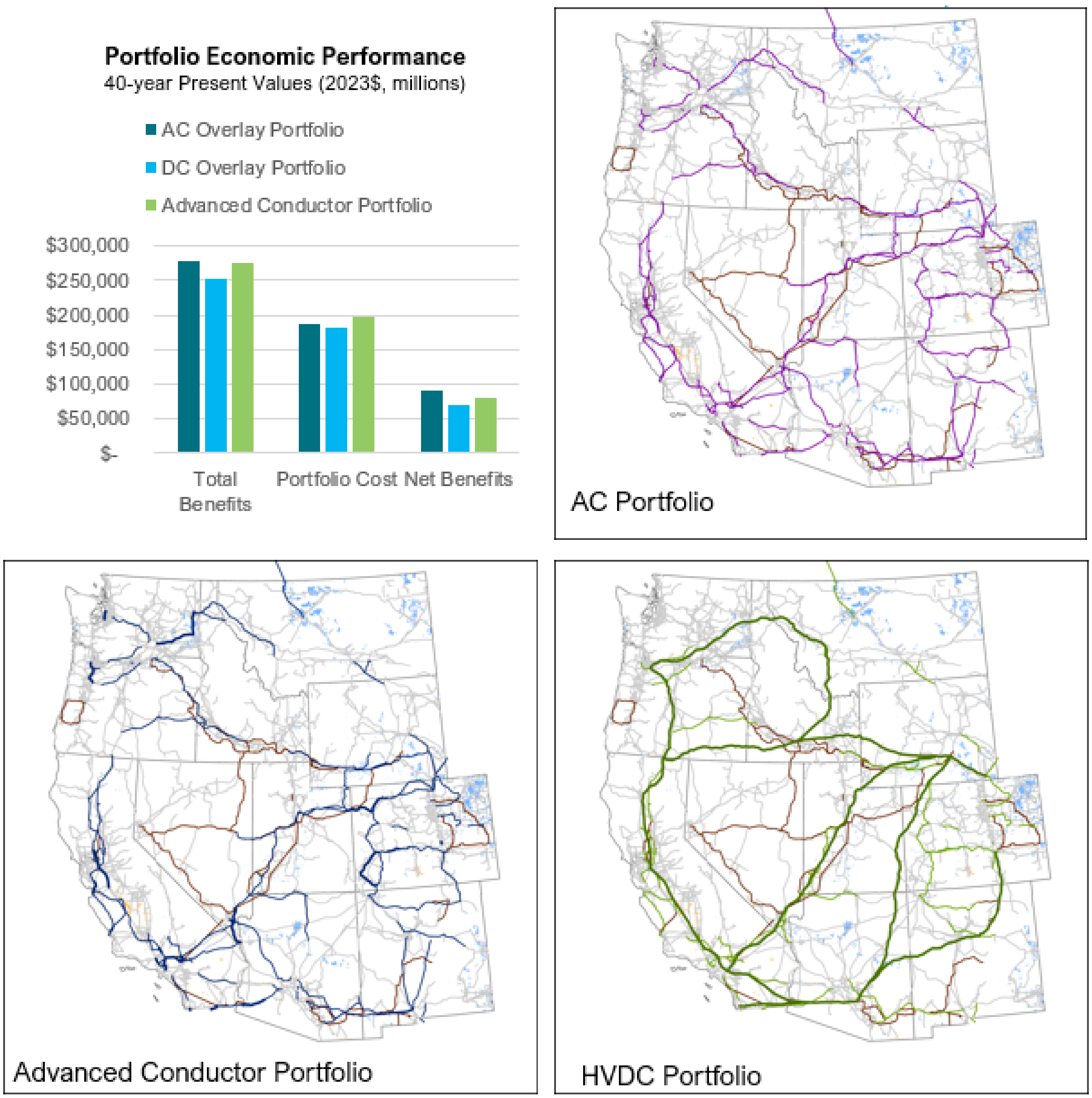
However, greenfield transmission development cannot be entirely avoided in certain cases based on the system's needs. After maximizing the use of the existing system and rights-of-way, the need for greenfield transmission expansion is more manageable, requiring approximately 2,400 miles of new transmission right-of-way. Critical areas for new greenfield development include corridors between Colorado its neighbors, Arizona and New Mexico, Montana and the Mid-Columbia area, and in-state California paths.

Comparable Costs, Benefits, and Performance Observed Across Portfolio

The Connected West study evaluates three transmission expansion portfolios—AC Greenfield, DC Greenfield, and Advanced Conductor—aimed at meeting the high-voltage transmission needs of a decarbonized and electrified Western grid by 2045. Each portfolio explores different strategies and technologies to improve grid capacity, reliability, and efficiency, combining both traditional and advanced methods to address the demands of a decarbonization and high electrification scenario.

The portfolios developed in the study were determined to have comparable costs and benefits, with all offering a favorable benefit-cost ratio of approximately 1.4. Net benefits are heavily driven by increased connectivity between regions, resulting in load diversity savings (avoided capacity investments), fuel/operational efficiencies, and the insurance value associated with avoiding economic harm caused by extreme events. In addition, all transmission portfolios commonly enhance connectivity between balancing areas and planning regions. Across the three portfolios, 33-42% of area-to-area connections needed upgrades, and all require at least one new area-to-area connection (the HVDC portfolio required seven new area-to-area connections). This underscores the need for robust planning coordination among utilities and regions, as piecemeal grid expansion could leave critical issues unaddressed.

Figure 6: Portfolio Summaries and Economic Performance



The results also suggest that the optimal 20-year transmission expansion strategy likely involves a blend of reconductoring existing lines, co-locating upgrades, and selective use of advanced conductors, HVDC solutions, advanced transmission technologies, along with continued use of traditional transmission expansion approaches. This "all-of-the-above" approach balances economic, environmental, and technical considerations to support long-term decarbonization and electrification goals.

Additional Takeaways

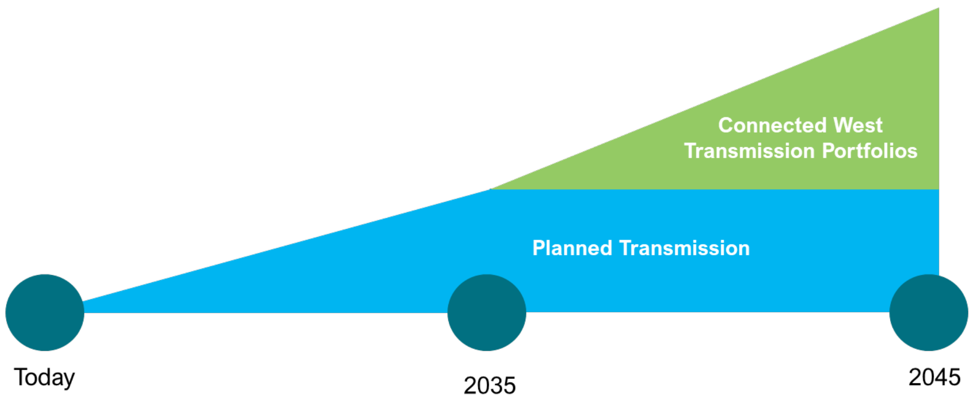
The study's results support several additional takeaways:

- **The degree of planning coordination that actually occurs will significantly impact the scope and amount of transmission needed, with less coordination resulting in the need for more transmission (in most circumstances).** Seamless planning coordination and collaborative project execution were important assumptions in the study. Continued coordination and private-sector collaboration on grid investments is critical to efficient expansion under this future.
- **Advanced high-capacity conductors proved effective**, making up roughly one-third of the line miles in the relevant portfolio as a Grid Enhancing Technology (GET). Other GETs like dynamic line ratings and power flow controllers were evaluated but were not well suited for this study's needs, as they did not offer sufficient incremental and firm capacity given the severity of reliability and capacity needs in the 20-year timeframe. Such technologies are often better suited for incremental or developing issues, likely to be identified in nearer-term studies focused on a subset of issues. Additional investigation of dynamic line ratings, advanced power flow control, and topology optimization to complement the regional transmission expansion and improve system performance while the new transmission is built would be worthwhile.
- **Substantial transmission backbone reinforcements are required** in local 115-kV and 230-kV systems in rural areas with rich resource potential like Montana, Wyoming, and Colorado. This suggests a need for significant rural transmission deployment and robust collector systems to achieve the decarbonization and electrification targets envisioned in this study.
- **Incremental transmission needs are sensitive to planned expansion**, with areas assumed to have substantial planned transmission investments requiring fewer portfolio upgrades (e.g., Nevada and its Greenlink project complex). However, in some states, planned transmission did not keep up with forecasts of load and generation growth (e.g., Wyoming, California).
- **While transmission lines in this future have a significant cost**, these investments will be offset by the influx of new customers and the increased demand that does not exist today but is assumed in the study, thereby helping to address concerns about high transmission costs.

1. Motivation and Purpose of Connected West

The Connected West study is a 20-year transmission planning assessment aimed at forecasting long-range transmission infrastructure needs of the Western grid required to support a highly decarbonized and electrified future. The study focuses on identifying "next generation" transmission investments for this scenario, targeting the identification of portfolios of new transmission expansion projects that represent investment above and beyond upgrades that have been previously proposed by Western utilities and developers.

Figure 7: Connected West Transmission Portfolios Help to Meet Decarbonization and Electrification Targets



The study's long-range view of Western transmission needs is responsive to the following observations regarding the state of transmission planning in the West:

1. Outside of the California Independent System Operator (CAISO), FERC Order 1000 has not led to the construction of any new regional transmission upgrades;
2. Current planning processes are likely not identifying sufficient interregional transmission upgrades;
3. Most Western transmission expansion is occurring within single transmission owner footprints and there is a pressing need for a long-term view considering a consolidated assessment of system-wide transmission expansion options;
4. Few studies have highlighted specific corridors that may need to be prioritized for transmission expansion that facilitate decarbonization, electrification, and reliability of the grid.

The study aims to help address these concerns by providing information surrounding a "bookend" view of transmission expansion, exploring a future where the West's economy is highly decarbonized, significant electrification and load growth occurs, leaving the West reliant on a yet-to-be-planned regional grid that is robust, reliable, and efficient. This study's holistic perspective on future transmission expansion is crucial for identifying the "next generation" of potential transmission investments that support the Western grid's decarbonization and reliability goals. This study is positioned to complement other scenario-based views of future transmission need, reflecting one of many potential outcomes.

Study Purpose

The Connected West study serves several critical purposes. Primarily, it acts as an informational resource for stakeholders, providing insights into long-term transmission needs of the Western grid for a decarbonized and electrified future. The study identifies portfolios of projects, demonstrates how they work together, backed by detailed analyses and forecasts of transmission expansion. The study also helps stakeholders understand the trade-offs, costs, and benefits associated with different transmission expansion strategies. By identifying high-value corridors, the study aims to aid in strategic planning for future transmission developments. Finally, another key purpose of the study is for the new study methods, models, and resulting transmission expansion portfolios to serve as inputs into other planning processes, such as WestTEC, future Order 1920 planning processes, among other use cases.

Key Questions

The Connected West was structured around several critical questions the study endeavored to answer.

1. **Capabilities of Projected Transmission:** How far do planned and anticipated transmission projects take the Western grid towards meeting 2045 transmission needs under a high electrification and decarbonization future?
2. **Transmission Gaps:** If the planned projects do not fully meet the 2045 needs, what is the remaining transmission gap in terms of investment and additional transmission capacity?
3. **Geographic Corridor Prioritization:** Based on the transmission portfolios identified for the Connect West future, what geographic corridors should be prioritized for the next tranche of transmission investments over the coming 20 years?
4. **Portfolio Comparisons:** How do new greenfield corridors compare with upgrades to existing lines? What portfolios of transmission technologies appear to make the most sense to achieve the West’s long-term goals?

These questions guided the development of the study's analytical framework, ensuring that the findings are relevant and insightful for advancing the Western grid's transmission infrastructure.

2. Power of Place: West

The *Power of Place: West* report, released in August 2022 by The Nature Conservancy, explores the land use requirements and conservation impacts of achieving net-zero greenhouse gas emissions across eleven Western states by 2050.[1] The study analyzes two scenarios using economy-wide models: a high electrification scenario using a variety of clean energy technologies, and a renewables-only scenario. The "High Electrification" scenario in the *Power of Place: West* study models the use of all commercially available clean energy technologies to achieve economy-wide net-zero emissions by 2050.

The Connected West study leverages the "High Electrification" scenario results from *Power of Place: West*, adopting load forecasts and resource buildouts for the West as *inputs* into Connected West. This study also leveraged extensive databases on land use and development sensitivities to inform transmission routing and costing analyses.

Power of Place: West focused predominantly on land use implications associated with economy-wide decarbonization pathways. While the modeling framework considered the need for transmission zone-to-zone transmission expansion, it did not include detailed (e.g., nodal or "line-by-line") transmission analysis and, by nature of the study scope, required generalizing assumptions about transmission operations, drivers, and investments. Connected West sought to fill this transmission analysis gap, repurposing the optimal generation resource expansion plan, load forecasts, and environmental databases offered by *Power of Place: West*, while doubling down on the transmission, grid reliability, and transmission business case analysis. In doing so, Connected West aims to provide a more detailed and precise view of what transmission may be required for the High Electrification scenario developed in *Power of Place: West.*

High Electrification Scenario

The Connected West Reference Case, further described in the ***Reference Case*** section of this report, was developed based on the *Power of Place: West* "High Electrification Level 3".[2] This scenario is consistent with a future in which:

- **Demand & Electrification:** High energy efficiency, 100% sales of electric building technologies by 2040, 100% ZEV sales by 2040, fuel switching for some process heat and other fuel use,

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[1] https://www.nature.org/content/dam/tnc/nature/en/documents/TNC_Power-of-Place-WEST-Executive_Summary_WEB-9.2.22.pdf

[2] Specifically, this study leverages the "High Elec Siting level 3" scenario, with some resource mix modifications made in Wyoming, Montana, and New Mexico based on transmission assessments. Siting Level 3 is in reference to environmental siting levels, representing the most conservative approach where wind and solar development is prohibited in high conservation value areas (crucial habitat, prime farmlands, etc.), administratively protected areas, and legally protected areas. More details on environmental constraints are in the Power of Place: West report.

direct reduced iron-making (DRI), which uses hydrogen and electricity instead of coal, in iron and steel, carbon capture on cement.

- **Supply**: All generation technologies allowed.
- **Carbon target**: Net-zero economy-wide emissions by 2050.
- **Environmental siting constraints**: Siting level 3, with additional details in the figure below.

Figure 8: Environmental Siting Levels from Power of Place: West[3]

ENVIRONMENTAL Siting levels	Siting level 1 (SL1)	Wind and solar: Exclude legally protected areas (Category 1, eg., national parks, wilderness areas, wildlife refuges, conservation easements). Biomass: all feedstocks included; exclude potential supply from conservation reserve program land
	Siting level 2 (SL2)	Wind and solar: Exclude administratively protected areas (Category 2; e.g., critical habitat for threatened and endangered species, wetlands, areas of critical environmental concern) and Category 1. Biomass: No net expansion of land for purpose-grown herbaceous biomass crops. Land for purpose-grown biomass is restricted to land that is currently used to grow bioenergy feedstocks. Specifically, land available for herbaceous biomass crops (miscanthus and switchgrass) is limited to the share of land currently cultivated for corn that is eventually consumed as corn ethanol, which is phased out in all net-zero scenarios by 2050 (14)
	Siting level 3 (SL3)	Wind and solar: Exclude areas with high conservation value (Category 3; e.g., priority and crucial habitat, intact grasslands, prime farmlands), category 2 and category 3. Biomass: Same as siting level 2

By reflecting these assumptions in this study's modeling in the Connected West Reference Case, Connected West aims to resolve planning challenges and provide a detailed analysis of transmission requirements aligned with future energy demands and environmental considerations.

[3] Source: https://www.pnas.org/doi/epdf/10.1073/pnas.2204098120

3. Reference Case

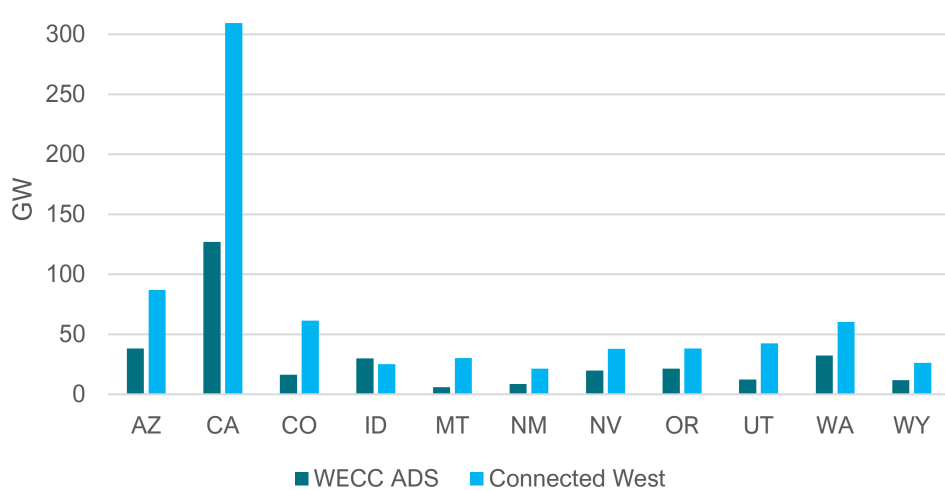
The Connected West 2045 Reference Case (or "Reference Case") captures a forward-looking representation of the Western Interconnection. The WECC 2032 Anchor Data Set (ADS) production cost model was used as the starting point for developing the Reference Case. The WECC 2032 ADS is a highly vetted "status quo" view of the WECC system in 2032. For this study, the WECC 2032 ADS case was modified to make the Reference Case and all study portfolios.[4]

The remainder of this section describes the approach & assumptions taken to develop three key assumptions of the Reference Case: generation, load, and transmission. Other assumptions are discussed in the Appendix.

Generation

The Reference Case represents a potential future electrical system for the Western United States in which state-by-state generation by fuel/technology type are consistent with the *Power of Place: West* High Electrification Future in 2045. To achieve outcomes consistent with *Power of Place: West*, the generation capacity in the Western United States is assumed to reach 746 GW of nameplate capacity in 2045 – a vast majority of the increases being solar and wind technologies.

Figure 9: Installed Generation Capacity Comparison (GW)

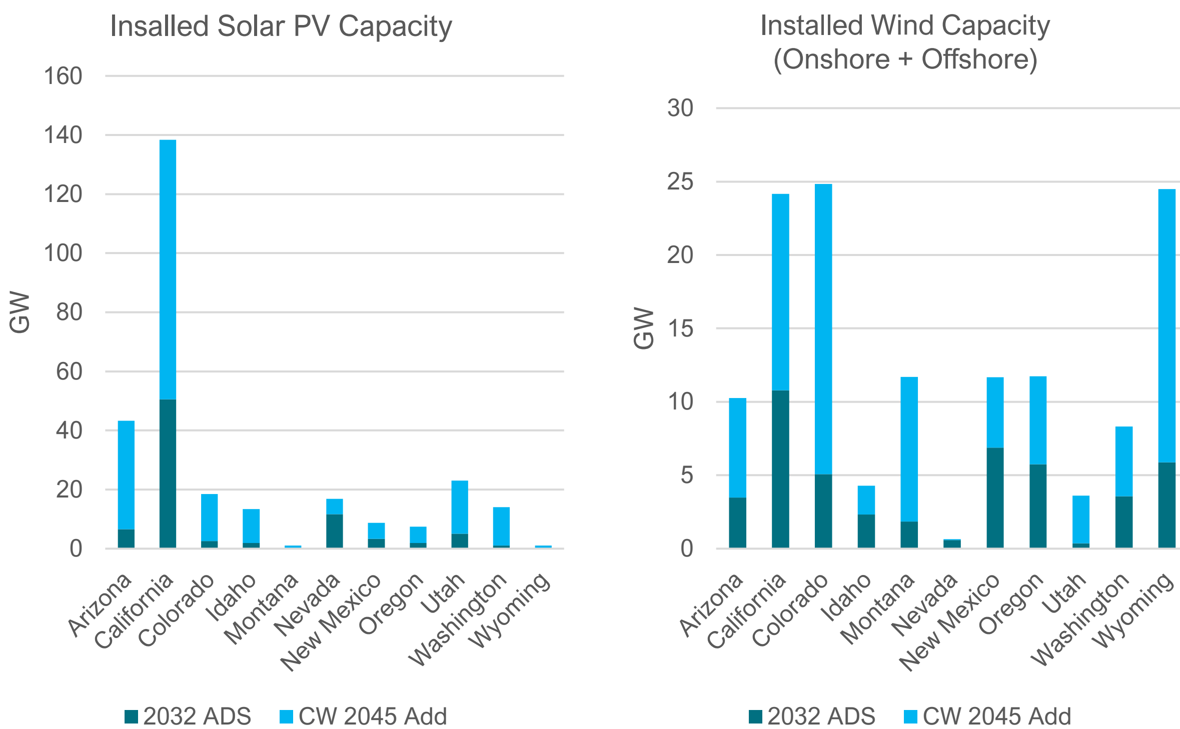


To accomplish this, a common set of "resource types" were identified between the seed case and results from the *Power of Place: West* study[5]. The difference between the nameplate capacity, by state, was calculated and a methodology was developed to add (or retire) resources to the seed case

[4] The WECC ADS 2032 case was expanded in California to include the latest generation and transmission additions consistent with the 2022-2023 CAISO TPP. The 2032 ADS with updates reflecting CAISO TPP is referred to hereafter as the study "seed case".
[5] https://zenodo.org/records/7460026#.Y8rnZ0HMKUk

to create the 2045 Reference Case. Since the study leveraged nodal representations of the transmission grid, resources needed to be located at specific buses on the system.

Figure 10: Installed Solar and Wind Capacity by State for ADS in 2032 and Connected West in 2045



As needed, existing generation units were repowered (or retired) to correct for state-resource differences. Otherwise, generation retirement dates were retained from WECC ADS. No coal-fired power plants were assumed to be operational in the 2045 timeframe. If repowering/retiring existing units was insufficient to meet state-resource differences (which occurred mostly for wind and solar resources), additional generic generating units with location-specific characteristics were added based on an in-house siting and busbar mapping algorithm.

Busbar Mapping Algorithm

The algorithm developed for this study process locates incremental resource additions, consistent with state-wide capacities, to reasonable substation locations nearby project areas in the *Power of Place: West* study. Selected Project Areas (SPAs) from *Power of Place: West* were joined to a single database containing the approximate locations of WECC buses. Thus, for every project area selected in *Power of Place: West*, the algorithm identified nearby buses, 230kV or higher, onto which the power from that project might be injected.

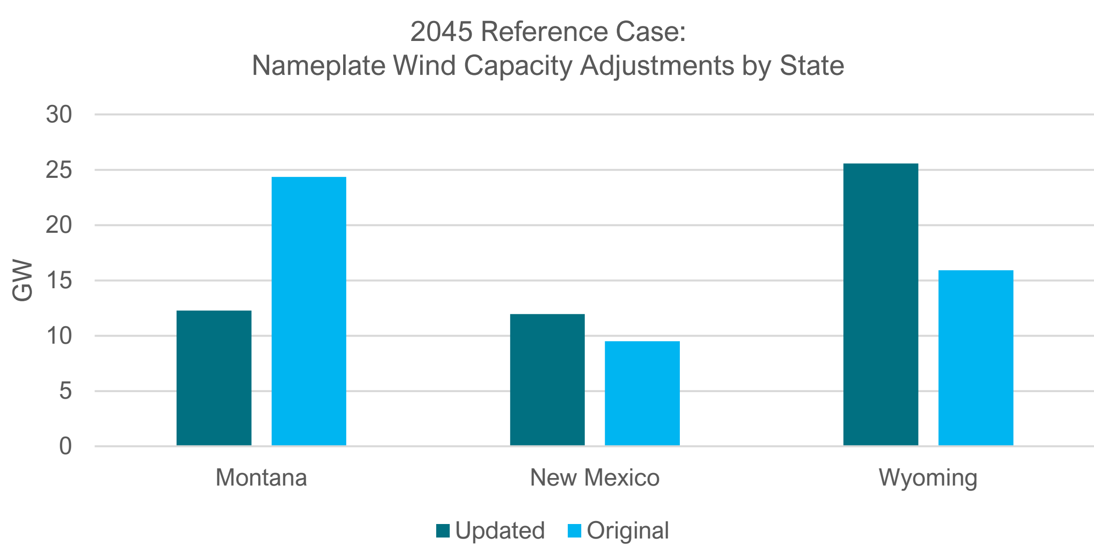
In general, the siting algorithm used in this study prioritized areas with transmission efficiency and commercial interest. Brownfield (locations where other plants had been retired), and high-voltage interconnection points with high resource quality (capacity factors) were also prioritized. The busbar mapping algorithm was adopted to find reasonable interconnection points on the grid based on proximity to the SPA and a voltage-based approximation of grid injection capability.

Offshore wind resources were mapped in a bespoke manner. Offshore wind capacity goes above and beyond what is modeled in the *Power of Place: West* study. In the Connected West study, the Reference Case assumes that 13.4 GW and 6 GW, of offshore wind is built in California and Oregon, respectively. These are meant to reflect assumptions consistent with recent offshore wind planning efforts in these states. Specific transmission solutions, consistent with stated development locations and interconnection plans were modeled in this study for all offshore wind resources.

The siting approach taken in the *Power of Place: West* study is a key factor in forming the findings of this study since it informs where and to what extent transmission is built to bring this generation to loads across the Western Interconnection.

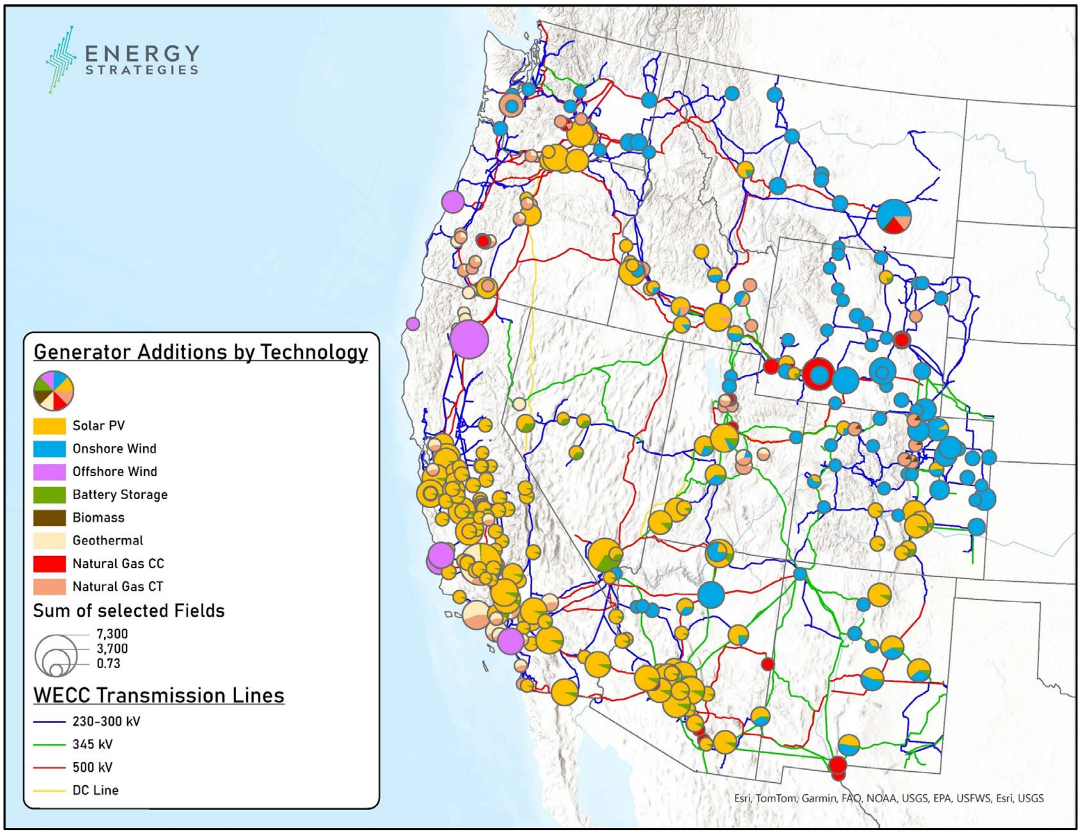
State-by-state wind resource capacities for three key Western states, Wyoming, New Mexico, and Montana, differ significantly between *Power of Place: West's* Level 1 siting criteria, and level 3 siting criteria. After a review of these differences, and in response to transmission constraints identified in Montana, 12 GW of wind resources were re-sited from Montana into Wyoming and New Mexico.

Figure 11: Wind capacity adjustments made to the 2045 Reference Case from relaxing land siting constraints



The final siting of resources added to the 2032 ADS seed case to create the 2045 Connected West Reference Case is shown in the figure below.

Figure 12: Connected West Reference Case Resource Additions[6]



In general, the *Power of Place: West* study prioritizes high-quality resource locations and avoids sensitive natural areas and working lands. Significant wind capacity is sited in remote and rural areas in the northern and eastern parts of the Western Interconnection, whereas solar resources are distributed across other areas with lesser wind quality.

Loads

Load forecasts for Connected West were sourced from the *Power of Place: West* High Electrification scenario, which assumes 100% sales of electric building technologies by 2040, 100% ZEV sales by 2040, and some fuel switching for industrial production required to achieve net-zero economy-wide emissions by 2050.

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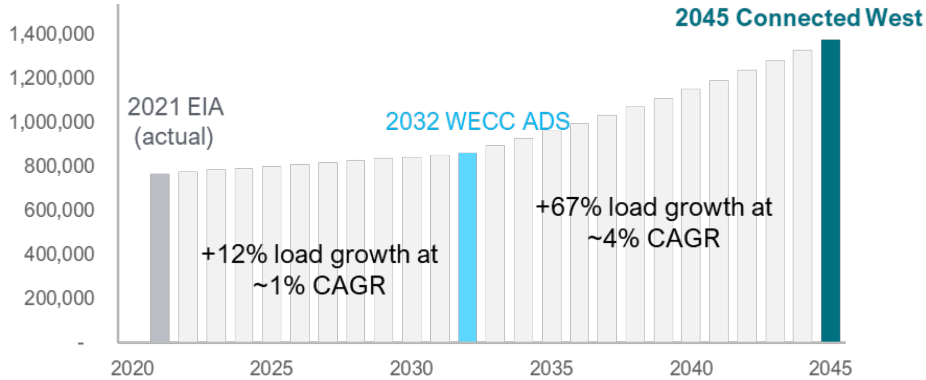
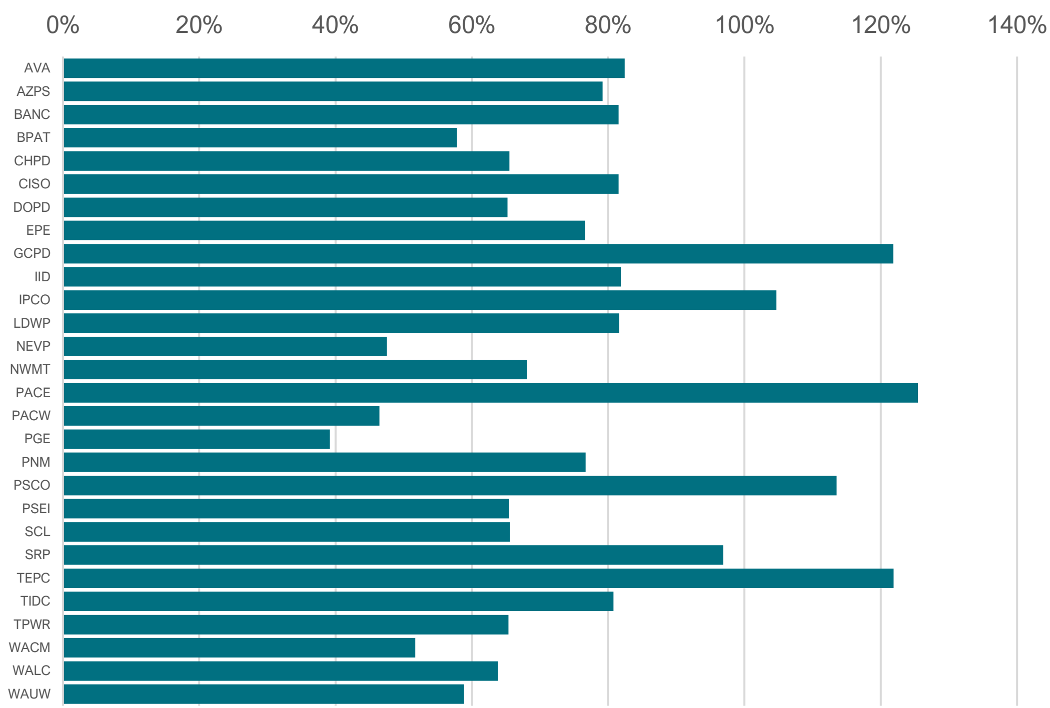
[6] Offshore wind facilities are identified at their grid integration point and not their physical location offshore.

Figure 13: Western US Annual Retail Energy Demand



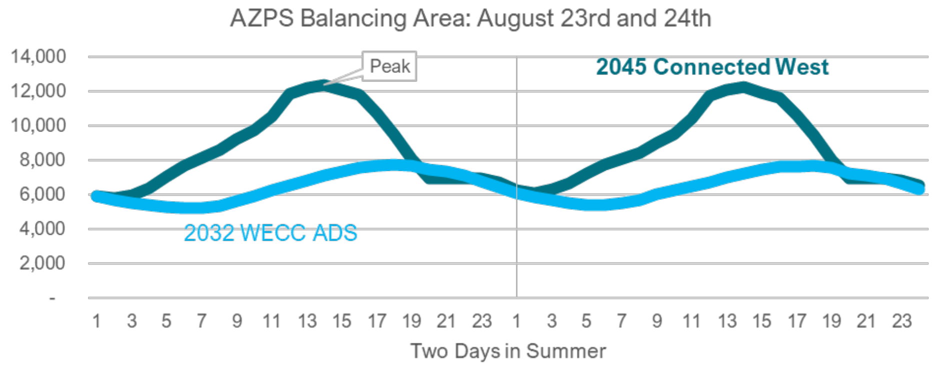
To incorporate *Power of Place: West* loads into the Connected West Reference Case, state-level forecasts from *Power of Place: West* were disaggregated to balancing areas based on historical BA-state load factors using the 2021 EIA-861 sales data.

Figure 14: Change in Annual Energy by Balancing Area (%) from 2021 to 2045 Connected West Reference Case



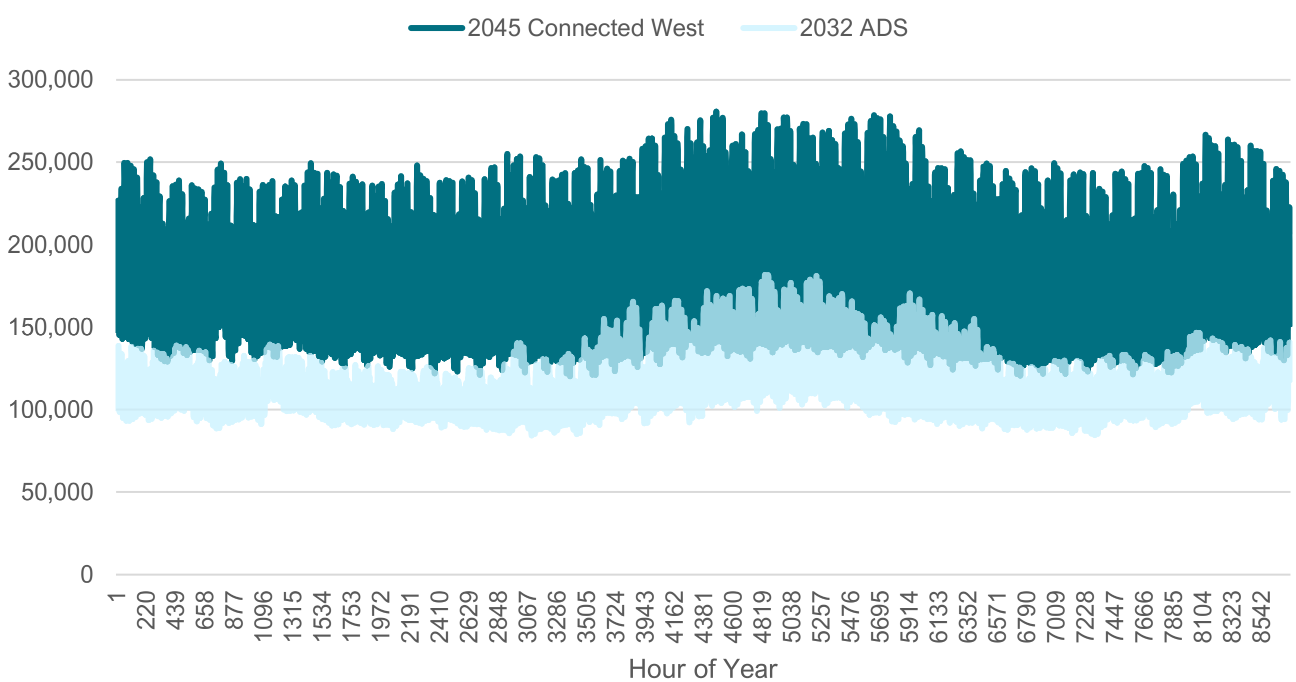
The *Power of Place: West* study included many flexible loads that were assumed to be dispatchable in that study. These flexible loads, primarily electrified appliances and vehicles and use of electricity in fuel production processes, were co-optimized alongside generation resources in the *Power of Place: West* study. This optimized dispatch of these flexible loads were incorporated into the load profiles used in the Connected West Reference Case – causing load shapes to differ significantly from those in the 2032 WECC ADS. **Because of this, Connected West considers transmission needs after factoring in load shifting and flexibility that much reduce such needs.**

Figure 15: Sample of Connected West Load Shapes



The Connected West High Electrification load forecast results in +100 GW of additional peak demand (+54%) over 2032 ADS levels. WECC-wide peak demand in the 2045 Reference Case reaches 281 GW, up from 182 GW in the 2032 WECC ADS seed case.

Figure 16: Hourly WECC Loads Comparison - 2045 Connected West vs. 2032 WECC ADS (MW)

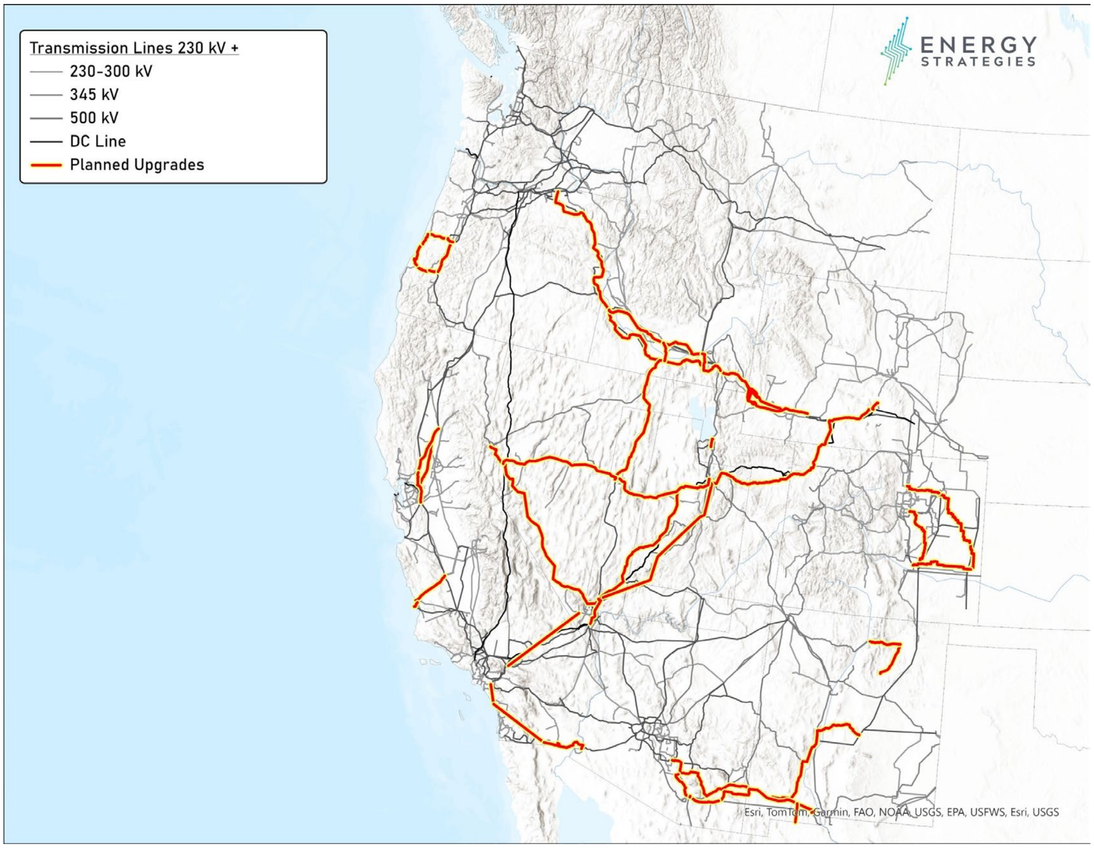


Transmission

Where the Reference Case captures generation and load consistent with 2045 expectations per the *Power of Place: West* study, a key part of this study is to identify the "next tranche" of transmission that is needed above and beyond near-term (10-year) plans. Accordingly, the transmission included in the Reference Case represents the transmission lines assumed in the 2032 WECC ADS plus nearly twenty major transmission lines in-development that are assumed to be in-service within a 10-year timeframe.

These projects, totaling over 5,900 line-miles, 35 GW of new capacity, and $30B of investment are shown in the figure below, and detailed in the Appendix.

Figure 17: Planned Upgrades Assumed in Connected West Reference Case

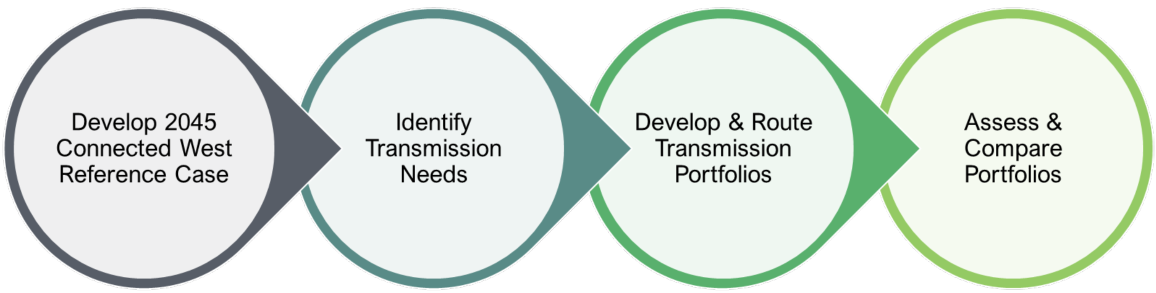


These projects were modeled explicitly in the nodal transmission system. Adjustments to WECC Path ratings were made whenever WECC progress reports were available. In a few instances, judgement was used to update ratings for projects not yet in Phase 2 or Phase 3 of process but that were deemed likely to cause an increase to one or more WECC path ratings.

4. Methodology

The Connected West study followed a 4-step process to determine study results & key findings. The study process was designed to provide insights into the necessary investments and the potential benefits of a modernized transmission network that meets the needs of an electrified and decarbonized future.

Figure 18: Connected West Study Process



The Reference Case was initially run in GridView, a nodal production cost model, with the assumptions outlined in Section 3 and in the Appendix.[7] Since the Reference Case is designed to explore the need for additional transmission investment, the case identified significant transmission congestion. The location and magnitude of potential transmission needs were identified based on observed congestion and nodal price differentials. The team used an iterative analytical process using power flow analysis of the WECC system to identify transmission upgrades that solved congestion issues and addressed deliverability issues. Once these portfolios were developed, tested, and determined to meet key clean energy and congestion mitigation metrics, they were assessed and compared against each other to derive study findings.

Targeted Transmission

In a nodal production cost model, certain simplifications and approximations are made to make computation requirements and simulation time tractable. One such assumption is how transmission is modeled in a GridView production cost model. In these models, the flows on the AC transmission grid are calculated based on physical properties (impedances) of the lines that make up the network. For a given grid topology, a distribution factor matrix is calculated that defines how electrical power flows through the network of lines. This matrix is enforced for every line so that an injection of power at one

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[7] Production cost models find the least-cost commitment and dispatch schedule of a fleet of generators (& other controllable devices) to serve load subject to a wide variety of system constraints. Similar to real-world operations, the power system is modeled in a "security-constrained" manner – i.e., in such a way that it would be able to handle any number of unexpected contingencies without causing wide-spread or prolonged system failures. In a nodal production cost model, buses (substations) and branches (transmission lines, transformers, etc.) above a certain voltage threshold are explicitly monitored and their limits enforced when determining the model's solution.

point in the system properly reflects how that power would propagate out across the transmission network. Since there are thousands of lines in a regional grid like the Western Interconnection, only certain lines are "monitored". When a line is monitored, flow on that line is tracked by the model, and the line's capacity limits, which define maximum power flow allowed on that line, are enforced. Monitored lines are selected strategically to balance model fidelity (i.e., to best capture system transmission limitations) and to computation time.

For all Connected West study models, all lines >300-kV were monitored, as well as lines with voltage of 200-kV and higher that span between two balancing authorities or states were monitored. This decision is aligned with the study objective of identifying "the next tranche" of large-scale, inter-regional transmission solutions. However, transmission planning at a multi-region scale, as this study does, is a complicated and multi-faceted endeavor. Therefore, more detailed transmission analysis would need to be done to vet and refine the transmission solutions identified in this study. Such an analysis would likely identify further upgrades as being required. The results in this study seek to reflect the magnitude and location of inter-area and inter-state transmission that would be needed to facilitate the generation and load portfolio identified in the *Power of Place: West* study.

Transmission Portfolios

The Connected West study evaluates three transmission expansion portfolios—AC Greenfield, DC Greenfield, and Advanced Conductor—aimed at meeting the high-voltage transmission needs of a decarbonized and electrified Western grid by 2045. Each portfolio, summarized below, explores represents a unique strategy to improve grid capacity, reliability, and efficiency:

- The **AC Greenfield Portfolio** consisted of reconductoring existing lines, expansion of existing rights of way, and new projects in new corridors using traditional conductor technology (ACSR or ACSS conductors).[8]
- The **HVDC Greenfield Portfolio** consisted of a network of HVDC lines across the WECC system with some AC upgrades required to allow power transfer to and from the DC network.
- The **Advanced Conductor Portfolio** consisted of new high-capacity transmission conductors located within existing transmission corridors, along with traditional ACSR or ACSS conductors used when advanced conductors were not feasible or practical.

The figure below outlines the key assumptions that differentiate the three studied transmission portfolios.

[8] One HVDC line upgrade in CA was included as an upgrade in all three portfolios since it was recommended in CAISO's 20-year transmission outlook study.

Figure 19: Summary of Thematic Transmission Portfolios

Portfolio	Reconductor Options	Co-Locate Options	Greenfield Options
AC Greenfield	Traditional AC conductors only	Traditional AC conductors only	Primarily traditional AC conductors
HVDC Greenfield	Traditional AC conductors to facilitate HVDC upgrades	Traditional AC conductors to facilitate HVDC upgrades	Primarily HVDC lines with some traditional AC conductors
Advanced Conductor	Advanced & traditional conductors	Advanced & traditional Conductors	Advanced & traditional conductors

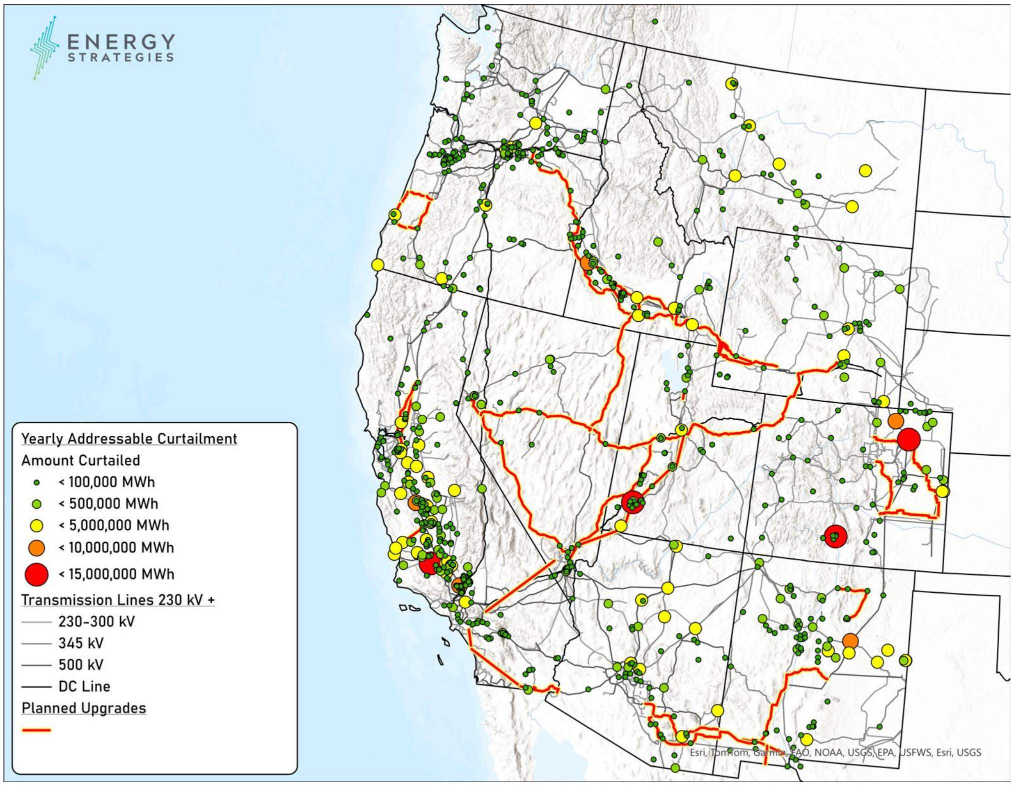
Identifying Transmission Needs

Reference Case production cost model results were used to identify the location and magnitude of 20-year transmission needs as a method to inform further planning analyses. An initial screening exercise quantifying three key transmission metrics in Reference Case results was used to inform subsequent reliability assessments.

Transmission Need Metric 1: Addressable Curtailment

A "copper sheet" version of the Reference Case was run. In the copper sheet study, all generation resources and loads were left the same as in the Reference Case, but all transmission constraints and limits were relaxed. By comparing this copper sheet case to the Reference Case, the modeling team identified areas where transmission congestion was the primary cause of limiting renewable resources from serving load, resulting in renewable curtailment. The locations with high levels of addressable curtailment were primary targets for transmission expansion.

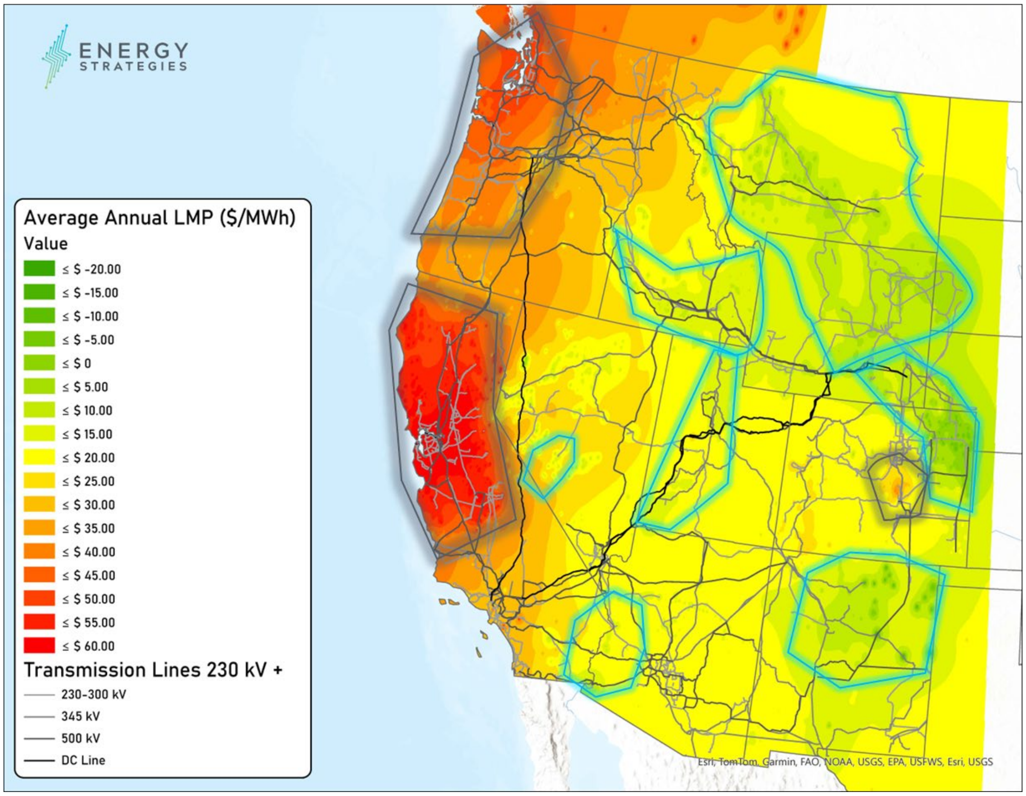
Figure 20: Difference in Curtailment between Reference Case and Copper Sheet Case (Addressable Curtailment)



Transmission Need Metric 2: Locational Marginal Prices

Export limited (source) areas were identified as areas where excess renewable energy was available but could not reach import limited (sink) areas. The sources and sinks were identified through an LMP heat map of the reference case. Areas with low LMPs (green areas of the map) are the sources, and the sinks are the regions with high LMPs (orange and red areas of the map). These areas are expected as the eastern side of the interconnection is rich in wind resources and the west coast has high loads. The price differences indicate transmission congestion which spurs additional transmission between these areas.

Figure 21: 2045 Reference Case LMP Heat Map



Transmission Need Metric 3: Transmission Line and WECC Path Congestion

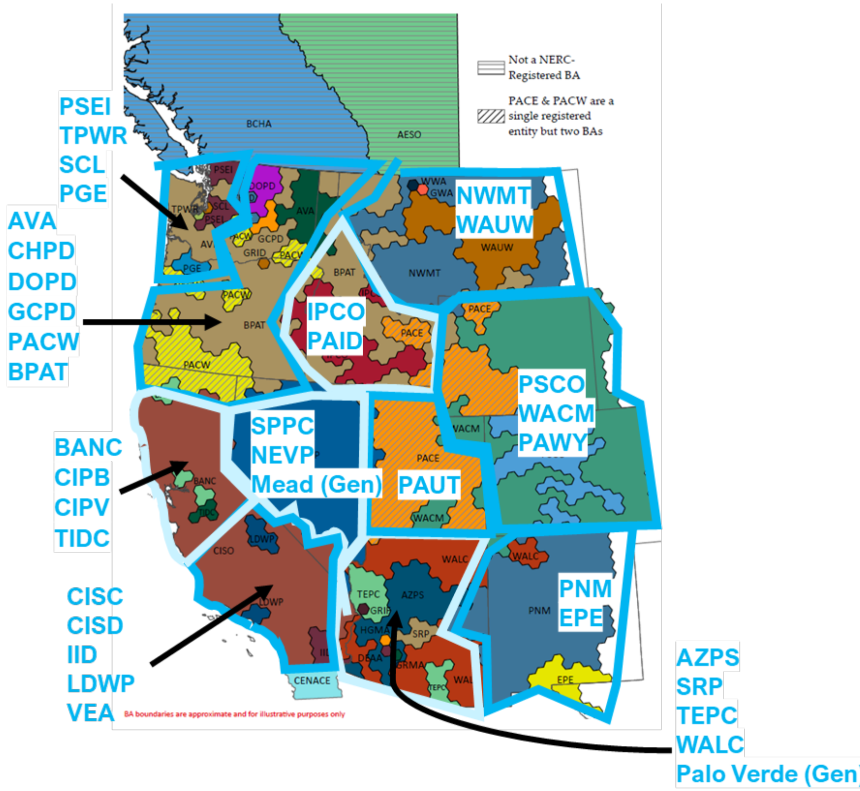
Transmission congestion or overloading of the transmission system obviously indicates a need for additional transmission. Transmission Congestion was identified in the production cost model as well as in the power flow deliverability study which will be discussed in more detail in the next section.

Developing & Routing Transmission Portfolios

Transmission Deliverability Analyses

The WECC system was divided into 11 sub-zones which were made up of largely groups of balancing authorities (BAs). This phase of study could be enhanced with a more granular topology to identify intra-area issues. The goal was to “group” generation and load areas with similar electrical characteristics to produce transmission results that aligned with the intent of the study. The deliverability approach was adopted to develop transmission solutions that address congestion issues identified in the Reference Case, allowed for the deliverability – or reliable transfer – of generation to loads, while supporting the general reliability of the bulk grid.

Figure 22: Deliverability Sub-Zones

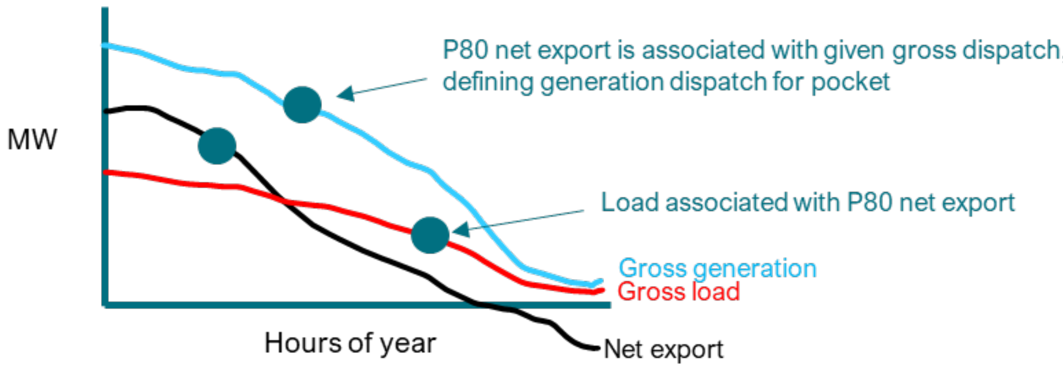


Deliverability Case Dispatch Assumptions

Generation dispatch and load conditions for each zonal deliverability case were determined through an analysis of hourly data from the 2045 Copper Sheet PCM results. Therefore, conditions studied reflect potential operating scenarios and are reasonable to base transmission analyses on. We identified average dispatch conditions that represented an 80th percentile (P80) exceedance net export (or import) condition for each study sub-zone. The P80 metric was chosen because addressing 100% of deliverability challenges is not economically feasible and would result in an overbuilt grid.

The P80 net dispatch (export or import) is representative of the condition that would capture 80% of hours with the highest export or import values. This approach highlights off-peak system conditions that test the ability of resources to be transferred out of an export zone or to supply load within an import zone. By focusing on the P80 exceedance level, we can better understand the system's performance under typical but challenging conditions without overcommitting to dispatch conditions that are less likely to occur.

Figure 23: Example of P80 Exceedance Calculation



"Pass through zones" were grouped with neighboring export or import zones to determine P80 exceedance conditions; because stressed system conditions in pass through zones usually occur during periods of high export or import in neighboring zones. For example, combined net export from Utah, Wyoming and Colorado was used to calculate P80 net export condition to get generation dispatch and load conditions for the Utah deliverability case.

Develop Transmission Upgrades

Steady-state contingency analysis (via DC approximate load flow) was performed independently for each zonal case developed as described above. Outage of single elements at 230-kV and higher were simulated in the PowerWorld software and violations on the local system, ties and WECC paths were noted. Some of the deliverability violations included:

- Voltage collapse and base case divergence as a result of insufficient transmission capacity to support P80 net exports from or imports to the study zone
- Thermal overloads on the monitored elements.

The team used the following criteria to develop network upgrades to mitigate deliverability violations:

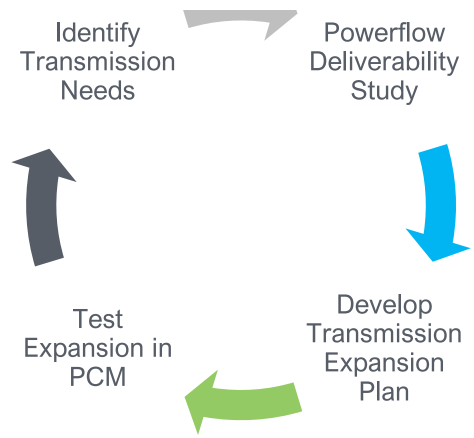
- A new line, either co-located on existing ROW or a greenfield project, was considered to prevent base case divergence.
- New lines are also assumed when overloads on a line exceed a threshold of 3000 amps for 345 kV and 500 kV lines or 2000 amps for 230 kV lines.
- Lines are assumed to be reconductored with a higher capacity conductor if thermal overloads are less than the new line threshold.
- Overloads on series capacitors are assumed to be mitigated by replacing existing capacitors with higher capacity ones.
- Transformer overloads are mitigated by adding additional ones at the same location.

List of network upgrades for each study zone were compiled into three separate transmission portfolios which were then tested in the production cost model (PCM).

Testing Expansion in Production Cost Model

Once the power flow deliverability analysis was performed, the performance of the identified transmission portfolios was evaluated in the production cost model and the process was repeated as necessary using transmission congestion and renewable curtailment metrics to refine identified network upgrades.

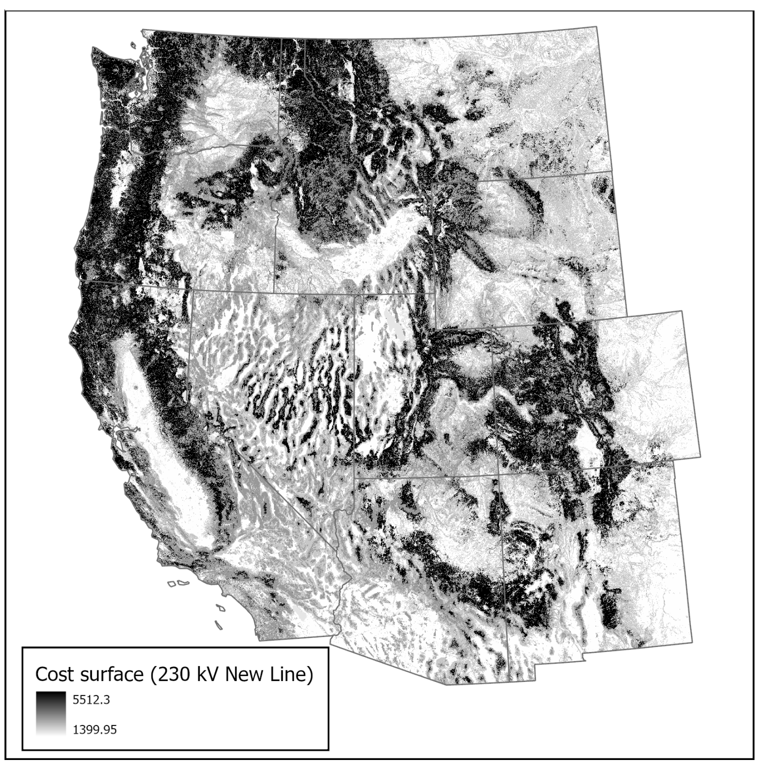
Figure 24: Iterative Process Used to Identify Transmission Solutions:



Transmission Routing and Costing

Project collaborator Montara Mountain Energy optimized the transmission portfolios by using their geospatial routing tool to determine the optimal-cost-path for each transmission project. The routing tool utilized geospatial cost surfaces to identify the most cost-effective route between two points on the grid, tailored for each portfolio. Energy Strategies provided per-mile base transmission costs to Montara, specific to the line types and technologies considered in the study. The routing tool included additional cost factors based on terrain, land use, and the ability to use existing rights of way. The cost surface used in the Connected West study to route transmission lines was consistent with that used in the *Power of Place: West* study, capturing reasonable balance between environmental sensitivities and construction cost efficiencies.

Figure 25: Transmission Routing Cost Surface Example



Assessing & Comparing Portfolios

Portfolio Cost Estimates

The team compiled a comprehensive transmission portfolio cost that combined routed transmission line costs provided by

Montara with estimated cost for other upgraded equipment such transformers, series capacitors, substation expansion and HVDC converter stations.

Equipment per unit costs were sourced from publicly available sources including MISO MTEP and WECC TEPPC cost calculators. Montara adjusted per mile costs based on terrain, land use, and the use of existing rights of way to develop a cost estimate for each line upgrade. For other equipment, per-unit costs were scaled based on the rating of the selected upgrade.

Benefit Estimates

Each portfolio was evaluated by comparing the costs to the benefits calculated for the specific portfolio. The resulting benefit-cost ratios help the study to explore tradeoffs between the transmission portfolios.

Seven benefit categories were assessed for each transmission portfolio. These benefits seek to capture the wide-ranging cost-savings resulting from building new transmission infrastructure. Both costs and benefits were compared on a present value basis, adopting a 3% (real) societal discount rate.

Figure 26: Transmission Benefits Captured

Benefit	Metric
Operational Savings	Change in WECC-wide production cost.
Avoided Emissions	Avoided emissions savings based on simulated emissions reductions and a forecasted carbon price
Avoided Loss of Load	Avoided loss of load valued at $40,000/MWh, with the benefit calculated as the product of reduced loss of load in simulation sand the loss of load price/value.
Resource Adequacy (Capacity Savings)	MWs of resource and load diversity enabled via transmission upgrade multiplied by the value of avoided capacity.
Extreme Event Mitigation	Use historical weather and grid condition data to simulate short-term operational conditions with and without project to determine change in load payments & potentially benefit of avoiding cost of unserved load (loss-of-load = $40,000/MWh).
Avoided Transmission Benefit	Cost of transmission upgrades that would be required to maintain system reliability and serve 20-year loads if the Connected West Transmission Portfolio is not built.
Reduced Transmission Losses	Generation Capacity avoided because of decrease in transmission losses as a result of the transmission upgrades.

The following assumptions were made for the transmission benefit analysis:

- Capital costs for upgrades are assumed to occur between 2035 and 2044, spread equally during this 10-year period.
- Benefits are assumed to begin accruing in 2040 and reach their full potential by 2045, continuing through 2080 for a 40-year analysis.
- Real escalation rate of 2% per year is assumed for production cost and emission cost savings.
- A weighted average value of lost (VOLL) of $40,000/MWh is assumed. This value is supported by analysis performed by ESIG (Energy Systems Integration Group, *Interregional Transmission for Resilience*, 2023) which cites VOLL of $20,000-40,000/MWh today. We adopt the higher end of this range based on independent research of similar studies and consideration of the importance of electric supply to the economy in the future being modeled.
- The avoided capacity cost is based on an average Net CONE (Cost of New Entry) values from major U.S. ISOs/RTOs, including PJM, NYISO, ISO-NE, MISO, and CAISO. The average Net CONE value is calculated to be approximately $230 per kW-year, based on the most recent estimates provided by the entities listed.
- Extreme events are assumed to occur once every 10 years (totaling four events during the lifetime of the transmission portfolio).
- Avoided transmission upgrade costs are assumed to be incurred starting in 2035 and ending in 2044. Avoided upgrades were determined based on analysis of thermal violations (N-0) without the transmission portfolios in-service.
- Transmission loss reductions are based on observed reductions in losses in the AC model after adding the transmission portfolios.
- Production cost was calculated for the US portion of the interconnection, including all costs associated with energy production.
- Avoided emission benefits were excluded from the production cost calculation and are included in the environmental cost savings. Avoided emission savings are based on the 2023 California Energy Commission IEPR CO_2 allowance reserve price of $66.74 per metric ton, which is assumed to escalate at 2% per year.

These assumptions provide a foundation for evaluating the economic and operational benefits of the proposed transmission upgrades.

Aside from benefit-cost, transmission portfolios were compared for their environmental impact. A summary of these assessments can be found in the Appendix.

5. Study Results and Findings

Connected West was a detailed analysis to identify portfolio of transmission needed to support a decarbonized and electrified future in the West. This section addressing study results and findings is structured into three parts: (1) Reference Case Results & Observations, highlighting the significant load growth and transmission constraints projected for 2045; (2) Transmission Expansion Portfolios, summarizing the three thematic portfolios—AC Greenfield, DC Greenfield, and Advanced Conductor—developed to address these needs; and (3) Key Questions and Findings, summarizing the study's insights into the capabilities of planned system, remaining transmission gaps and need for additional investment, prioritization of geographic corridors for transmission expansion, and the comparative effectiveness of different transmission technologies. These sections feature findings that are designed to inform future planning efforts that are essential for developing reliable and future-ready transmission infrastructure.

Reference Case Results & Observations

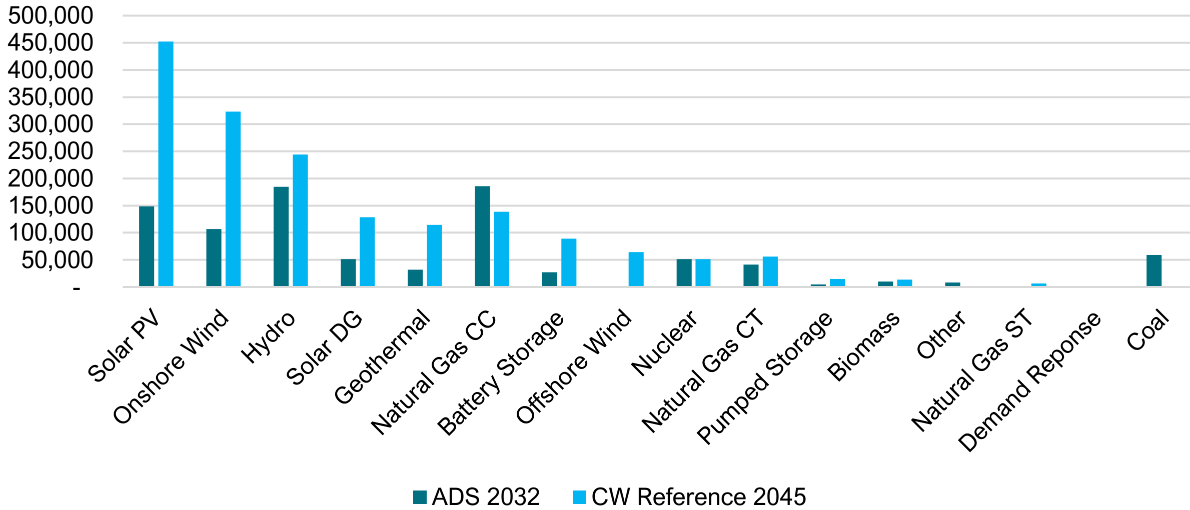
The Connected West Reference Case provides a forward-looking representation of the Western grid in 2045. The scenario captures the impacts of planned and anticipated transmission projects in a future with a resource mix and load profile consistent with a high electrification and decarbonization future. The results and observations from this scenario highlight the challenges and constraints the grid is likely to face.

Load Growth and Resource Mix Changes are Drastic

Growing demand: The WECC system experiences unprecedented load growth under this high-electrification future, with peak demand reaching 281 GW, up from 182 GW in 2032, representing a 54% increase in demand. This demand is heavily driven by the electrification of the Westen economy: adoption of electric building technologies, zero-emission vehicle (ZEV) sales, and industrial fuel switching all being key contributors. This forecast, while seemingly aggressive, does not account fully for additional demand that may arise from continued data center growth.

Generation Fleet Changes: The WECC generation fleet forecast in this study is projected to more than double, from 328 GW in 2032 to 746 GW in 2045. This increase is predominantly due to the addition of renewable resources and storage. Generation supply from solar, wind, geothermal, battery storage, and pumped storage all increase significantly, with comparable amounts of hydro and nuclear energy, less gas generation, and the elimination of coal generation from the fleet.

Figure 27: Total Annual Generation (GWh) by Resource Category: WECC 2032 ADS vs. 2045 Connected West Reference

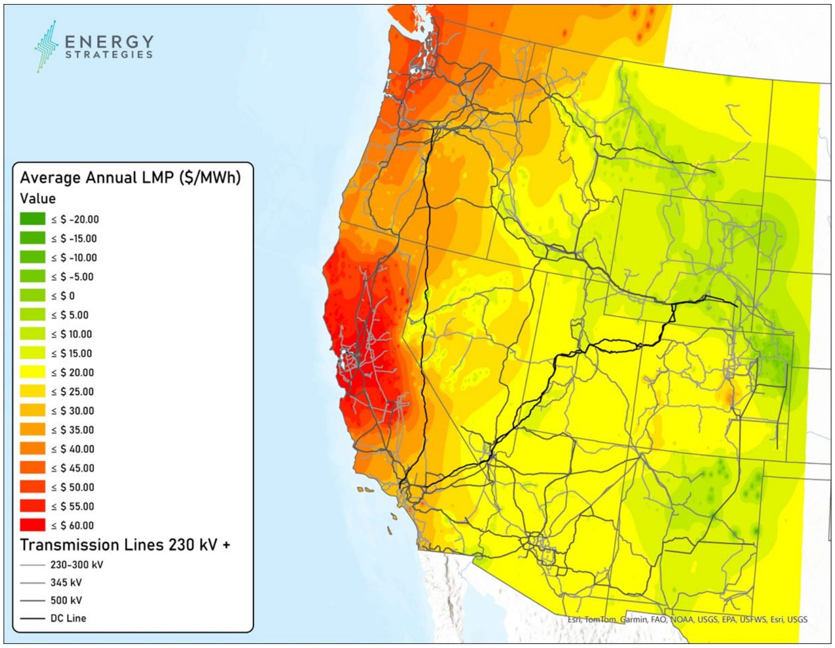


Even with significant transmission constraints present in the Reference Case, the 2045 grid achieves an 87% clean energy mix. Additional transmission is needed to achieve reliability, economic flow of power and deeper levels of clean energy penetration. By contrast, the 2032 ADS achieves a 67% clean energy penetration, so between 2032 and 2045 the grid makes substantial progress toward a net-zero emission future by 2050, which is the target set in Connected West.

Curtailment and Prices: Curtailment of renewable energy is prevalent in the Reference Case, with a substantial increase in solar and wind curtailments due to transmission limitations. Curtailments in 2045 Connected West Reference case are 36x greater than they are in 2032 WECC ADS. Peak curtailment in the Reference Case were 182 GW (in a given hour) occurring in spring. In total, 27% of renewable energy was curtailed in the Reference Case (prior to implementing the transmission portfolios).

Average energy prices or “location marginal prices” (LMPs) – which represent the price of electricity at specific locations, reflecting supply and demand balance, losses, transmission constraints, and generation costs – vary significantly across the Western region, indicating transmission congestion and inefficiencies in generation dispatch and operations. These prices vary by location (see Figure below), providing critical insights into grid constraints and transmission congestion.

Figure 28: 2045 Connected West Reference Case LMP Heat Map

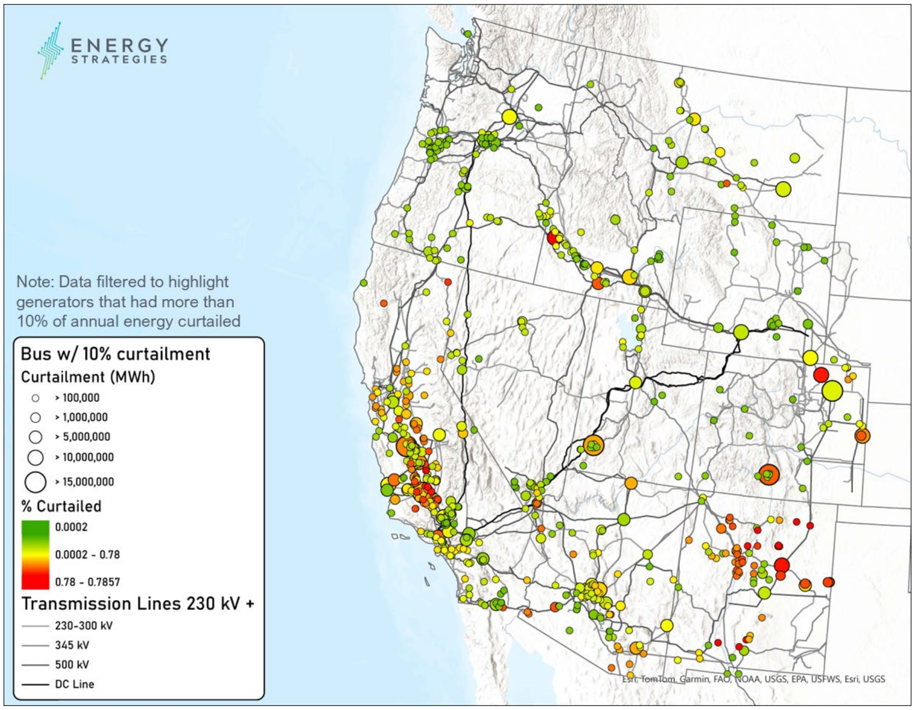


Areas with significant price differences indicate congestion, helping to prioritize regions needing transmission upgrades. The 2045 Connected West Reference Case identifies two dominant types of congestion based on annual average LMP data:

- Export Limited: Areas in Montana, SE Wyoming, NE Colorado, Eastern New Mexico, and certain locations in Idaho, Utah, Nevada, and Southern California experience constraints in exporting power.
- Import Limited: Central California, Pacific Northwest Coastal Loads, and Denver Metro face constraints in importing power.

Curtailment data reveals when and where the grid cannot handle full generation capacity, indicating potential transmission bottlenecks. While some curtailment is expected due to system-level overgeneration events or operational inflexibility, the 2045 grid frequently experiences locational transmission-driven curtailments, helping to identify transmission-constrained areas. This is demonstrated in the figure below, where Reference Case bus-level curtailment results are filtered for those generators with more than 10% of their forecasted annual energy being curtailed, then plotted to show the magnitude of curtailment (size of circle) and percentage of annual energy curtailed (shading). Dark red circles that are large represent areas with the most severe curtailment events on the system.

Figure 29: High Curtailment Areas in 2045 Connected West

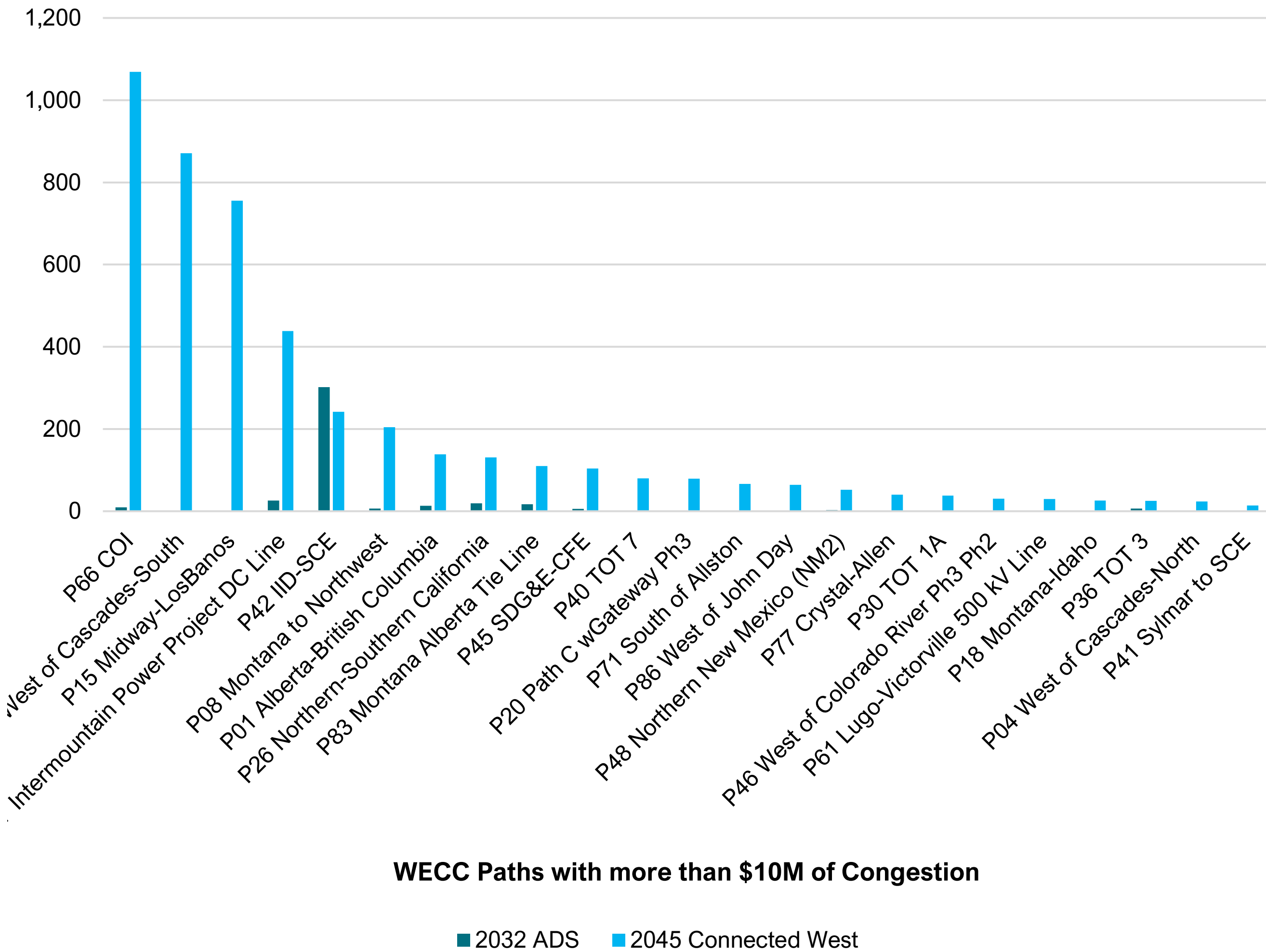


Addressing these constraints will enhance energy delivery to loads, improve the efficiency and reliability of operations. The 2045 Connected West Reference Case shows severe renewable curtailments in Montana, Colorado, Wyoming, and New Mexico, with frequent curtailments in Arizona and California—some driven by low system energy prices versus transmission limits. Utah and Idaho, along with parts of Nevada, also face material curtailments. Areas without highlighted circles on the map likely have sufficient transmission capacity.

Transmission Congestion on WECC Paths and Branches is Severe

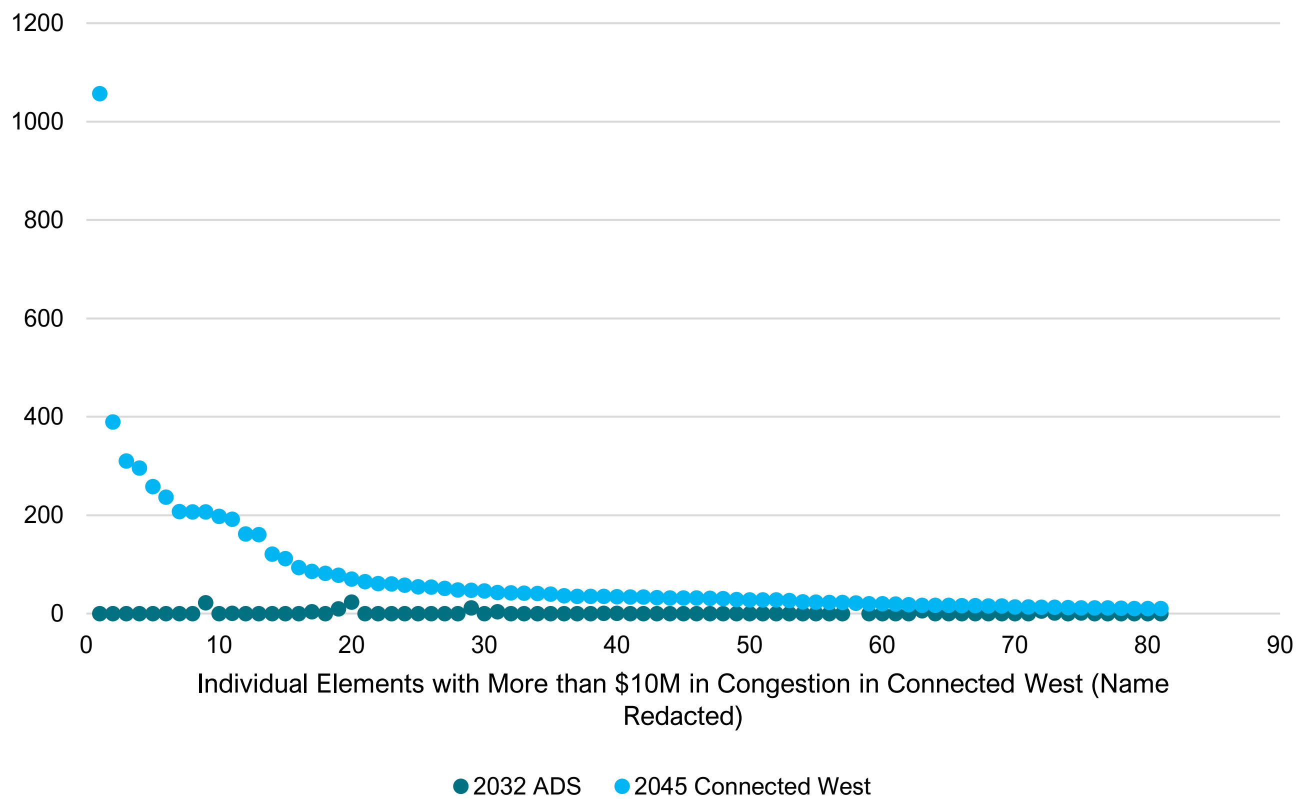
The 2045 Connected West Reference Case indicates a significant increase in transmission congestion on WECC paths, with annual congestion costs escalating by 947% compared to the 2032 ADS, increasing from $0.45 billion in the ADS to $4.7 billion. The top 10 congested paths are projected to be congested for nearly 41% of the year on average, compared to just 11% in 2032. Major transmission upgrades will be necessary to efficiently operate the system under the Connected West 2045 Reference Case scenario, with critical congestion observed on Cross-Cascade paths in the Pacific Northwest, the California-Oregon intertie, internal California upgrades, and export paths from Montana and Idaho. Addressing this congestion is essential for ensuring reliable and efficient grid operations in this future.

Figure 30: WECC Path Congestion ($M) - 2032 ADS vs. 2045 Connected West



In addition to the path-level congestion outlined above, the study also identified severe increases in congestion individual high-voltage elements, with a 403% rise in annual congestion costs compared to the 2032 ADS. While the 2032 ADS recorded $1.3 billion in annual congestion, this figure increases to $6.6 billion in the 2045 scenario. The number of branches experiencing more than $10 million in annual congestion increases to 81, with 15 branches exceeding $100 million. The total transmission congestion, including WECC paths and individual high-voltage elements, increased by 542%. The 2032 ADS saw $1.8 billion in annual congestion, this increased to $11.3 billion. This substantial congestion on high-voltage lines and transformers underscores the urgent need for additional transmission capacity to ensure the efficient operation of the grid under the high-electrification and decarbonization future envisioned in the Connected West study.

Figure 31: Branch Congestion ($M) in 2032 ADS vs. 2045 Connected West



Key Observations for the 2045 Connected West Reference Case

The 2045 Connected West Reference Case modeling provides several important insights into future needs and limitations of a Western grid attempting to accommodate both deep decarbonization and electrification of the economy:

- **Renewable Integration:** The high levels of renewable curtailment and transmission congestion indicate that the existing and planned transmission infrastructure is insufficient to integrate the projected generation capacity that is required to meet future load demands.
- **Transmission Gaps:** Even with substantial transmission investments projected by 2045, many regions will still require upgrades to unlock generation and help reduce power prices near load centers. Transmission congestion is the primary driver of many curtailment and pricing issues. Significant additional investments in high-voltage transmission are required to alleviate congestion, reduce curtailment, and enable efficient operation of the grid.
- **Clean Energy Penetration:** The Reference Case achieves an 87% clean energy penetration by 2045, despite significant transmission constraints. Flexible loads and demand response are embedded in this work and do not address all transmission challenges.

The Reference Case results underscore the need for substantial transmission investments to support a decarbonized and electrified future for the Western grid. Addressing transmission constraints and congestion will be critical to achieving the ambitious clean energy and electrification goals assumed in the Connected West study.

Transmission Expansion Portfolios

The Connected West study identifies and evaluates three distinct transmission expansion portfolios designed to address many high-voltage transmission needs of a decarbonized and electrified Western grid by 2045. Each portfolio explores different strategies and technologies to enhance grid capacity, reliability, and efficiency. The three portfolios—AC Greenfield, DC Greenfield, and Advanced Conductor—represent varied approaches to transmission development, leveraging traditional and advanced technologies to address many transmission needs for a decarbonization and high electrification scenario. The following sections provide an in-depth look at each portfolio, detailing their makeup, benefits, and the challenges they address.

AC Greenfield Portfolio

The AC Greenfield Portfolio focuses on utilizing traditional reconductoring upgrades, expansion of existing rights-of-way, and new transmission projects using traditional conductor technology (ACSR or ACSS conductors). This portfolio aims to enhance the capacity and reliability of the Western grid through well-established transmission technologies.

The AC Greenfield Portfolio includes approximately 5,779 miles of reconductoring, 7,444 miles of co-located upgrades, and 2,526 miles of new lines, totaling 15,749 miles of transmission enhancements. The capital cost for the portfolio is $75.1 billion.

Figure 32: AC Greenfield Portfolio Summary

Operational Performance in 2045	
Annual curtailment (%)	22%
Average energy price (LMP)	$23
US Clean energy penetration (%)	94.4%
US CO_2 reduction from Ref Case (%)	23%
Transmission congestion cost ($M)	$2,277
Branches with > $50M of Congestion	11

Technical Details	
Total Length (mi.)	15,749
Reconductoring miles	5,779
Co-located miles	7,444
New build miles	2,385
HVDC miles	140
Advanced conductor miles	0
New corridors land use (acres)	73,246
230-kV miles	2,447
345-kV miles	3,302
500-kV miles	9,998

Portfolio Costs & Benefits (present value)	
Total Cost ($M)	$188,366
Total Benefit ($M)	$278,851
Net Benefit ($M)	$90,486
Benefit-Cost Ratio	1.48

AC Greenfield Portfolio

The following list highlights significant greenfield transmission corridors identified in the AC Greenfield Portfolio. This information is provided to demonstrate the nature and scope of some of the longer or inter-state upgrades in the AC Greenfield Portfolio.

Figure 33: Greenfield Transmission Corridors >200 mi or Between Two States in the AC Overlay Portfolio

Corridor Name	Num of Upgraded Circuits	Upgrade Types	Corridor Cost ($M)	Corridor Length (miles)	Region
WSPIRIT - ARROYO - PINAL_C 500 kV	1	New Line	$2,592	493	NM, AZ
GARRISON - BELL BPA - ASHE 500 kV	1	New Line	$2,436	420	MT, WA
MEAD - PERKINS 500 kV	1	New Line	$1,431	254	AZ
NAVAJO - CRYSTAL 500 kV	2	New Line	$2,680	231	AZ, NV
COMANCHE - PONCHA - MONTROSE 345 kV	1	New Line	$1,151	211	CO
BONANZA - CLOVER 500 kV	2	New Line	$2,337	184	CO, UT
ELDORDO - LUGO 500 kV	1	New Line	$1,045	182	NV, CA
MARKETPL - ADELANTO 500 kV	1	New Line	$1,000	173	NV, CA
INTERMT - GONDER 230 kV	1	New Line	$479	146	UT, NV
STORY - WAYNE CHILD 345 kV	1	New Line	$420	104	CO, WY
MALIN - ROUND MT 500 kV	2	New Line	$1,711	100	OR, CA
N.GILA - IMPRLVLY 500 kV	3	New Line	$1,013	74	AZ, CA
ADELANTO - TOLUCA 500 kV	1	New Line	$442	74	NV, CA
ADELANTO - VICTORVL 500 kV	4	New Line	$126	6	NV, CA

DC Greenfield Portfolio

The DC Greenfield Portfolio introduces a network of HVDC (High Voltage Direct Current) lines across the WECC system, supplemented by some AC upgrades to facilitate power transfer to and from the DC network. This portfolio aims to capitalize on the efficiency of HVDC technology for long-distance power transfer.

This portfolio includes approximately 5783 miles of new HVDC lines, 890 mile of new AC lines, 3,531 miles of reconductoring, and 3,805 miles of co-located upgrades, totaling 14,008 miles of enhancements. The capital cost of this portfolio is $72.7 billion. The DC Greenfield Portfolio is particularly suited for connecting remote renewable energy sources to urban load centers efficiently.

Figure 34: DC Greenfield Portfolio Summary

Operational Performance in 2045	
Annual curtailment (%)	21.5%
Average energy price (LMP)	$25.6
US Clean energy penetration (%)	94.2%
US CO_2 reduction from Ref Case (%)	21%
Transmission congestion cost ($M)	$3,081
Branches with > $50M of Congestion	17

Technical Details	
Total Length (mi.)	14,008
Reconductoring miles	3,531
Co-located miles	3,805
New build miles	890
HVDC miles	5,783
Advanced conductor miles	0
New corridors land use (acres)	198,370
230-kV miles	2,137
345-kV miles	2,106
500-kV miles	9,765

Portfolio Costs & Benefits (present value)	
Total Cost ($M)	$182,522
Total Benefit ($M)	$253,365
Net Benefit ($M)	$70,843
Benefit-Cost Ratio	1.39

DC Greenfield Portfolio

The following list highlights significant greenfield transmission corridors identified in the HVDC Overlay Portfolio. Again, these lines are provided on an information basis to demonstrate the type of transmission infrastructure included in the portfolio.

Figure 35: Greenfield Transmission Corridors >200mi or Between Two States in the HVDC Overlay Portfolio

Corridor Name	Num of Upgraded Circuits	Upgrade Types	Corridor Cost ($M)	Corridor Length (miles)	Region
PINAL C - AEOLUS 500 kV	2	New HVDC Line	$2,295	419.4	WY, AZ
GARRISON - OSTRNDER 500 kV	2	New HVDC Line	$1,741	290.2	MT, WA
MIDPOINT - AEOLUS 500 kV	2	New HVDC Line	$1,227	258.5	WY, ID
MIDPOINT - MALIN 500 kV	2	New HVDC Line	$1,076	229.9	OR, ID
PINAL C - CLINECORNER 345 kV	2	New HVDC Line	$1,201	229.9	NM, AZ
TESLA - MIRALOMA 500 kV	2	New HVDC Line	$944	212.5	CA
MIRALOMA - PINAL C 500 kV	2	New HVDC Line	$949	211.3	AZ, CA
CLOVER - AEOLUS 500 kV	2	New HVDC Line	$1,053	202.0	WY, UT
MIGUEL - PINAL C 500 kV	2	New HVDC Line	$859	198.8	AZ, CA
H ALLEN - CLOVER 500 kV	2	New HVDC Line	$814	187.0	UT, NV
TESLA - MALIN 500 kV	2	New HVDC Line	$902	179.0	CA, OR
GARRISON - MIDPOINT 500 kV	2	New HVDC Line	$864	167.2	MT, ID
OSTRNDER - MALIN 500 kV	2	New HVDC Line	$925	151.0	WA, OR
MOSSLAND - DIABLO 500 kV	1	New HVDC Line	$1,600	140.5	CA
COMANCHE - CLINECORNER 345 kV	2	New HVDC Line	$714	137.3	CO, NM
H ALLEN - MIRALOMA 500 kV	2	New HVDC Line	$683	123.0	NV, CA

Corridor Name	Num of Upgraded Circuits	Upgrade Types	Corridor Cost ($M)	Corridor Length (miles)	Region
ARCHER - AEOLUS 500 kV	2	New HVDC Line	$310	71.5	CO, WY
NAVAJO - CRYSTAL 500 kV	1	New Line	$1,340	231.3	AZ, NV
COMANCHE - PONCHA - MONTROSE 345 kV	1	New Line	$1,151	210.6	CO
ELDORDO - LUGO 500 kV	1	New Line	$1,045	182.5	NV, CA
CRAIG - AEOLUS 500 kV	1	New Line	$825	136.9	CO, WY
STORY - WAYNE CHILD 345 kV	1	New Line	$420	104.5	CO, WY
MALIN - ROUND MT 500 kV	1	New Line	$855	100.0	OR, CA
N.GILA - IMPRLVLY 500 kV	1	New Line	$338	74.3	AZ, CA
ADELANTO - VICTORVL 500 kV	1	New Line	$32	6.4	NV, CA

Advanced Conductor Portfolio

The Advanced Conductor Portfolio employs new high-capacity transmission conductors within existing transmission corridors, along with traditional conductors where advanced options are not feasible. This portfolio aims to maximize the capacity of existing infrastructure using advanced technologies.

The Advanced Conductor Portfolio comprises approximately 6,397 miles of reconductoring, 7,554 miles of co-located upgrades, and 2,362 miles of new builds, totaling 16,313 miles. The cost of this portfolio is $78.5 billion. This portfolio is designed to provide a significant boost in transmission capacity while minimizing environmental impact by utilizing existing corridors.

Figure 36: Advanced Conductor Portfolio Summary

Operational Performance in 2045	
Annual curtailment (%)	22%
Average energy price (LMP)	$21.6
US Clean energy penetration (%)	94.4%
US CO_2 reduction from Ref Case (%)	23%
Transmission congestion cost ($M)	$2,094
Branches with > $50M of Congestion	7

Technical Details	
Total Length (mi.)	16,313
Reconductoring miles	6,397
Co-located miles	7,554
New build miles	2,222
HVDC miles	140
Advanced conductor miles	4,681
New corridors land use (acres)	68,362
230-kV miles	2,419
345-kV miles	3,198
500-kV miles	10,696

Portfolio Costs & Benefits (present value)	
Total Cost ($M)	$196,958
Total Benefit ($M)	$276,527
Net Benefit ($M)	$79,569
Benefit-Cost Ratio	1.40

Advanced Conductor Portfolio

The following list highlights significant greenfield transmission corridors identified in the Advanced Conductor Portfolio.

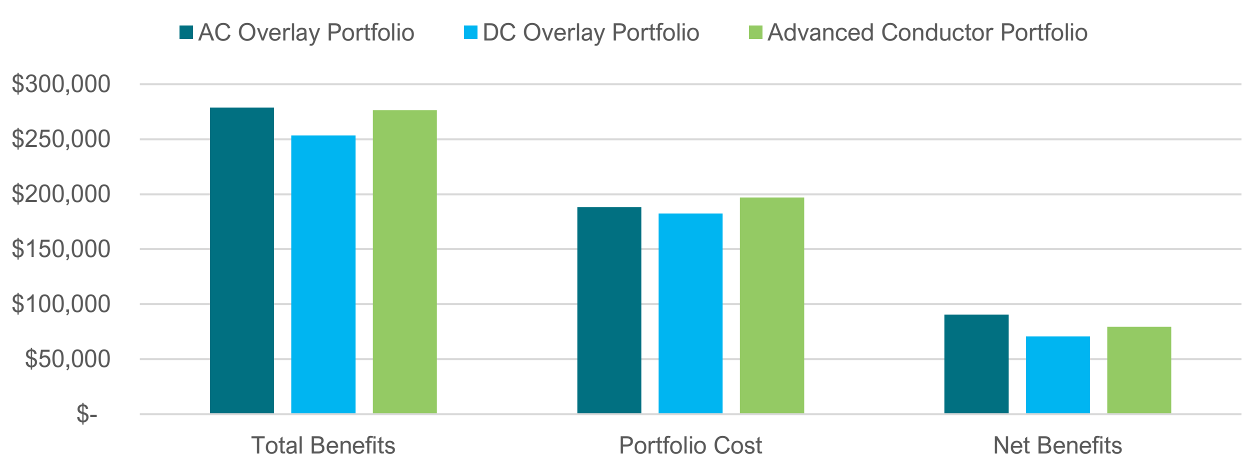
Figure 37: Greenfield Transmission Corridors >200 mi or Between Two States in the Advanced Conductor Portfolio

Corridor Name	Num of Upgraded Circuits	Upgrade Types	Corridor Cost ($M)	Corridor Length (miles)	Region
COMANCHE - PONCHA - MONTROSE 345 kV	1	Adv conductor New Line	$1,265.97	210.61	CO
WSPIRIT - ARROYO - PINAL_C 500 kV	1	New Line	$2,591.94	493.02	NM, AZ
GARRISON - BELL BPA 500 kV	1	New Line	$1,762.55	288.10	WA
MEAD - PERKINS 500 kV	1	New Line	$1,430.85	253.56	AZ
NAVAJO - CRYSTAL 500 kV	2	New Line	$2,679.63	231.35	AZ, NV
BONANZA - CLOVER 500 kV	2	New Line	$2,336.86	183.61	CO, UT
ELDORDO - LUGO 500 kV	1	New Line	$1,044.96	182.47	NV, CA
MARKETPL - ADELANTO 500 kV	1	New Line	$999.71	173.06	NV, CA
INTERMT - GONDER 230 kV	1	New Line	$478.94	146.37	UT, NV
MALIN - ROUND MT 500 kV	2	New Line	$1,710.66	100.00	OR, CA
N.GILA - IMPRLVLY 500 kV	3	New Line	$1,013.31	74.35	AZ, CA
ADELANTO - TOLUCA 500 kV	2	New Line	$442.06	74.24	NV, CA

Benefit-Cost Analysis

Each transmission portfolio identified in the Connected West study was assessed using a common benefit-cost analysis framework. In this framework total portfolio benefits were calculated, relative to the study Reference Case, and were compared to the total portfolio cost. Both benefits and costs of transmission portfolios were calculated as a 40-year present value for comparison.

Figure 38: Portfolio Economic Performance (40-year Present Values in $2023)



All transmission portfolios exhibit comparable economic performance, with no outliers in terms of net benefits or benefit-cost ratios. The two AC portfolios (AC Greenfield and Advanced Conductor) cost more than the DC portfolio but deliver slightly higher benefits – approximately 10% greater. The results are sensitive to various inputs, including financial assumptions, per-unit cost assumptions of transmission, and benefit quantification factors.

Since no single technology dominates in terms of economic efficiency, the study suggests that a blend of transmission technologies could be the most efficient expansion strategy. This mixed approach would leverage the strengths of each technology, ensuring a balanced and comprehensive enhancement of the Western grid's capacity, reliability, and efficiency.

Portfolio Comparisons

The figure below offers a high-level comparison of some key portfolio metrics.

Figure 39: Summary of Portfolios and Reference Cases

Metric	2032 WECC ADS	2045 Connected West Reference	2045 AC Greenfield Portfolio	2045 DC Greenfield Portfolio	20454 Advanced Conductor Portfolio
Meets Reliability Goals of Study	Not Assessed	No	Yes	Yes	Yes
US Wind and Solar Annual Curtailment (%)	3%	26.4%	22%	21.5%	22%
Average Energy Price, LMP ($/MWh)	$29.7	$27	$23	$25.6	$21.6
US Clean Energy (%)	67.6%	92%	94.4%	94.2%	94.4%
Transmission Congestion Cost ($M)	$1,299	$6,574	$2,277	$3,081	$2,094
US CO_2 Reduction (From Reference)	N/A	N/A	23%	21%	23%
Total Portfolio Costs ($M, present value)	N/A	N/A	$188,366	$182,522	$198,958
Total Portfolio Benefits ($M, present value)	N/A	N/A	$278,851	$253,365	$276,527
Net Benefit ($M, present value)	N/A	N/A	$90,486	$70,843	$79,569
Benefit-Cost Ratio	N/A	N/A	1.48	1.39	1.40

Importantly, the first row highlights that the 2045 Connected West Reference Case did not have sufficient transmission for this to be considered a reliable future, making direct comparisons with scenarios that include transmission expansion challenging. Regardless, curtailment increases drastically from the 2032 ADS to the 2045 Connected West studies, with curtailment bottoming out around 22% after grid expansion. Western US clean energy penetration reaches nearly 95% in the studies with the transmission portfolios, a significant increase from the 2032 ADS. Additionally, the study shows substantial reductions in transmission congestion costs across all portfolios, with the AC Greenfield portfolio achieving the lowest congestion costs. Furthermore, energy prices decrease notably, and both the AC Greenfield and Advanced Conductor portfolios result in higher net benefits and benefit-cost ratios compared to the DC Greenfield portfolio.

Greenfield Routing Sensitivities

Montara Mountain Energy conducted sensitivity analyses to explore how increased consideration of environmental and conservation factors in line routing impacts new build projects in the Reference Case transmission portfolios. This analysis focused specifically on greenfield transmission lines, which represent only a portion of the transmission solutions identified in the study's portfolios. Sensitivities were performed to assess the potential effects on the AC Greenfield and HVDC Greenfield portfolios, with an emphasis on avoiding protected areas, environmentally sensitive zones, tribal lands, and regions with high conservation value.

The sensitivity results indicate that in some cases, avoiding environmentally or culturally sensitive areas does not significantly impact the total transmission line miles or costs within a portfolio. For the AC Greenfield portfolio, prioritizing impact avoidance led to a modest increase in both total costs and line miles, estimated at just 1-2%. However, for the HVDC Greenfield portfolio, the impact was more pronounced, with total portfolio costs increasing by 4-13% and line miles increasing by 18-22%. This suggests that while environmental and cultural considerations are crucial, they may have varying effects depending on the transmission technology and the specific characteristics of each portfolio.

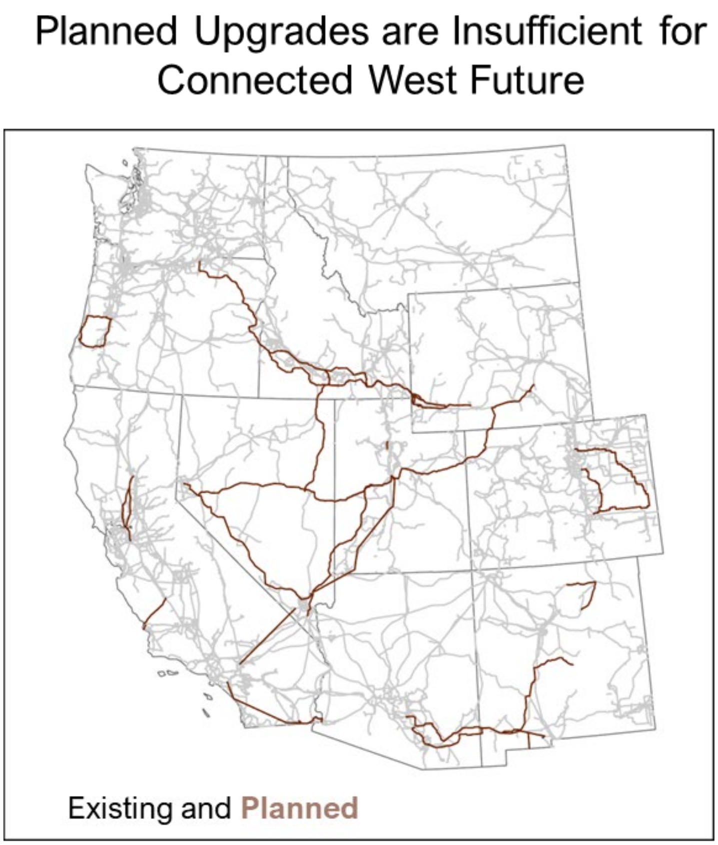
Answers to Key Questions

This section synthesizes the study's results, addressing several key questions related to the capabilities of planned projects, the remaining transmission gaps, the prioritization of geographic corridors, and the comparative effectiveness of different transmission technologies.

Capabilities of Projected Transmission: How far do planned and anticipated transmission projects take the Western grid towards meeting 2045 transmission needs under a high electrification and decarbonization future?

The planned and anticipated projects included in the 2045 Reference Case represent 5,900 line miles of new transmission with total capital costs of approximately $30 billion. Despite this significant investment, nearly the entire Western system experiences severe economic congestion, totaling more than $6 billion annually—a figure about four times greater than what is forecasted for the 10-year horizon. Transmission systems in rural areas of Montana, Colorado, and New Mexico are unable to support the export of power from generation-rich areas, leading to significant reliability-driven outages. Net-zero emissions by 2050 are not achievable under the current plans due to significant renewable curtailments, totaling approximately 27% of annual renewable generation, which is 36 times greater than what is planned for in the 10-year horizon. **These findings indicate that the high-voltage transmission upgrades assumed in the study are insufficient for an electrified and highly decarbonized 20-year future, underscoring the need for additional transmission investment.**

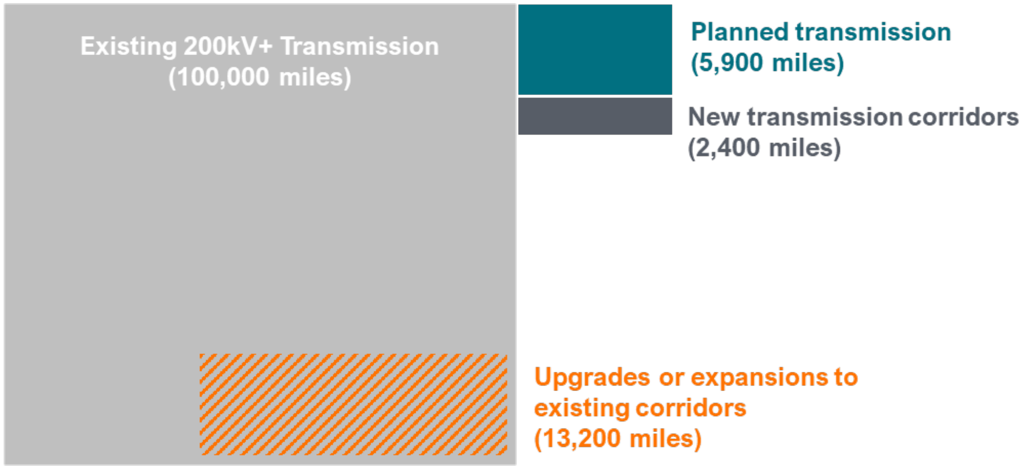
Figure 40: Planned Upgrades Assumed in Study are Not Sufficient



Transmission Gaps: If the planned projects do not fully meet the 2045 needs, what is the remaining transmission gap in terms of investment ($) and additional transmission capacity (MW)?

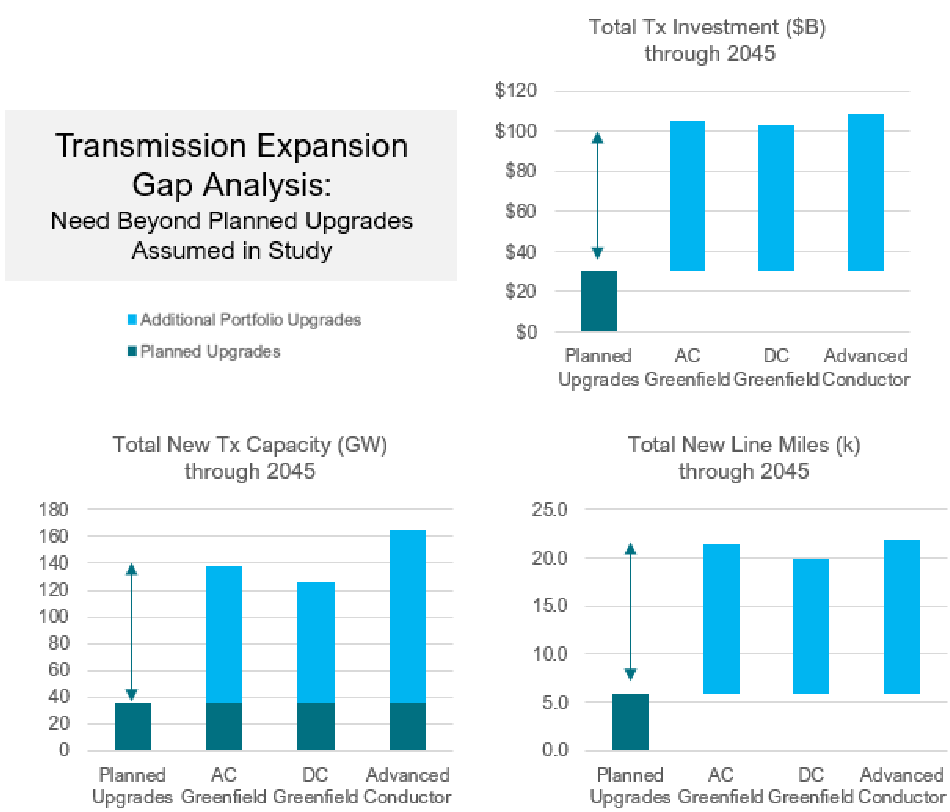
To fully meet the future needs of the Western grid, approximately $75 billion of additional high-voltage transmission investment is required, representing an investment above and beyond the $30 billion of planned upgrades already assumed in this study. This transmission gap can also be quantified as an incremental need for roughly 15,000 miles of new high-voltage transmission upgrades and approximately 110 GW of additional transmission capacity. With around 100,000 miles of existing 200-kV and higher transmission in the West today, this means that the Connected West AC Portfolio would rebuild 13% of these lines and add an additional 2,400 miles (2-3%).

Figure 41: Connected West Transmission Gap Context (Transmission >200 kV only)



Note: Transmission solutions identified in Connected West portfolios focus on high-voltage and inter-regional transmission needs. Line-mile estimates do not capture all transmission necessary to facilitate the future envisioned in this study.

Figure 42: Gap Analysis Showing Transmission Need Above and Beyond Planned Investments



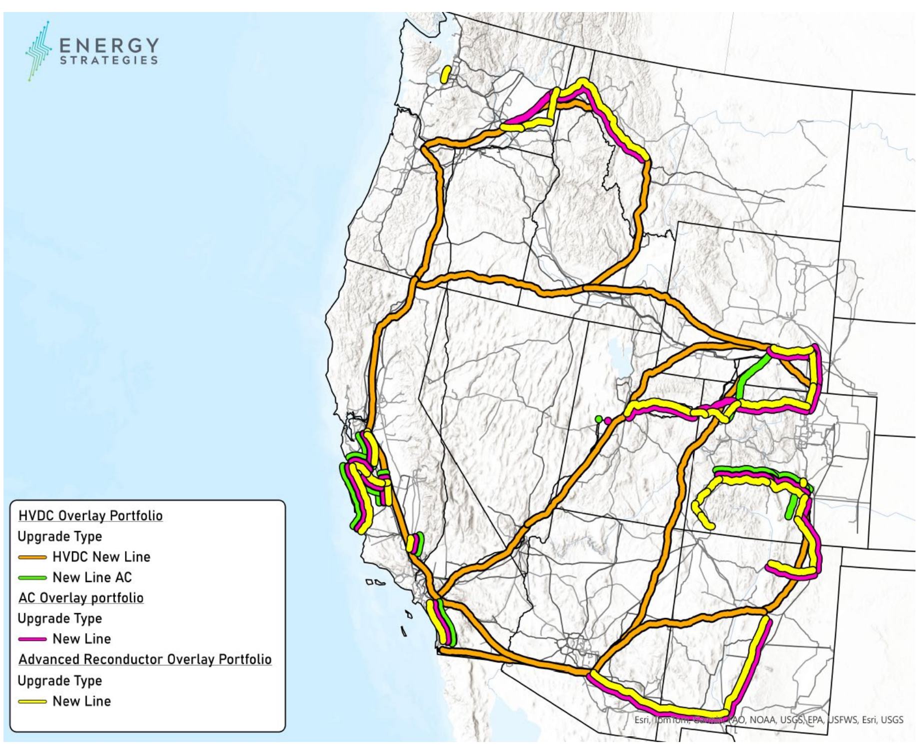
These gaps highlight the necessity for further grid investment to ensure a reliable, efficient, and decarbonized future grid.

Geographic Corridor Prioritization: Based on the transmission portfolios identified for the Connect West future, what geographic corridors should be prioritized for the next tranche of transmission investments over the coming 20 years?

Given the extensive scope of the transmission portfolios identified in the Connected West study, prioritizing or "ranking" greenfield development corridors is challenging due to the network effects and scale of transmission required in each portfolio. Many new physical corridors are necessary, each playing a crucial role in achieving the desired technical outcomes and benefits for the grid. When combined with reconductoring and co-located lines, these corridors host the transmission capacity needed to enhance grid reliability and efficiency.

However, while the upgrade scope in each portfolio is considerable, there are relatively few areas where new greenfield development is essential. These areas include corridors between Colorado and its neighbors, Arizona-New Mexico, Montana to the Northwest/Mid-C area, and California in-state 500 kV upgrades. Notably, the HVDC Portfolio is an exception, requiring significant new greenfield transmission development across multiple corridors. This analysis and need for these corridors (or others) will evolve as additional diligence on the feasibility of reconductoring or co-located projects included in the portfolios is conducted, potentially impacting the prioritization and necessity of certain greenfield developments.

Figure 43: Greenfield Development Corridors Across Portfolios



Portfolio Comparisons: How do new greenfield corridors compare with upgrades to existing lines? What portfolios of transmission technologies appear to make the most sense to achieve the West's long-term goals?

When comparing new greenfield corridors with upgrades to existing lines, the Connected West study suggests that the optimal 20-year transmission expansion strategy likely involves a blend of approaches. Each transmission technology has unique strengths and weaknesses, making a mixed strategy the most sensible for achieving the West's long-term decarbonization and electrification goals. Reconductoring upgrades emerge as the most common and cost-effective strategy, representing 37% of the line miles in the portfolios. This approach, which involves upgrading existing lines to carry more power, should be heavily relied upon as a first option for addressing grid reliability and inefficiencies.

Co-locating upgrades, which involve expanding existing rights-of-way or rebuilding lines in existing corridors, account for nearly 50% of the line miles in both the AC Greenfield and Advanced Conductor portfolios. This strategy minimizes environmental impacts by using or expanding current corridors, thus reducing the need for entirely new developments. On the other hand, greenfield AC upgrades are crucial for some regions but make up only about 16% of line miles, as they require entirely new rights-of-way. Advanced conductors, although offering the highest incremental capacity, are limited to shorter distances due to cost and efficiency issues over long lines.

HVDC solutions present an efficient way to transfer power in large amounts across great distances with fewer losses, making them ideal for connecting remote energy sources to urban load centers. However, HVDC lines often require new rights-of-way due to their unique infrastructure needs, which can make them less suitable in areas where existing corridors suffice.

In summary, the study suggests that a comprehensive transmission development strategy will likely need to combine all available technologies: reconductoring and co-locating upgrades should form the backbone of expansion efforts, with selective use of advanced conductors and HVDC solutions for specific high-capacity, long-distance needs. This "all-of-the-above" approach ensures that each area's unique requirements are addressed effectively while balancing economic, environmental, and technical considerations. The study indicates that adopting a multi-faceted approach will be critical to supporting the West's aggressive clean energy and electrification targets.

Additional Considerations

When interpreting the findings of Connected West, several caveats and considerations should be kept in mind by readers to fully understand the context and limitations of the analysis.

- **Limited scope of transmission additions:** The study does not identify all necessary transmission additions for the future considered and may therefore understate the transmission investment required to achieve low carbon and high electrification outcomes by 2045. For example, it does not forecast lines needed to address local load growth, connection of generators to the grid (tie lines or substation upgrades), or lower voltage upgrades.

- **Single scenario focus:** Connected West focuses on a single future scenario, with results being a product of the assumptions made and methods adopted. Transmission needs are sensitive to resource siting assumptions, meaning the results could change materially if a different resource mix is considered or if resources are sited in new locations. The
- **Potential changes in baseline transmission forecast:** Additional transmission not included in the 2045 Reference Case may be constructed, which could lead to the study overstating the need for transmission in certain areas. Conversely, if certain assumed projects are *not* constructed, the need for transmission would be greater than forecasted.
- **Evolving industry:** Industry views on acceptable levels of curtailment, LMPs, and congestion may evolve between now and 2045. The study suggests a potential paradigm shift in how we operate and plan the system if highly electrified low carbon grids come to pass.
- **Market expansion:** The study assumes a highly integrated West-wide market that is optimally dispatched, which may lead to an understatement of transmission needs if such a market does not materialize.
- **Local operational and planning factors:** While the results are based on sophisticated grid analyses and forecasts, local operational and planning expertise not accounted for could impact the feasibility or appropriateness of the transmission solutions identified, or their underlying need. The study relies heavily on reconductoring of transmission lines, and outside of the data available and their regional experience, the authors did not have local insight into challenges associated with reconductoring a particular line or repurposing a particular right of way.

Readers are encouraged to consider these caveats and maintain a holistic view when interpreting the study's findings and recommendations. The insights provided are intended to guide strategic planning and inform other planning processes, but they should be supplemented with ongoing assessments and adaptive strategies to address the evolving landscape of the Western grid.

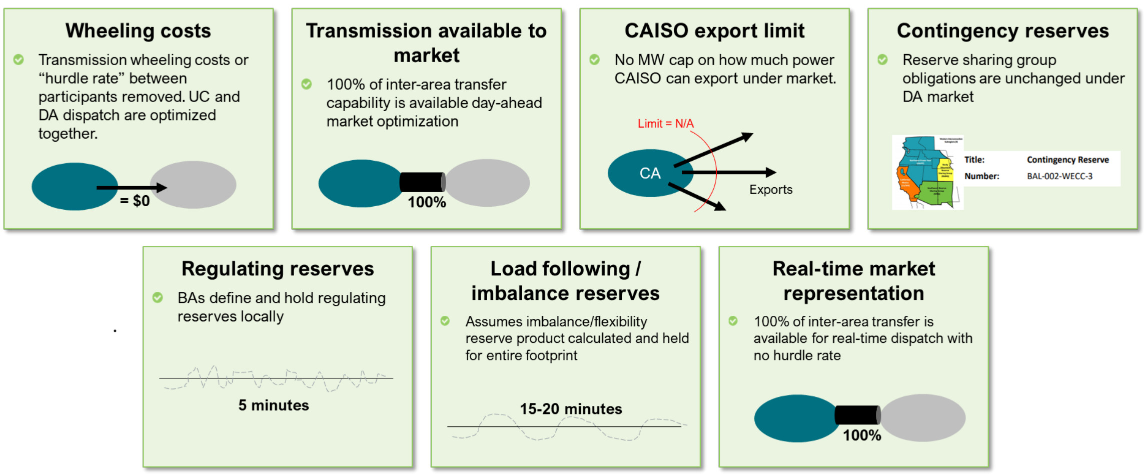
6. Appendices

Other Reference Case Assumptions

Market Modeling

The 2045 Reference Case production cost model made several key assumptions around the operations of a west-wide day-ahead market that is assumed to be active by 2045. A number of these assumptions are summarized below.

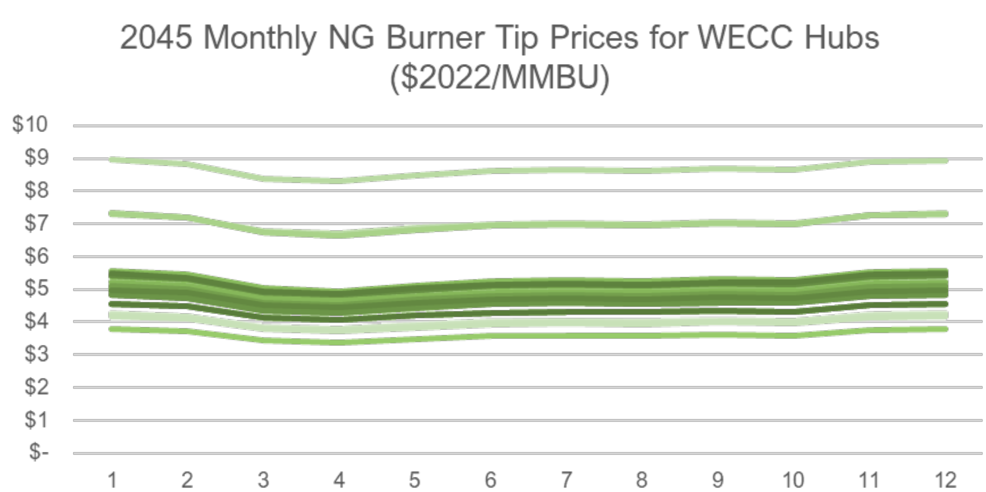
Figure 44: Summary of Market Modeling Assumptions



Fuel Prices

Fuel prices were updated to 2045 values for natural gas, oil, and uranium-fueled generators. Natural gas prices were sourced from the CEC's 2023 Preliminary IEPR Natural Gas prices. Oil and Uranium fuel prices were sourced from the 2023 EIA Annual Energy Outlook 2023.

Figure 45: Natural Gas Price Assumptions

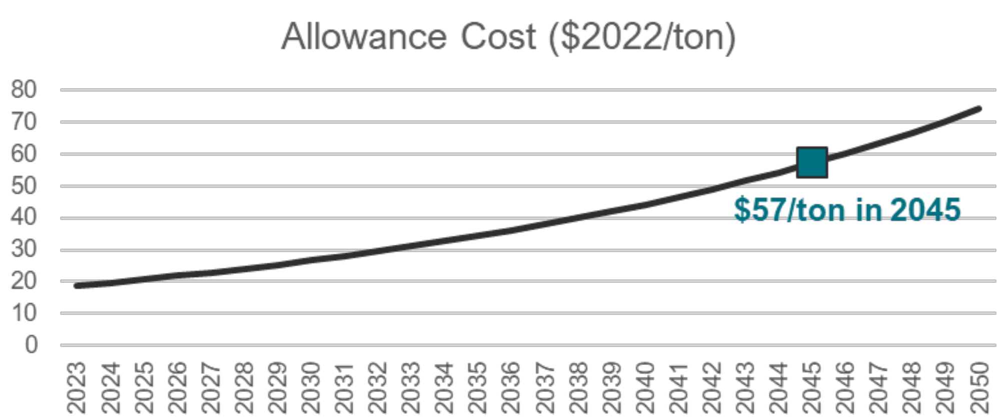


Carbon Price

This study assumes that California, Oregon, and Washington benefit from a linked carbon market by 2045 where emitting generators within these states are charged a $/ton penalty that emulates the cost of purchasing an allowance and imbedding that cost in energy bid prices. In addition, imports into these three states (but not between the states) are charge a $/MWh carbon adder import charge, similar to the AB-32 program in California today, to prevent leakage.

The carbon price (allowance cost) for the Connected West 2045 Reference Case was sourced from the CEC's 2022 IEPR and is assumed to be $57/ton in 2045.

Figure 46: Carbon Price Assumed for Emissions Reduction Benefit



Financial Assumptions

All dollar figures in this report are presented as real dollars with a 2023 base year unless specified otherwise.

Transmission Additions to Reference Case

The following transmission projects were assumed in the 2045 Reference Case.

Figure 47: Transmission Additions Assumed Built in Connected West 2045 Reference Case

Project Name	Description	Length (miles)	Cost* ($M)	Capacity (MW)	Estimated Completion**
Boardman to Hemmingway (B2H)	500-kV line from Longhorn (Boardman) to Hemingway	290	$1,200	1,000	2026
CAISO 22-23 TPP	~46 transmission upgrades of varying size	460	$7,300	N/A	2034 or sooner
CAISO OSW upgrades	Conceptual upgrades from CAISO 20-Year Outlook (500 kV)	220	$2,400	5,000	2044 or sooner
Oregon OSW upgrades	Conceptual upgrades from NorthernGrid Economic Study Request for Offshore Wind in Oregon (500 kV loop	373	$820	4,000	2032

Project Name	Description	Length (miles)	Cost* ($M)	Capacity (MW)	Estimated Completion**
	and upgrades to 115 and 230 kV system)				
Colorado Power Pathway	Double-circuit 345-kV transmission connecting Denver front range to NE, E, and SE Colorado (5 segments)	610	$2,000	3,500	2027
Crosstie Project	500-kV line from Clover to Robinson Summit	214	$750	1,500	2027
Gateway South	500-kV line from Aeolus to Mona/Clover	416	$2,500	2,000	2024
Gateway West (all segments)	Includes all remaining 500-kV segments west of Bridger/Anticline (D3 & E)	500	$2,880	2,000	2028
Greenlink West and North	525-kV loop from Robinson Summit to Reno area to Las Vegas	700	$2,420	2,800	2028
Lucky Corridor - Mora Line	345/115-kV line between Springer and Arriba substations	115	$83	180	2025
Lucky Corridor - Vista Trail Line	345-kV line between Springer and Taos substations	65	$800	850	2027
Southline	345-kV line between NM and AZ	280		1000	2028
SunZia (Line 1)	525 kV HVDC line from eastern NM to Pinal Central (AZ)	550	$3,000	3,000	2026
SWIP North	500-kV line between Midpoint and Robinson Summit	285	$1,090	2,070	2027
TransWest Express	HVDC line from Wyoming to Utah to Nevada with AC component terminating at Eldorado 500-kV	732	$3,000	3,000	2027
TenWest Link	500-kV line between Delaney and Colorado River substations	125	$400	3,200	2024

Additional Considerations of Transmission Portfolios

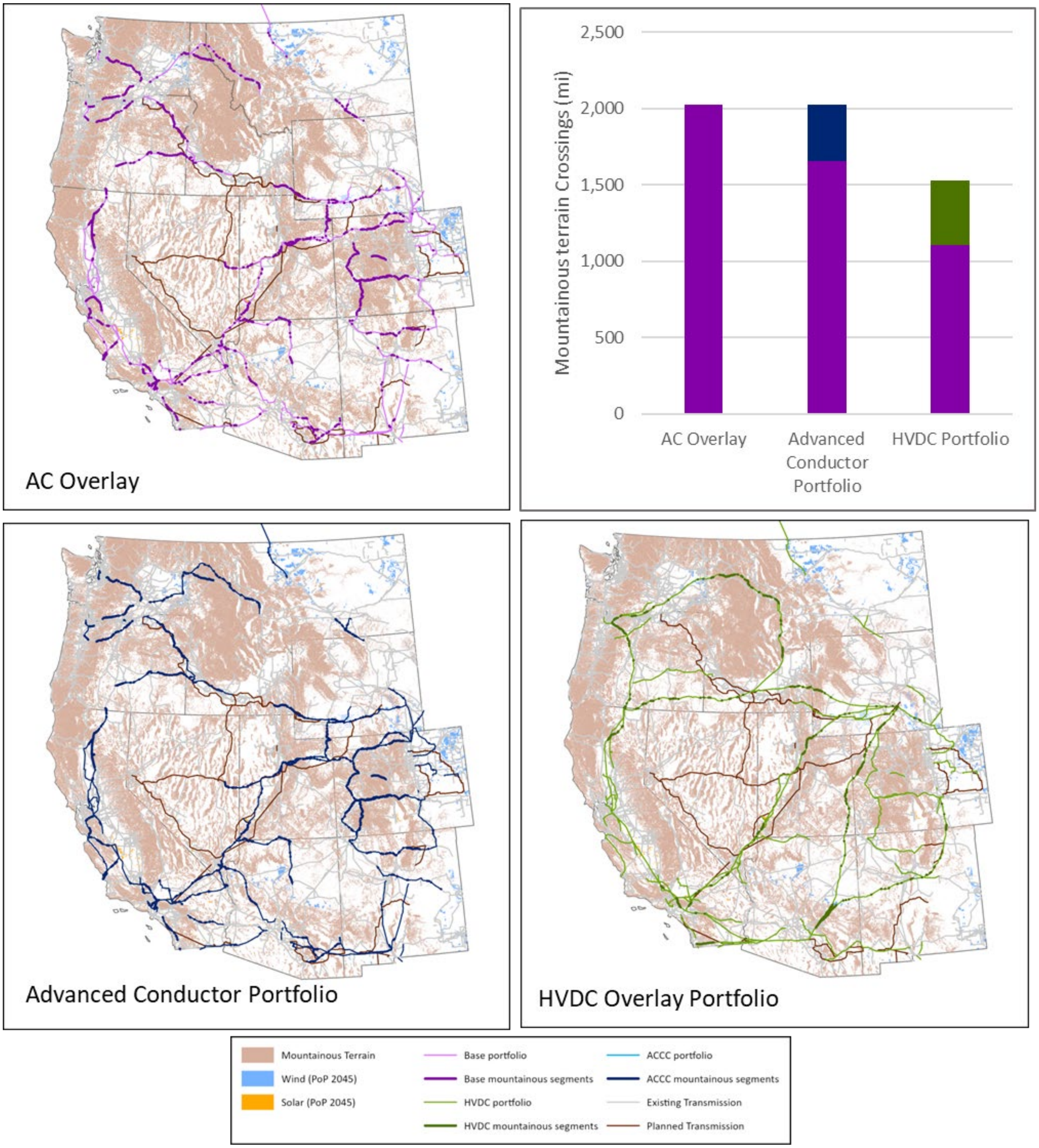
Non-monetary considerations of transmission portfolios were analyzed using GIS data in the routing process by Montara Mountain Energy.

Mountainous Terrain

All portfolios require significant distances of transmission to be routed through mountainous terrain. The AC portfolio includes transmission in mountainous terrain scattered throughout most states.

Advanced Conductor lines are mostly in Colorado. HVDC lines are primarily in Montana to Washington and eastern Arizona.

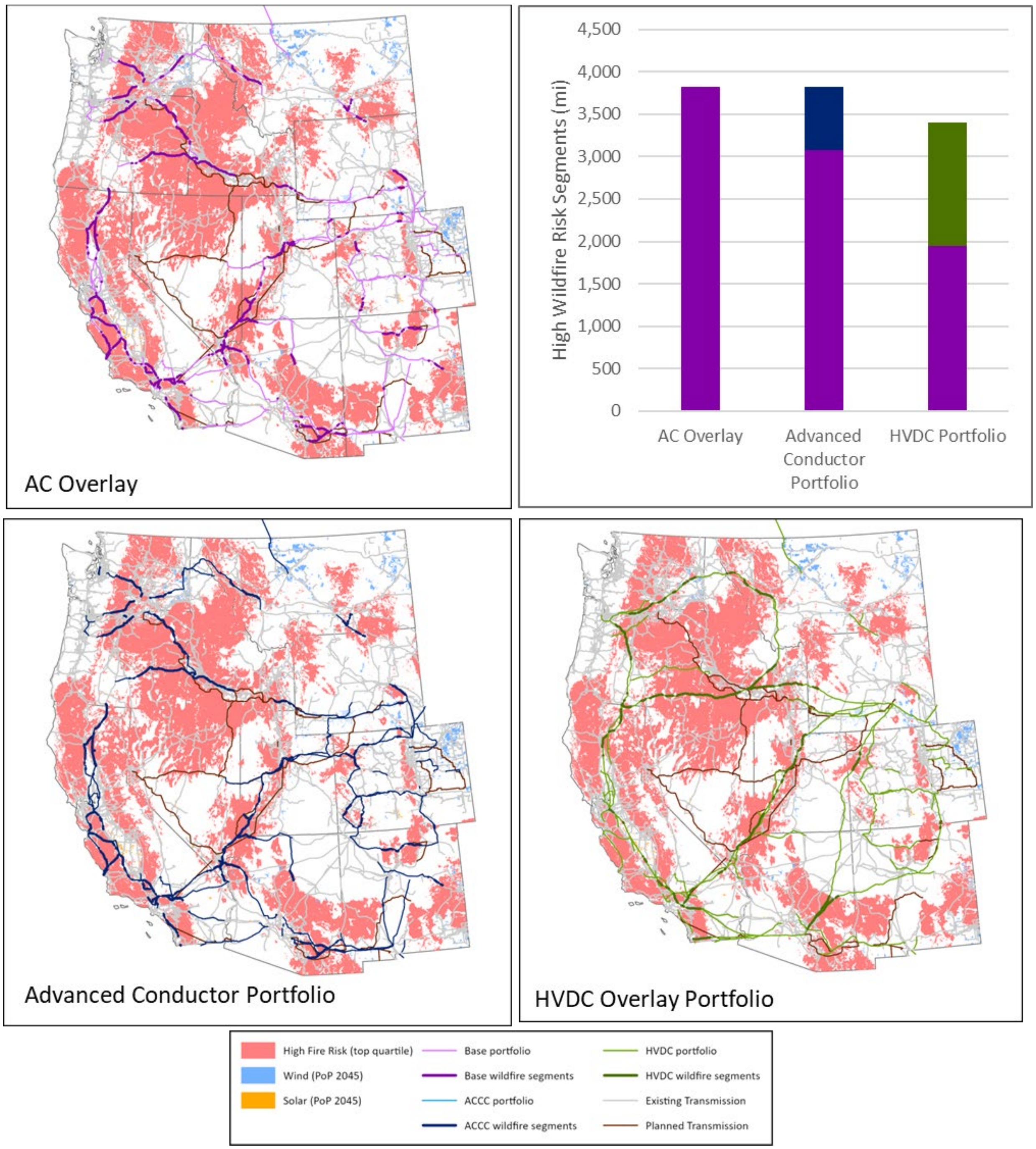
Figure 48: Transmission Portfolio Mountainous Terrain Maps & Line-Miles



High Wildfire Risk

All portfolios require significant distances of transmission to be routed through high wildfire-risk terrain. The AC and ACCC portfolios include transmission in high-fire-risk areas in Washington, Idaho, California, Southern Nevada, and Southern Arizona. HVDC lines are primarily in Oregon instead of Washington with additional hotspots in Utah and Arizona.

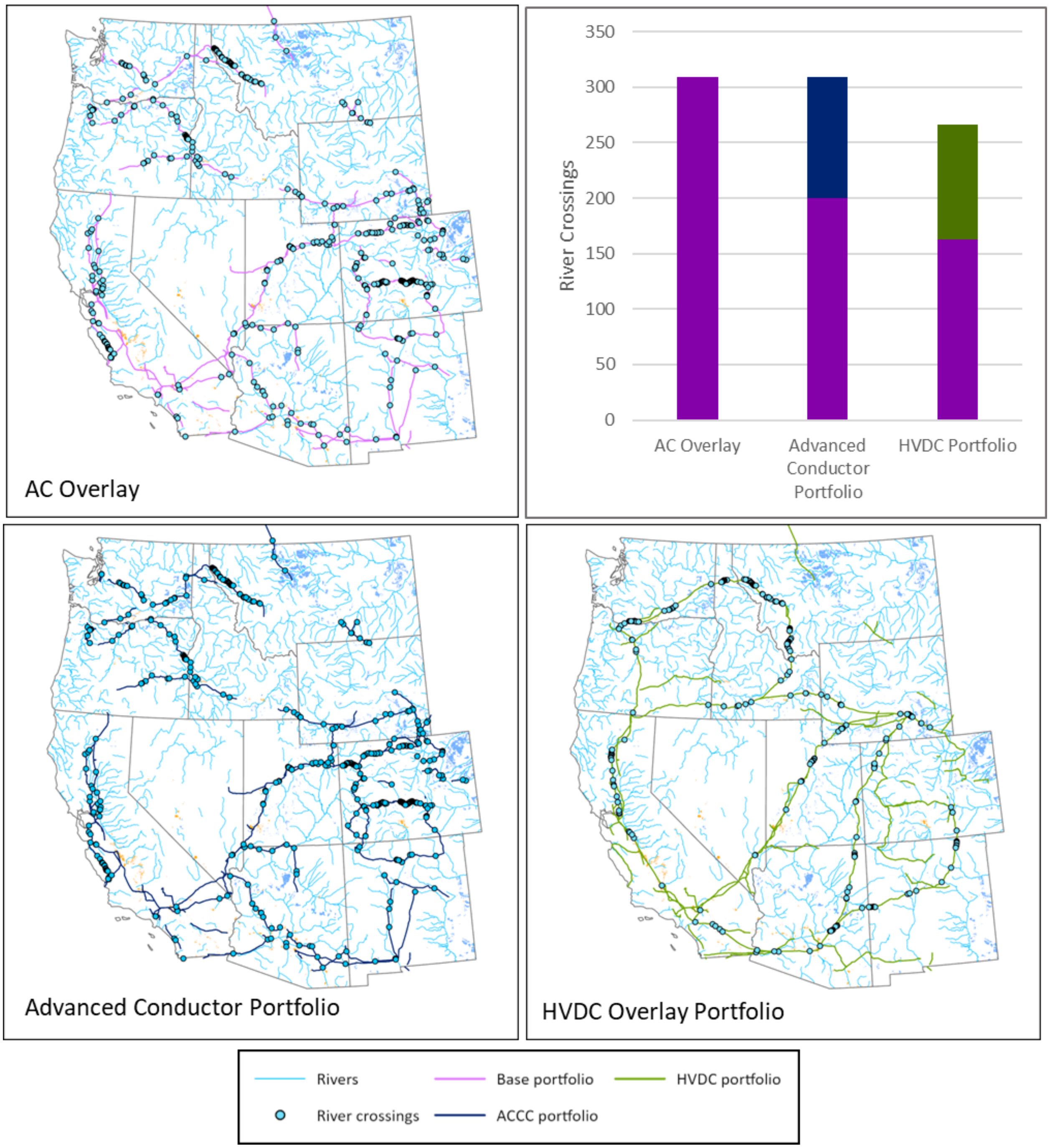
Figure 49: Transmission Portfolio Wildfire Risk Maps & Line-Miles



River Crossings

The AC overlay portfolio includes river crossings scattered throughout most states except Nevada. Advanced conductor lines primarily cross lines in Wyoming, Colorado, and Arizona. HVDC lines follow a similar pattern to the AC overlay portfolio.

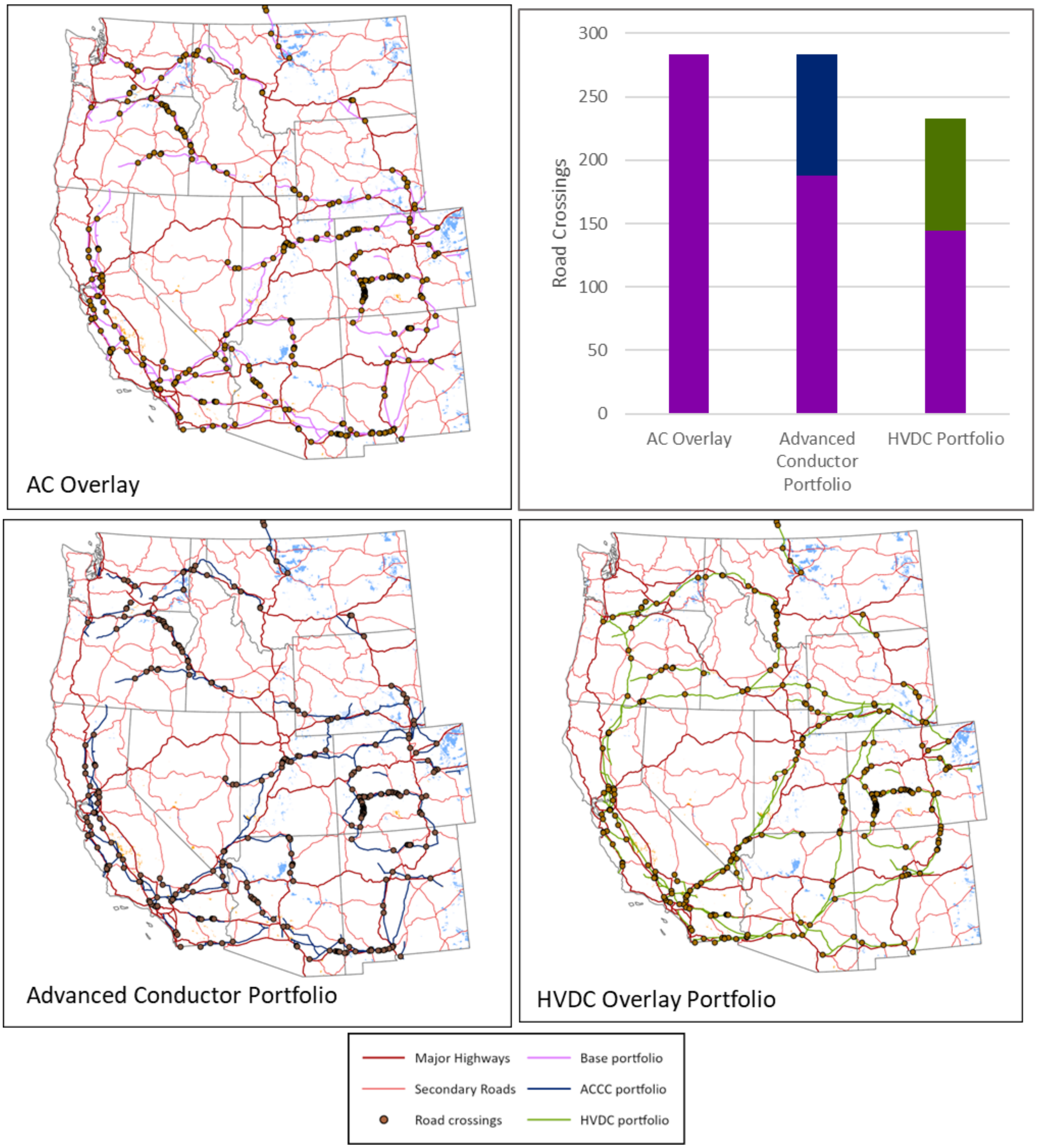
Figure 50: Transmission Portfolio River Crossings Maps & Line-Miles



Road Crossings

Road crossings largely follow the same trends as river crossings.

Figure 51: Transmission Portfolio Road Crossings Maps & Line-Miles



Comparison to Other Studies

Gridworks and GridLab compiled a comparison of Western planning studies, available below:

- https://www.westernpowerpool.org/private-media/documents/2024-01-25_Transmission_Studies_in_the_West.pdf

Datasets Used as Inputs to Cost Surface

"TIGER/Line Shapefile, 2020, Nation, U.S., 2020 Census Urban Area," May 12, 2024. https://catalog.data.gov/dataset/tiger-line-shapefile-2020-nation-u-s-2020-census-urban-area.

"USGS EROS Archive - Digital Elevation - Shuttle Radar Topography Mission (SRTM) 1 Arc-Second Global," July 30, 2018. https://doi.org//10.5066/F7PR7TFT.

Dewitz, J. "National Land Cover Database (NLCD) 2021 Products: U.S. Geological Survey Data Release," 2023. https://doi.org/10.5066/P9JZ7AO3.

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