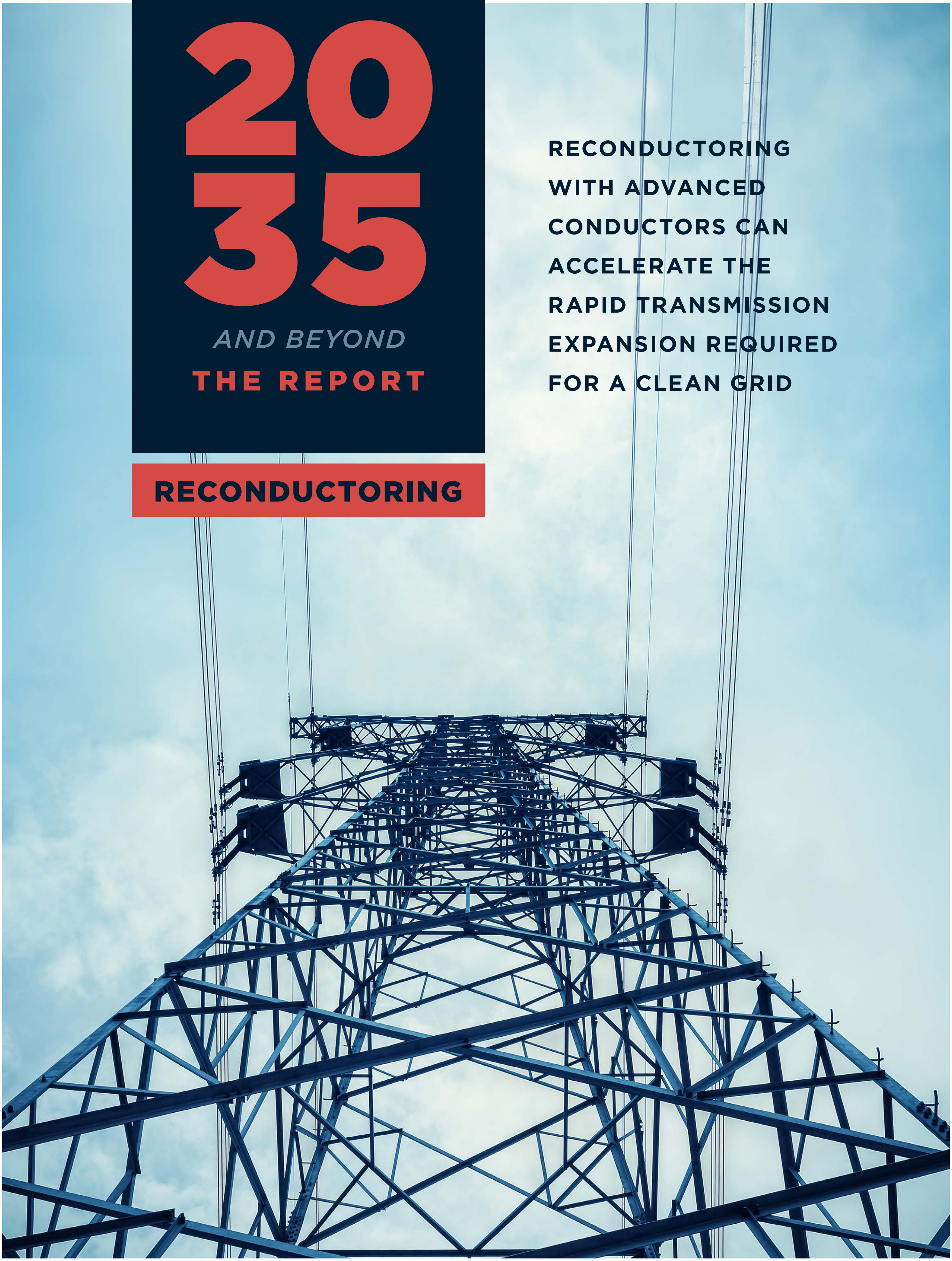
2035

AND BEYOND

THE REPORT

RECONDUCTORING

RECONDUCTORING WITH ADVANCED CONDUCTORS CAN ACCELERATE THE RAPID TRANSMISSION EXPANSION REQUIRED FOR A CLEAN GRID



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GridLab is an innovative non-profit that provides technical grid expertise to enhance policy decision-making and to ensure a rapid transition to a reliable, cost effective, and low carbon future.

CONTENTS

ACRONYMS

AC	Alternating Current
ACCC	Aluminum Conductor Composite Core
ACSR	Aluminum Conductor Steel Reinforced
ACSS	Aluminum Conductor Steel Supported
AECC	Aluminum Encapsulated Carbon Core
DC	Direct Current
DLR	Dynamic Line Rating
DOE	U.S. Department of Energy
ERCOT	Electric Reliability Council of Texas
EV	Electric Vehicle
FACTS	Flexible AC Transmission System
GET	Grid-Enhancing Technology
GW	Gigawatt
HTLS	High Temperature Low Sag
HVDC	High Voltage Direct Current
IRA	Inflation Reduction Act
ISO	Independent System Operator
kV	Kilovolt
LCOE	Levelized Cost of Electricity
MVA	Mega Volt-Ampere
MWh	Megawatt hour
N/A	Not Applicable
NREL	National Renewable Energy Laboratory
NTNS	National Transmission Needs Study (by the U.S. Department of Energy)
RE	Renewable Energy
ReEDS	Regional Energy Deployment System
REPEAT	Rapid Energy Policy Evaluation and Analysis Toolkit
ROW	Right(s)-of-way
SIL	Surge Impedance Loading
TSO	Transmission System Operator
TW	Terawatt
U.S.	United States

EXECUTIVE SUMMARY

Plummeting costs of clean energy and growing power demand from electrification, manufacturing, and data processing have made grid capacity one of the primary constraints in the energy transition. In the United States (U.S.), achieving the federal goal of 100% clean electricity by 2035 will require the massive build-out of not only clean energy but also transmission capacity — both within each of today's transmission planning regions and between regions as detailed in the recent Department of Energy National Transmission Needs Study. Far outpaced by the amount of new RE coming available, transmission capacity across the U.S. has grown only 1%/year over the past decade. Over 2 TW of available generation and storage resources today remain untapped, awaiting grid access in interconnection queues. Meanwhile, fast-growing electricity demand and the increasing frequency and severity of extreme weather outages are placing the grid under unprecedented strain. To relieve stress on the grid and avoid jeopardizing decarbonization goals, near-term action to increase transmission capacity is crucial.

Recent policy measures from the Federal Energy Regulatory Commission (FERC) have identified planning and interconnection policy reforms that will help grow transmission capacity over the long term. However, implementing these policies will take time, leaving significant gaps in the interim if not coupled with concurrent near-term strategies.

Advances in grid technologies have opened up new ways of increasing the transmission capacity of existing lines, that can be deployed in parallel to much-needed efforts to develop new lines. This report identifies one such option, reconductoring with advanced conductors in existing corridors, as particularly promising; explains the technology; and demonstrates its viability as an efficient, cost-effective, implementation-ready

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solution that is deployable to scale. When advanced conductors are used, reconductoring in existing rights-of-way (ROW) can substantially increase transmission capacity in the current grid, allowing clean energy to be more fully tapped during the years-longer period it takes to develop the new lines for long-term system needs. Building additional capacity into the existing system can unlock otherwise stranded clean energy, especially sources available near existing grid infrastructure, helping meet electricity demand and contributing to grid decarbonization.

This report combines the latest energy cost data with state-of-the-art grid modeling to quantify three key elements: the cost of reconductoring with advanced conductors; the associated gains in transmission capacity; and the associated contribution to meeting transmission needs by 2035. From these elements emerge the following key findings:

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1. Advanced conductors can up to double line capacity within existing rights-of-way (ROW).

While some technological solutions may offer greater transmission capacity increases in specific cases, reconductoring with advanced conductors offers the most significant and relatively unexplored opportunity to substantially increase transmission capacity, considering costs, permitting, and implementation speed. The vast majority of transmission lines in the U.S. are short (i.e., <50 miles) and thus most likely limited by the conductor's thermal capability. In these cases, reconductoring with advanced conductors, combined with marginal substation additions as needed (reactive power compensation, transformer replacements, relay and breaker upgrades, etc.), can up to double the power transfer capacity within an existing ROW. For the 2% of lines that are too long to benefit from reconductoring and compensation (i.e., >50 miles), sectionalization—i.e., the addition of new substation(s) with active and reactive power generation sources along the line—can help improve voltage and angular stability, allowing grid planners to reap the high-capacity benefits of advanced conductors.

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2. Reconductoring projects typically cost less than half the price of new lines for similar capacity increases.

By avoiding many of the costs involved in creating new ROW and building new structures, reconductoring projects typically cost less than half the price of new lines, across all voltage levels, for similar capacity increases. These findings are based on both bottom-up cost estimates and empirical project cost data from the U.S. and Europe.

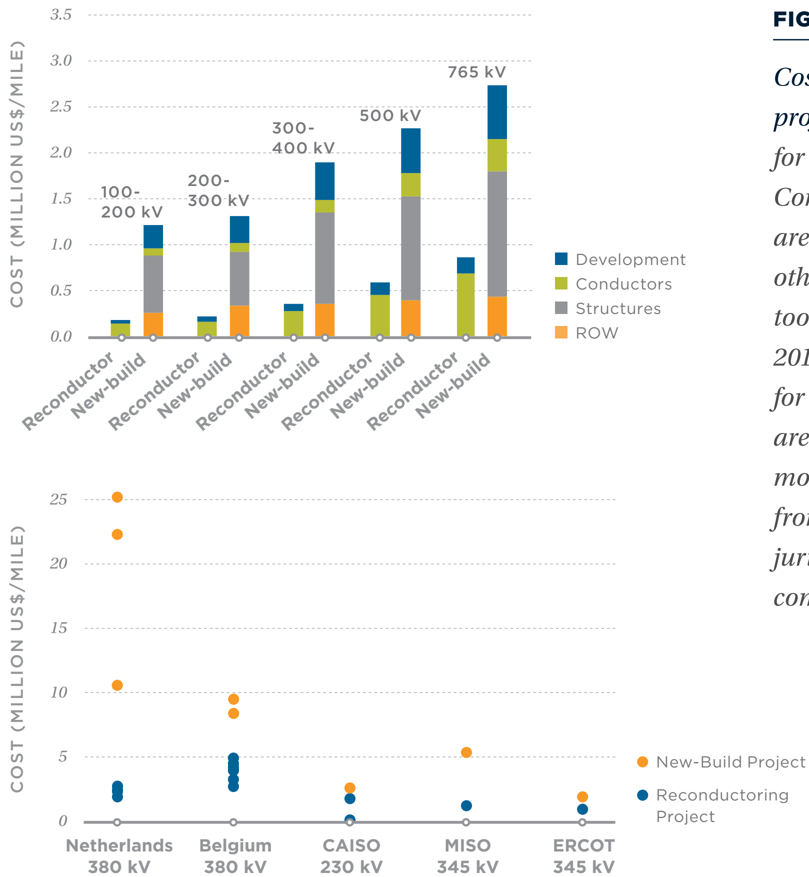


FIGURE ES-1.

Cost estimates for reconductoring projects vs new-build. Our estimates for new-build projects with Aluminum Conductor Steel Reinforced (ACSR) are in line with generic estimates from other popular transmission planning tools (Black & Veatch, 2014; NREL, 2013; MISO, 2022), falling within 20% for each voltage level. Terminal costs are accounted for separately in the modeling. Empirical project cost data from Europe and the U.S., presented by jurisdiction since cost definition and composition may vary.

3. Reconductoring enables nearly four times (4x) the interzonal transmission capacity expansion by 2035 compared to new-build alone, given restrictions on greenfield transmission build-out.

In the business-as-usual scenario without widespread reconductoring and with restricted new transmission build-out, only 16 TW-miles of interzonal transmission capacity are added by 2035, well short of the anticipated transmission capacity needed to support widespread decarbonization and electrification. However, if the build-out of new transmission lines remains at recent historical rates, large-scale reconductoring with advanced conductors can enable nearly four times the interzonal transmission capacity (i.e., across balancing areas of the Regional Energy Deployment System [ReEDS] model) by 2035 at only a 20% higher total transmission investment. These capacity additions through reconductoring account for nearly 90% of the new interzonal transmission capacity added in this scenario which reaches more than 90% clean electricity by 2035.

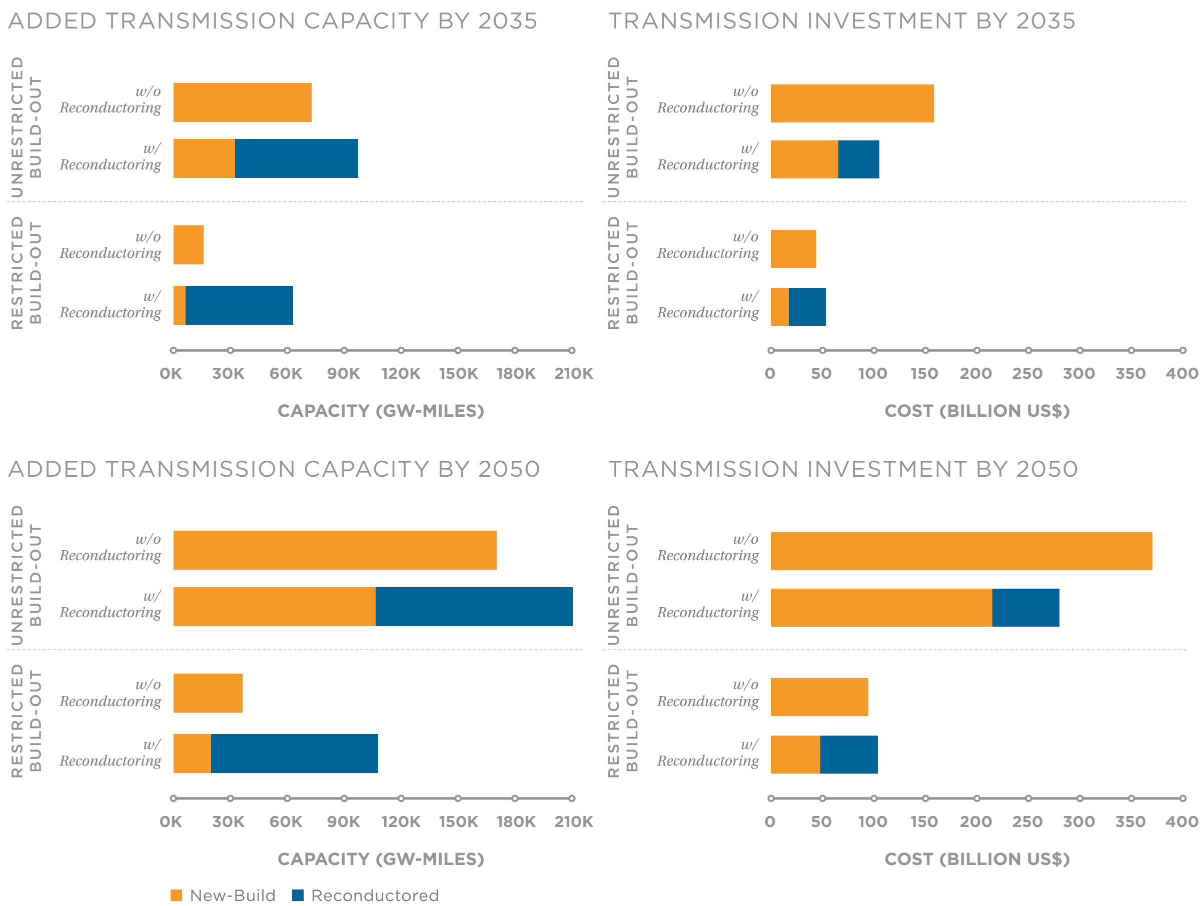


FIGURE ES-2.

Transmission capacity added (left) and associated investment (right) in 2035 (top) and 2050 (bottom). All four scenarios (with and without reconductoring, with and without build-out rate restrictions) are shown. When reconductoring with advanced conductors is allowed, significantly more transmission capacity is added in both restricted and unrestricted cases.

4. Reconductoring with advanced conductors can help provide the majority of near-term interzonal transmission capacity needs, providing time for new lines to be developed for long-term needs.

Reconductoring with advanced conductors can rapidly and cost-effectively provide substantial increases of transmission capacity in the near-term. Beginning in the mid-2030s, however, greenfield transmission development begins to play an increasingly larger role in new interzonal transmission capacity additions, as opportunities for reconductoring with present-day advanced conductors are exhausted. Given that new transmission lines can often take 10–15 years to complete due to hurdles such as permitting and cost allocation, this indicates that the optimal transmission expansion strategy on the path to full grid decarbonization should leverage large-scale reconductoring with advanced conductors in the near-term, while new lines for long-term needs are concurrently planned, permitted, and constructed. However, we haven't fully assessed whether reconductoring is sufficient for expanding transfer capacity between transmission planning regions, as it may be hindered by a smaller existing supply of interregional lines to reconductor and cost-allocation challenges.

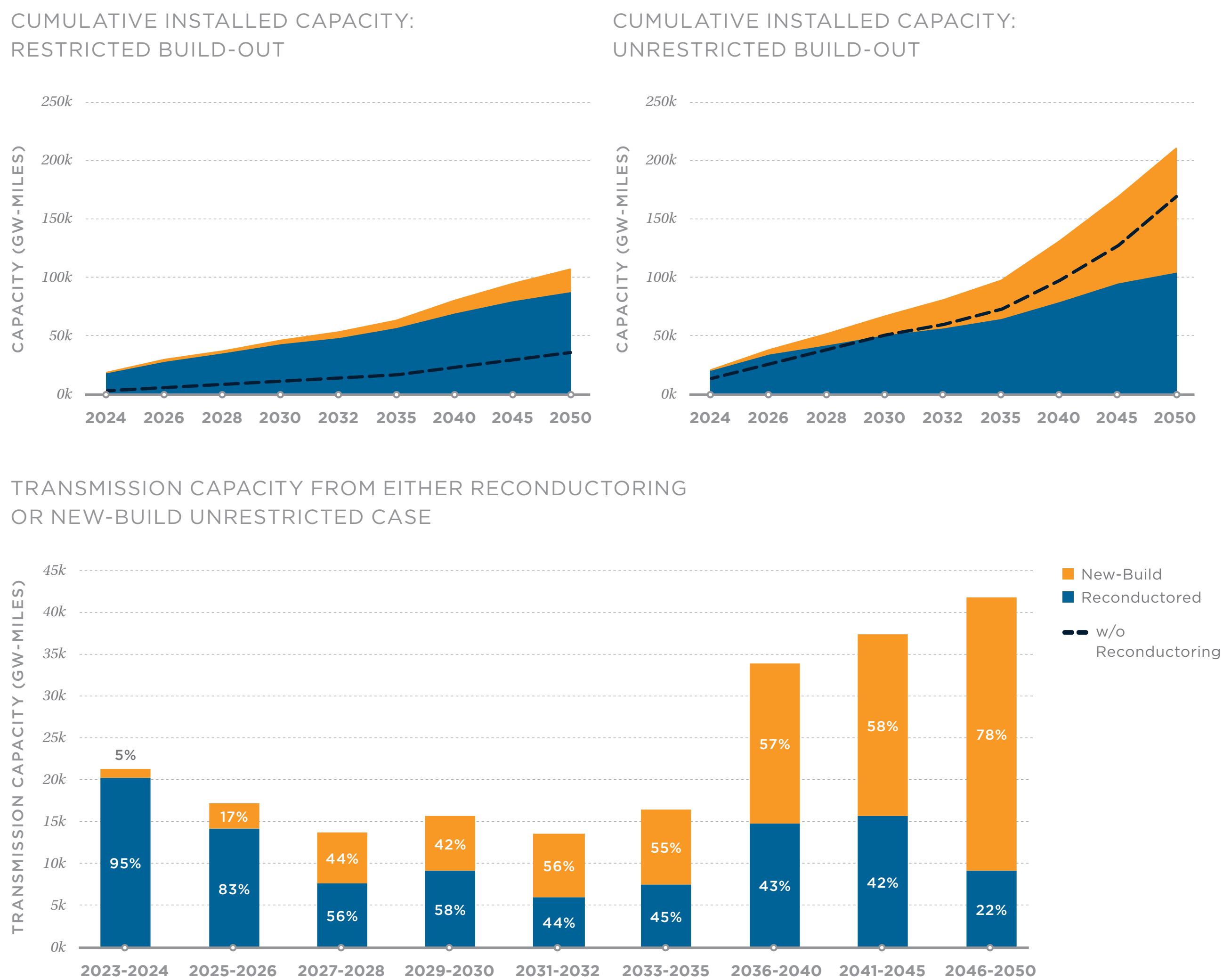


FIGURE ES-3.

Cumulative added transmission capacity, with restricted build-out (top left) and unrestricted build-out (top right). The scenario without reconductoring is shown as a dashed red line in each. Added transmission capacity from new-build and reconductoring with advanced conductors in the unrestricted build-out case. (bottom).

5. **Pursuing a strategy of simultaneously reconductoring with advanced conductors and addressing barriers to new greenfield transmission provides the largest savings in total system costs of all considered scenarios, yielding cumulative savings of over $400 billion by 2050 compared to the business-as-usual case.**

Reconductoring not only enables an increase new interzonal transmission capacity, but also distributes the new transmission capacity over more transmission corridors, compared to the business-as-usual case.

This unlocks access to lower-cost, higher-quality clean energy in more locations across the country, thereby lowering wholesale electricity costs and resulting in $85 billion in system cost savings by 2035 and $180 billion by 2050.

Meanwhile, simultaneously pursuing widespread reconductoring along with greenfield expansion, without restrictions on transmission build-out – shows how resolving permitting and cost allocation issues can further yield significant cost savings of over $400 billion by 2050, over the business-as-usual case.

ELECTRIC ENERGY SYSTEM COST SAVINGS COMPARED TO BUSINESS-AS-USUAL INCLUDING IRA INCENTIVES

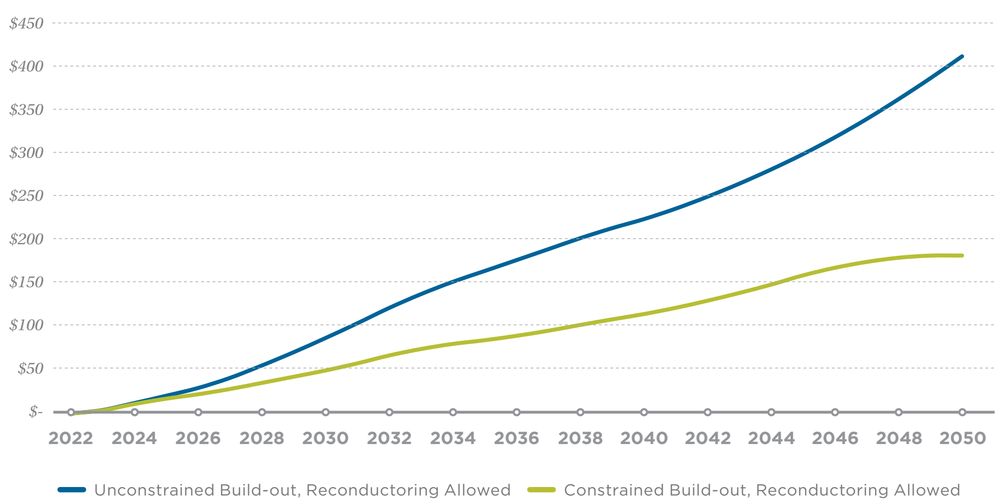


FIGURE ES-4.

Comparison of Cumulative Electric Energy System (Transmission and Generation) Cost Savings from Reconductoring with Advanced Conductors and New Greenfield Transmission Versus Business-as-usual. Reconductoring with advanced conductors offers approximately half of the available savings from 2022–2050. Pursuing both strategies in tandem resulted in the greatest savings.

This report aims to broaden awareness of reconductoring with advanced conductors in existing ROW as a rapid, widely deployable, and cost-effective way to increase the transmission capacity of the U.S. grid in the near term, providing time for new lines to be developed for long-term needs.

Capturing the technical potential identified in this report requires overcoming several barriers. There are technical considerations that must be integrated into any grid expansion plans, and there are policy and regulatory barriers that have impeded widescale deployment of advanced conductors. A companion paper from Energy Innovation and GridLab explores these barriers and provides regulatory and policy recommendations that can promote the cost-effective use of advanced conductors in grid planning.

1 INTRODUCTION

With electrified energy uses growing and ready clean energy surpassing what the grid can absorb, there is an urgent need for large-scale expansion of transmission capacity in the United States. The 2023 U.S. Department of Energy (DOE) National Transmission Needs Study (NTNS) found that transmission capacity must increase by up to 128% within regions and by 412% inter-regionally by 2035 to accommodate the high load growth and high clean energy growth (DOE, 2023) needed to hit U.S. and many state clean energy targets. These findings echo similar recent studies indicating that U.S. transmission capacity must increase multifold by 2050 to meet the country's growing electricity demands (REPEAT Project, 2022). However, over the last decade, transmission capacity growth across the United States has averaged an anemic 1% per year. Figure 1 compares this recent historical rate with the forecasted transmission capacity growth requirements from the primary scenarios examined in the NTNS. Figure 2 presents the cumulative regional transmission capacity additions needed to meet a net-zero U.S. energy system by 2050 as compared to the projected build-out under several policy scenarios.

DOE NTNS FORECASTED CUMULATIVE NEW REGIONAL TRANSMISSION CAPACITY NEEDS VS HISTORICAL BUILD RATE

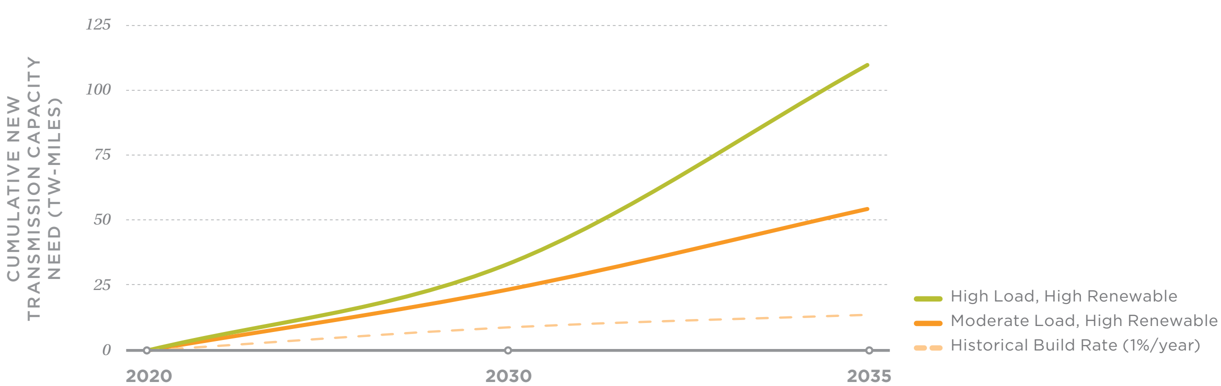


FIGURE 1.

Forecasted U.S. regional transmission capacity expansion needs. U.S. Department of Energy National Transmission Needs Study (NTNS) compared to the historical growth rate of 1%/year (DOE, 2023). To meet a high renewable energy future, the DOE estimates that the U.S. must increase its transmission capacity by 60–125% by 2035.

REPEAT PROJECT CUMULATIVE NEW TRANSMISSION CAPACITY NEED (TW-MILES) FOR EACH SCENARIO

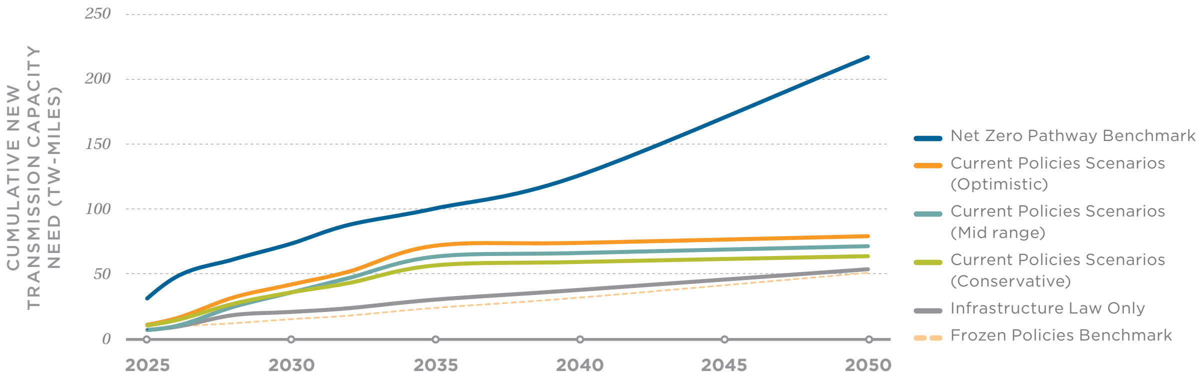


FIGURE 2.

Forecast U.S. regional transmission capacity expansion needs. The Princeton Net-Zero Lab's Rapid Energy Policy Evaluation and Analysis Toolkit (REPEAT) Project (REPEAT Project, 2022) found that to reach a net-zero energy system by 2050, the U.S. needs to install an additional 217 TW-miles of transmission capacity. Under current policy frameworks, the U.S. is expected to install only 51 TW-miles.

Both studies (NTNS and REPEAT) demonstrate that if the U.S. transmission build-out rate does not increase dramatically, transmission capacity will be insufficient to meet clean energy goals and serve the electrification demands of U.S. industrial growth.

1.1 CLEAN ENERGY GAINS HELD BACK BY GRIDLOCK

The limitations of the existing transmission system are already slowing the deployment of clean energy and leaving savings and reliability benefits on the table. The costs of solar and wind energy and batteries have rapidly declined in recent years, with cost projections, such as those in the National Renewable Energy Laboratory (NREL) Annual Technology Baseline (ATB), regularly being revised downward based on market trends. The latest ATB (2023) predicts that the Levelized Cost of Electricity (LCOE) of utility-scale solar photovoltaics (PV) and land-based wind energy will fall to $24/MWh and $22/MWh, respectively, across the U.S. by 2035 (NREL, 2024). Meanwhile, the 2023 average LCOE for the lowest-cost thermal technology (combined cycle natural gas generation) in the U.S. was approximately $40/MWh. The low costs of solar and wind are in large part due to generous incentives for zero-carbon electricity generation in the Inflation Reduction Act (IRA) including updates to the Production Tax Credit (PTC) and Investment Tax Credit (ITC). This has made clean energy increasingly and more broadly economically viable across the U.S., as presented in Figure 3.

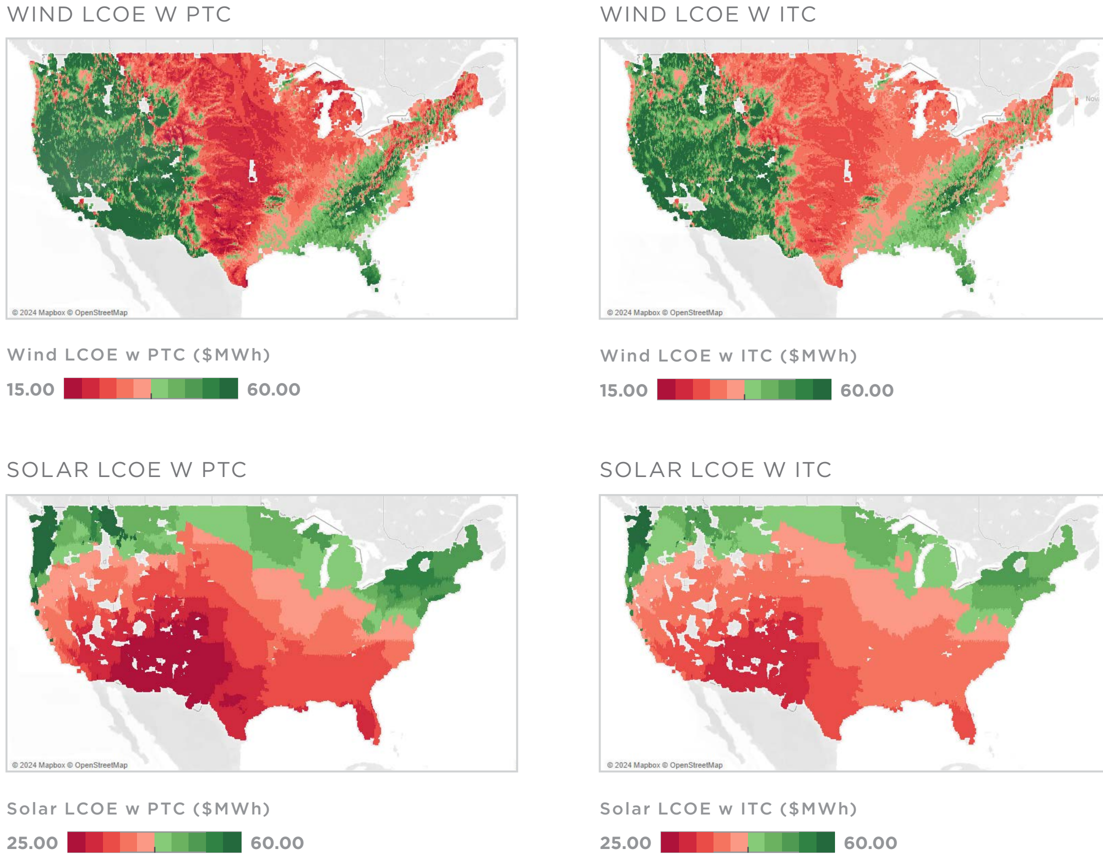


FIGURE 3.

The economic viability of new clean energy resources since Inflation Reduction Act (IRA) incentives (updated Production Tax Credit [PTC] and Investment Tax Credit [ITC]) were enacted. *The maps show cost-competitiveness based on Levelized Cost of Electricity (LCOE), ranging from deep green (generally uncompetitive with average fleet costs) to deep red (highly competitive with average fleet costs): (A) Wind LCOE with the PTC; (B) Wind LCOE with the ITC; (C) Solar LCOE with the PTC; (D) Solar LCOE with the ITC.*

The maps in Figure 3 show that, based on LCOE, and since the introduction of IRA incentives, wind and solar facilities can now be cost-effective across most of the United States. Strikingly, clean energy is now also the lowest-cost energy source throughout most of the country. This means that renewable developers can now prioritize clean energy project siting near the existing transmission system, instead of the historical paradigm of siting clean energy only in the best resource locations and then relying on long "lead lines" to connect to the grid. In short, the IRA has significantly increased the viability of siting clean energy near existing transmission corridors. However, today, approximately 2 TW of proposed clean generation and storage resources are stuck in interconnection queues across the country, often due to grid congestion. Clean energy project developers face extended delays as, first, multiple interconnection studies must be conducted, and then the necessary transmission improvements must be completed (LBNL, 2023). Increasing the transmission capacity of the existing system will unlock much needed capacity, not only to integrate clean energy projects already queued, but also to encourage continued RE development near existing transmission infrastructure.

1.2 GRID UNDER UNPRECEDENTED STRAIN

The effects of worsening grid congestion are far-reaching and costly. Total transmission congestion costs were estimated to exceed $20 billion nationwide in 2022, a 58% increase from 2021, with the key driver being the failure of transmission expansion to keep up with the growth of low-cost clean energy (Grid Strategies, 2023). Increasingly frequent and severe extreme weather events, including Winter Storms Uri (2021) and Elliott (2022), have also demonstrated the need for greater interregional transmission capacity across the U.S., to improve power system resilience in the face of severe weather outages (Grid Strategies, 2021).

Adding to the magnitude of the challenge, demand for electricity is growing again. After several years of stagnant demand growth—primarily resulting from energy efficiency improvements offsetting newly added loads—the rapid electrification of industrial, residential, and transportation demand, along with rising demand from data centers, is causing growing strain on the grid (**Grid Strategies, 2023**). For example, the Texas grid operator ERCOT saw unprecedented peak load growth of 9% in 2022, followed by large growth again in 2023, at 7% (Federal Reserve Bank of Dallas, 2023). Recent industry analysis of electric vehicle (EV) adoption forecasts that the American EV market could grow tenfold times by 2030 (PWC, 2023). In that same time, the nationwide datacenter load is forecast to double to nearly 35 GW/year—more than the New York Independent System Operator (NYISO) record annual peak load for the entire state of New York (McKinsey, 2023). If clean energy is not available to meet this load growth, the gap will be filled by existing and new fossil energy.

1.3 COUPLING NEAR-TERM AND LONG-TERM ACTIONS TO INCREASE TRANSMISSION CAPACITY

Clearly, the current slow pace of transmission development threatens decarbonization, resiliency, and economic growth. Building new transmission lines is an essential, but currently slow, piece of grid development strategy:

challenges such as cost allocation and permitting related to land acquisition and environmental assessments mean that it typically takes 10–15 years to bring greenfield transmission projects to completion in the U.S. (Harvard, 2022). With the grid already strained under the demands of decarbonization and electrification, and clean energy development spurred by the IRA being held back by grid congestion, this study seeks to answer the question: what can feasibly be done in the near term to increase transmission capacity in the existing system?

There are many tools available to increase efficiency and capacity within existing rights-of-way (ROW). However, on a cost- and time-adjusted basis, **reconductoring with advanced conductors offers the most feasible path to up to double transmission capacity along existing transmission corridors**. For that reason, we focused on modeling and estimating the net value afforded by reconductoring with advanced conductors as the U.S. moves towards a highly decarbonized grid.

1.4 PURPOSE

The objective of this report is to raise awareness about the practice of reconductoring existing transmission lines using advanced conductors. This approach is particularly advantageous due to its speed, wide applicability, and cost-effectiveness. By implementing this strategy, we can boost the transmission capacity of the U.S. grid in the short term.

The accompanied companion paper, jointly authored by Energy Innovation and GridLab, delves into the realm of regulatory and policy adjustments. It focuses on facilitating the economic adoption of advanced conductors in grid planning and ratemaking processes. The goal is to ensure that this option receives thorough consideration as we navigate the complexities of grid management and development. These efforts collectively aim to enhance U.S. grid reliability, increase RE deployment, and accommodate the country's ever-growing energy demands.

2
TECHNOLOGIES FOR INCREASING THE TRANSMISSION CAPACITY OF EXISTING CORRIDORS

Leveraging existing ROW helps reduce or bypass the extensive permitting processes involved in greenfield transmission build-out, allowing capacity to be increased within a much shorter timeframe (Reed et al., 2020). The past few decades have seen a proliferation of new technologies that can appreciably increase the efficiency and capacity of the existing system. We group these into two broad categories: those that enhance the efficiency of existing lines; and those that structurally add transmission capacity to infrastructure in existing corridors. The first group includes Grid Enhancing Technologies (GETs) and Flexible AC Transmission Systems (FACTS), which improve the performance of existing lines so that grid operators can use them to their full potential. The second group increases the physical power density of existing corridors—i.e., boosting transmission capacity with little or no expansion of the ROW footprint—by either adding new lines to existing towers or upgrading to higher-capacity conductors within an ROW. These technologies include multi-circuit and advanced towers, and AC-to-DC conversion, and—our focus here—**advanced conductors**. The extent to which different technologies can help increase power density is presented in Figure 4.

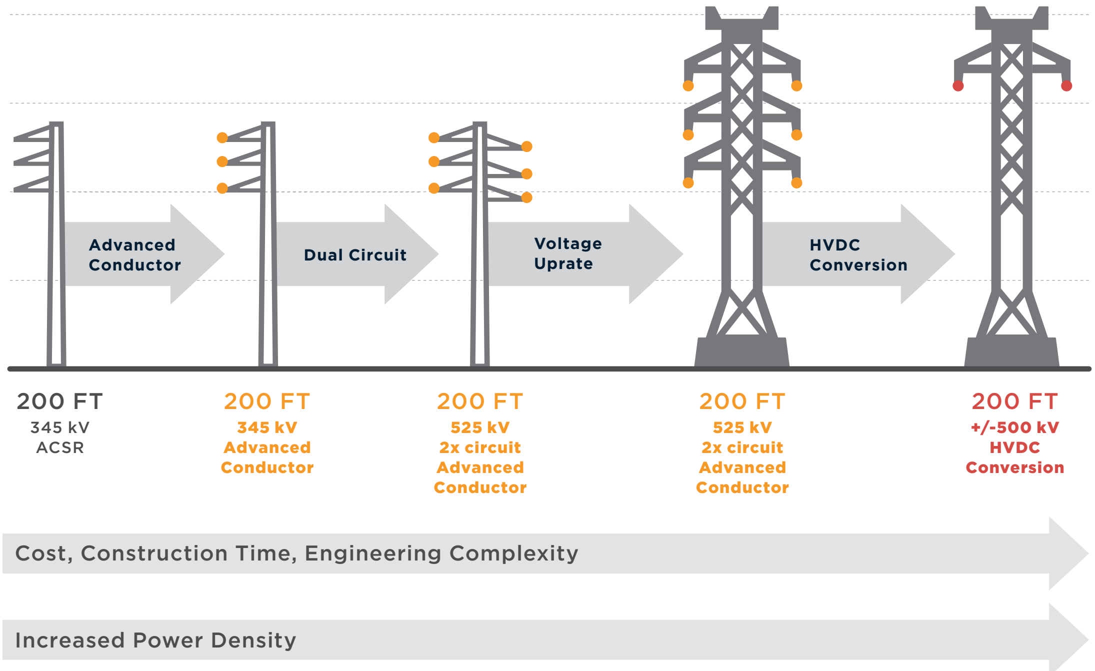


FIGURE 4.

Illustrative example of technologies that can increase power density. From left to right, as power density increases, so do cost, time, and engineering complexity. However, in most cases, these options will still cost less and be permitted faster than new greenfield transmission.

These new technologies can be used in tandem with other well-established options, such as increasing the circuit voltage, installing multiple circuits within the same ROW, and reconductoring with larger or different conductors for increased ampacity—offering grid planners a portfolio of strategies for substantially increasing the power density of existing corridors. However, despite the commercial availability of these technologies, with well-established benefits backed by robust global deployment, uptake in the U.S. remains limited.

While long-term system needs will require new high-capacity long distance transmission corridors, leveraging the technologies already on the market today can help meet near-term system needs and advance towards clean energy policy goals. Further, these technologies can be implemented incrementally, increasing the power density of existing corridors in step with forecasted capacity needs. These investments can be carefully calibrated and deployed according to project needs, grid topology, environmental conditions, and timeline constraints, as well as budget considerations.

2.1 EFFICIENCY-ENHANCING SOLUTIONS

Some solutions, known under the umbrella term of Grid-Enhancing Technologies (GETs), can provide an operational enhancement of a transmission line or the efficiency of power flow throughout the system. They include technologies such as Dynamic Line Rating (DLR), Power Flow Controllers (PFCs), and demand-side measures. Flexible Alternating Current Transmissions Systems (FACTS) such as synchronous condensers, static synchronous compensators (STATCOMs), and Series Compensation Systems can increase the throughput of an existing line by addressing dynamic instability limitations. However, these limitations are typically only applicable on lines longer than 50 miles, which, as described later in this report, is a small minority of transmission lines. One FACTS device with broader opportunities for deployment is a Static Series Synchronous Compensator, which can be used to reduce congestion by controlling power flow and offloading congested lines and redirecting the power to underutilized lines.

2.2 STRUCTURAL SOLUTIONS TO PHYSICALLY INCREASE ROW POWER DENSITY

Other solutions, such as reconductoring with advanced conductors, voltage upgrades, multi-circuit and advanced towers, and AC-to-DC conversion, can provide a larger, more structural increase in power transfer capacity. These commercially available technologies are presented in detail in Appendix I.

There are also emerging technologies that may offer novel opportunities to increase power density, such as high-temperature superconductors with near-zero impedance that offer 5–10 times power transfer capacity compared to conventional conductors. However, with no present-day real-world commercial deployment, significant research and development is required before such solutions can be considered viable.

2.3 DETERMINING THE BEST SOLUTION

Selecting the solution best suited to a given project is a case-by-case process which must carefully weigh the benefits and trade-offs of different options according to various key criteria, such as: speed of implementation (including permitting), capital costs, operating expenses, and technological and commercial readiness at scale, etc. We conducted a literature review and power system planning industry interviews on the current and emerging tools to increase the existing transmission system capacity. This investigation yielded insights into the strengths and weaknesses of each tool. A more in-depth discussion on these solutions and industry attitudes is provided in the companion study, but a simplified overview of the technological options is presented in Figure 5, along a continuum from relatively fast and low-cost at the top to complex and more expensive at the bottom.

ADVANCED TRANSMISSION TECHNOLOGY	DEVELOPMENT TIME	TYPICAL CAPACITY INCREASE	PERMITTING SPEED	DESIGN SPEED	CONSTRUCTION SPEED	VIABLE OPPORTUNITIES	COST
GETS including Dynamic Line Ratings	3+ MONTHS	10-30%	Green	Green	Green	MOST	$
(FACTS) Flexible AC Transmission Systems	8-18 MONTHS	30-50%	Green	Orange	Yellow	MORE	$$
Reconductoring w/ Advanced Conductors	18 - 36 MONTHS	50-110%	Yellow	Yellow	Yellow	MOST	$$
Tower Raising	2-4 YEARS	10%	Orange	Yellow	Yellow	LEAST	$$
Double Circuit Towers	2-4 YEARS	80-100%	Orange	Yellow	Orange	MOST	$$$
Advanced Tower Design	2-4 YEARS	30-100%	Orange	Orange	Orange	MOST	$$$
Voltage Uprate	3-5 YEARS	100-300%	Orange	Orange	Red	LEAST	$$$
HVDC Conversion	5-7 YEARS	100-300%	Orange	Red	Red	LEAST	$$$$
Greenfield Transmission	5-15 YEARS	N/A	Red	Red	Red	LEAST	$$$$

FIGURE 5.

Technologies to increase power density with associated deployment times and capacity gains, ranked according to deployability parameters (speed, implementation readiness at scale, cost): excellent (blue), good (green), weak (orange), or poor (red). Parameters were based on interviews with industry professionals and represent the average case. Exceptional cases that vary from these averages should be expected.

Generally, the more capacity increase provided by a solution, the longer the development timeline and higher the cost. In cases where only modest, dynamic capacity increases are needed, GETs and FACTS provide a quick and relatively inexpensive solution. Conversely, in situations where significant new transmission capacity is needed (200–300%), planners are limited to expensive options that take many years to develop. However, reconductoring with advanced conductors can typically increase transmission capacity of existing lines by up to 110% while still being implemented in a relatively short time-frame (typically 18–36 months). **The combination of speed and capacity gains afforded by reconductoring with advanced conductors makes it a particularly advantageous strategy to increase transmission capacity in the near term, compared to other options.** In addition, any transmission line with adequate structure health is eligible for reconductoring, making it a widely available solution across the country. Thus, on a cost- and time-adjusted basis, reconductoring with advanced conductors offers the most feasible path to double transmission capacity along existing transmission corridors.

As reflected in Figure 5 above, reconductoring with advanced conductors is overall the most promising technology opportunity to increase the physical transmission capacity of the existing U.S. transmission system for the purpose of facilitating rapid near-term load growth and clean energy additions. Whereas voltage upgrades may require ROW widening, and AC-to-DC conversion is generally best suited to long, interregional lines, reconductoring can be done without increasing the ROW footprint, even on shorter lines. Utility companies commonly use reconductoring to increase an existing line's ampacity by upgrading its transmission lines with larger-diameter or more efficient conductors. Because reconductoring projects do not involve new transmission towers or new ROW, the extensive permitting processes that impede the construction of new lines can be bypassed, delivering comparable capacity gains within a shorter time-frame (EPRI, 2021; Reed, 2020; Grid Strategies, 2022).

Having identified **reconductoring with advanced conductors** as the best option for near-term physical capacity building, we investigated the technology's history and real-world use cases.

3 ADVANCED CONDUCTOR TECHNOLOGY

The emergence of advanced conductors since the early 2000s represents a significant technological leap in the high-voltage power transmission landscape, with particular advantages in reconductoring applications.

3.1 HISTORICAL CONTEXT

Since the early 1900s, the most common conductor utilized for overhead high-voltage power transmission in the United States has been Aluminum Conductor Steel Reinforced (ACSR) cable, featuring conductive aluminum strands around a supporting steel core. Its good conductivity, low weight, low cost, utilization of common materials, and corrosion resistance cemented its place as the industry standard to this day. However, lines wired with ACSR are typically limited to normal operating temperatures of approximately 75°C, above which the tensile strength decreases over time, weakening the conductor and increasing susceptibility to failure (Southwire, 2019). When used in reconductoring, ACSR has typically increased the conductor size or the number of conductors per phase bundle.

Despite ongoing efforts to improve conductor design over the decades, enhancing one aspect of conductor design often led to trade-offs with other features. For example, Aluminum Conductor Steel Supported (ACSS) cable, first introduced in the 1970s, utilized aluminum strands that were fully annealed so that the conductor could withstand higher operating temperatures and thus higher ampacities (Southwire, 2015). However, operation at higher temperatures ran the risk of excessive sag due to the high thermal expansion of steel; this drawback limited the benefits of ACSS, necessitating taller structures or shorter spans in new lines to accommodate prescribed minimum clearances. Using ACSS in reconductoring projects would often require modifying structures to abide by pre-existing clearances or, to avoid extensive structural modifications, underrating the reconductored line below its thermal capacity limit. In the last few decades, ACSS technology has improved by adding a trapezoidal stranding of the aluminum conductor and a variety of coatings to improve performance. This trapezoidal wire

(TW) increases the cross-sectional area of the conducting aluminum, thereby increasing the line's efficiency and capacity rating.

3.2 ADVANCED CONDUCTORS OFFER A NEW PATH FORWARD

In recent years, advances in materials science have given rise to advanced composite-core conductors which can carry up to double the current of conventional conductors. Also known as High Temperature Low Sag (HTLS) conductors, these conductors swap the conventional steel core for a smaller and lighter composite core (typically ceramic, glass, or carbon fibers) without compromising structural strength. This means that more aluminum—typically annealed aluminum, as it has the highest temperature capabilities—can fit within an equivalent diameter, enabling higher operating temperatures, all while reducing line sag and abiding by the clearances that often limit a line's rated capacity (3M, 2014; CTC Global, n.d.; TS Conductor, 2023; Southwire, 2017). Figure 6 compares a cross-section of a conventional ACSR conductor with an advanced composite-core conductor.

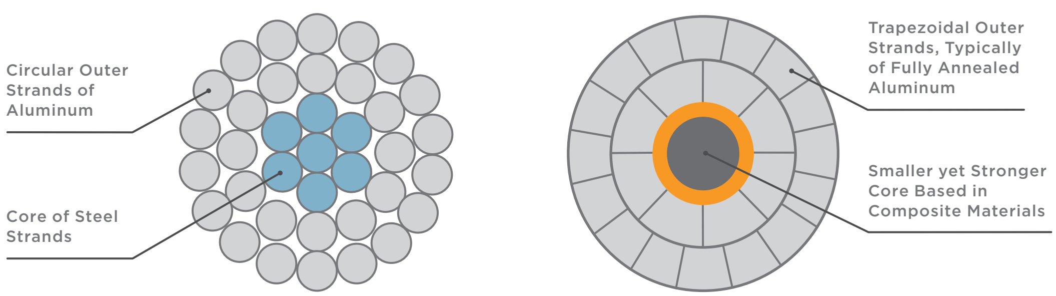


FIGURE 6.

Conductor cross-section comparison. A comparison of a cross-section of a conventional Aluminum Conductor Steel Reinforced (ACSR) cable compared to an equivalent-diameter advanced composite-core conductor. While ACSR and Aluminum Conductor Steel Supported (ACSS) cables can also be stranded with trapezoidal outer strands, the most commonly utilized conductor design features circular outer strands.

Examples of advanced composite-core conductors include Aluminum Conductor Composite Reinforced (ACCR) made by 3M, Aluminum Conductor Composite Core (ACCC) made by CTC Global, and Aluminum Encapsulated Carbon Core (AECC) made by TS Conductor—all of which are based and manufactured in the U.S.

Table 1 provides an overview of conventional conductors compared to these different types of advanced conductors, showing how the many advantages of advanced conductors make them well-suited for reconductoring projects.

TABLE 1.

Comparison of conventional conductors with different types of advanced conductors.[1]

	ABBR.	FULL NAME	YEAR INVENTED	AMPACITY INCREASE OVER ACSR	OPERATING TEMPERATURE	"DRAKE"-SIZE AREA[2]	"DRAKE"-SIZE STRENGTH[3]	"DRAKE"-SIZE AC RESISTANCE AT 75°C	SAG AT HIGH AMPACITIES	PROPRIETARY?	DEPLOYMENT	SOURCE(S)
STEEL-BASED CORE	**ACSR**	**Aluminum Conductor Steel Reinforced**	1900s	1x	75°C cont., 100°C emerg.	795 kcmil	31,500 lbs	0.0263 Ohms/kft	-	No	En masse	*(Southwire, 2019)*
	ACSS	**Aluminum Conductor Steel Supported**	1970s	<1.7x	250°C cont./emerg.	795 kcmil	25,900 lbs	0.0257 Ohms/kft	high	No	En masse	*(Southwire, 2015)*
	ACSS/TW	**ACSS/Trapezoidal Wire**	2000s	<2.1x	250°C cont./emerg.	960 kcmil	30,700 lbs	0.0213 Ohms/kft	high	No	En masse	*(Southwire, 2014)*
COMPOSITE-BASED CORE	**ACCR**	**Aluminum Conductor Composite Reinforced**	2000s	-2x	210°C cont., 240°C emerg.	958 kcmil	37,000 lbs	0.0213 Ohms/kft	low	Yes 3M	>6,000 miles installed on >325 projects	*(3M, 2014)*
	ACCS	**Aluminum Conductor Composite Supported**[5]		-2x	180°C cont., 225°C emerg.	995 kcmil	33,500 lbs	0.0290 Ohms/kft[6]	low	Yes Southwire	N/A	*(Southwire, 2017)*
	ACCC	**Aluminum Conductor Composite Core**[7]		-2x	180°C cont., 200°C emerg.	1026 kcmil	41,200 lbs	0.0202 Ohms/kft	low	Yes CTC Global	>81,000 miles installed on >1,100 projects in 60+ countries	*(CTC Global, n.d.)*
	AECC	**Aluminum Encapsulated Carbon Core**		-2-3x	180°C cont., 200°C emerg.	1051 kcmil	42,200 lbs	0.0199 Ohms/kft	low	Yes TS Conductor	>300 miles	*(TS Conductor, 2023)*

1 Technical conductor specifications are taken from manufacturers' data sheets and may vary slightly due to different environmental parameters. Further, we compare the standard conductor models, although manufacturers typically offer a portfolio of designs that may incorporate higher strength cores, different coatings and/or different aluminum alloys for different performance characteristics.

2 Conductor size is measured in units of thousand circular mils (kcmil), where one circular mil equals the area of a circle with a diameter of one mil (a thousandth of an inch). We display characteristics for the standard "Drake"-size conductor (total cable diameter is approx. 1.1 inches); similar trends hold across different conductor sizes.

3 Composite-based conductors typically utilize a trapezoidal shape of the outer aluminum wires, in contrast to the more common round-wire construction of conventional conductors. The trapezoidal shape incorporates more aluminum, meaning strength and weight values for ACSS/TW, ACCR, ACCC, and AECC conductors may be slightly elevated compared to ACSR and ACSS conductors.

4 Standard strength, although high strength options are also available.

5 Also known as the C7 overhead conductor.

6 AC resistance at 180°C since AC resistance at 75°C was not available.

7 Other models include the ACCC AZR conductor (using an aluminum-zirconium alloy for greater strength) and the ACCC ULS conductor (incorporating more carbon fiber for ultra-low sag properties).

Advanced conductors have undergone significant laboratory testing by relevant institutions such as the Electric Power Research Institute (EPRI), the International Council on Large Electric Systems (CIGRE), and others, with their work publicly available in technical reports and brochures. Results indicate that other advantages of advanced conductors may include improved resistance and resilience to bending failure, oxidation, ultraviolet (UV) rays, galvanic corrosion, and general environmental damage, varying by conductor model (CTC Global, 2011; CTC Global, 2013; TS Conductor, 2023). Some advanced conductors also embed an optical fiber to monitor line temperature and elongation in real time, enabling validation testing after installation, dynamic line rating, or insulation-based wildfire protection. Furthermore, their installation often follows similar procedures and tools as for ACSR, minimizing the need for special training or equipment.

3.3 REAL-WORLD ADOPTION OF ADVANCED CONDUCTORS

Globally, robust adoption of advanced conductors has produced a strong track record and a growing body of regulatory practice to support this approach. Recognizing the ability of advanced conductors to deliver increased transmission capacity within a limited timeframe, a number of countries are pursuing large-scale reconductoring projects in their high-voltage networks, and in some cases, using advanced conductors in new lines. In total, from 2003 to 2023, over 90,000 miles of advanced conductors have been deployed worldwide. Case studies of leading countries, including Belgium, Netherlands, Italy, India, and China, are detailed in Appendix II. In the U.S., one strong example of reconductoring with advanced conductors took place in Texas, where a 345kV line was reconductored with CTC Global's ACCC conductor, successfully doubling the line's capacity in a land- and time-constrained area without taking the existing line out of service.

CTC Global Corporation

ADVANCED CONDUCTORS SAVE RELIABILITY IN TEXAS

While, globally, several other countries have led in the large-scale deployment of advanced conductors, when completed in 2016, the Lower Rio Grande Valley (LRGV) reconductoring project in southeastern Texas was the longest in the world. The project involved reconductoring the two single-circuit double-bundle 345 kV transmission lines that serve the LRGV, doubling transmission capacity with CTC Global's ACCC conductor (to a 1988/2426 MVA normal/emergency rating) (EEI Energy Biz, 2016). Motivating factors included rapid population growth in the area and seasonal peak demands that exceeded previously modeled projections, leading to rolling blackouts during the South Texas Ice Storm of February 2011. The local utility, American Electric Power (AEP), considered conventional solutions, such as building new lines, but saw the risk of permitting delays and the difficulty of ROW acquisition as serious deterrents given the urgency of the project. To meet the pressing reliability demands within a constrained timeframe, energized reconductoring of the line emerged as the only option. This would require the construction of temporary poles, but by placing these within the existing right-of-way, the need for time-intensive permitting and new land acquisition was averted. Approved the same day it was presented to ERCOT's Board of Directors in 2011 (ERCOT, 2011), the $225 million project went on to be completed several months ahead of schedule and millions of dollars under budget (Power Engineering, 2011).

CTC Global Corporation

4
METHODS AND SCENARIOS

Given the potential of reconductoring with advanced conductors to increase transmission capacity in existing ROW by up to 100%, we investigate this technology as a near-term pathway to the substantially greater grid capacity needed to unlock clean energy resources and support growing electrification. This report combines the latest energy cost data with state-of-the-art power system modeling to quantify **reconductoring with advanced conductor costs**, capacity increases and role of reconductoring with advanced conductors towards meeting future transmission needs. Specifically, the study aims to address gaps or inconsistencies in previous studies by: 1) building bottom-up cost estimates of reconductoring, 2) assesses the capacity increases possible through reconductoring while respecting thermal and stability line loading characteristics, and 3) exploring reconductoring's contribution to decarbonization by comparing scenarios with reconductoring to base scenarios without reconductoring.

In addition, we use a novel approach to reflect how transmission planning practices are likely to evolve as the electric system moves towards high penetration of inverter-based generation. Today, lines longer than 50 miles are typically not limited by their conductors but rather by the stability limitations inherent to AC power lines. In these cases, reconductoring with advanced conductors will provide little to no additional transmission capacity. To work around this constraint, we present the concept of sectionalization of long lines (> 50 miles) with collector substations supported by inverter-based resources, such as solar plus storage. This approach presents two advantages: first, the collector substations provide additional interconnection points for new low-cost clean energy resources, and second, the new resources and/or storage can provide voltage support and reactive compensation to address the stability limitations on the line.

The study's modeling investigates four scenarios, outlined in Table 2. In each scenario, the model added transmission and generation capacity, and the cost of these additions was estimated to show the relative savings of these technology pathways against the business-as-usual (BAU) case.

TABLE 2.

Scenarios investigated in the study.

Restricted build-out rate, Reconductoring not allowed (Business-as-usual)	**Restricted build-out rate, Reconductoring allowed**
Unrestricted build-out rate, Reconductoring not allowed	**Unrestricted build-out rate, Reconductoring allowed**

The modeling assumes high load growth and high clean energy growth in all scenarios. Additionally, to reflect pending policy from the Environmental Protection Agency (EPA) and investment uncertainty regarding the construction of new fossil plants, we add additional constraints to retire coal capacity by 2035—implemented linearly with the oldest plants retiring first—and disallow new natural gas-fired capacity without carbon capture and storage (CCS) post-2023, except plants that are already under construction.

A detailed description of the methods used to conduct the study is presented in Appendix III.

5
KEY FINDINGS

The preceding sections demonstrate the urgency of increasing transmission capacity to achieve a cleaner, more affordable, more resilient grid that can meet growing demand. Because building transmission along new rights-of way (ROW) is such a long and difficult process in the U.S., we surveyed the technologies that can increase power density along existing transmission corridors, identifying **reconductoring with advanced conductors** as a particularly promising pathway to reaching U.S. and state clean energy goals. We find that not only can advanced conductors increase power density by up to 100% along existing ROW, but also that these technologies are being widely and successfully deployed in many nations around the globe. Using these demonstrated technology properties and global case studies, we developed supply curves for reconductoring and supplied them to the National Renewable Energy Laboratory (NREL) Regional Energy Deployment System (ReEDS) model.

Our investigation of the extent to which reconductoring can reduce the cost and increase the speed of clean energy deployment in the U.S. yielded five key findings. First, considering the challenges of building new lines, reconductoring can increase interzonal transmission capacity by nearly four times (+280%) by 2035 versus greenfield expansion only, with only 20% higher transmission expenditures over the same period. Second, reconductoring projects typically cost less than half the price of new lines for similar capacity increases. Third, this reconductoring path yields net consumer savings of $85 billion by 2035 and $180 billion by 2050. Fourth, reconductoring can provide nearly 90% of the new interzonal transmission added in this scenario which reaches more than 90% clean electricity by 2035, complementing the parallel development of new ROW to meet long-term grid needs. Finally, a strategy of concurrently reconductoring with advanced conductors while also developing new greenfield transmission provides the most savings in overall system costs (the sum of generation and transmission costs).

1. Advanced conductors can up to double line capacity within existing rights-of-way (ROW).

The capacity increase achieved through reconductoring depends on the line's limiting constraint, which is typically related to line length: short transmission lines are generally constrained by thermal limits, whereas long lines are generally constrained by voltage drop or angular stability limits. Other situational limits independent of line length, such as those derived from contingency analysis, may also constrain the line's maximum power transmission capacity.

POWER TRANSFER CAPABILITY AS A FRACTION OF THERMAL LIMIT BASED ON ST. CLAIR'S CURVES FOR LINE LOADABILITY

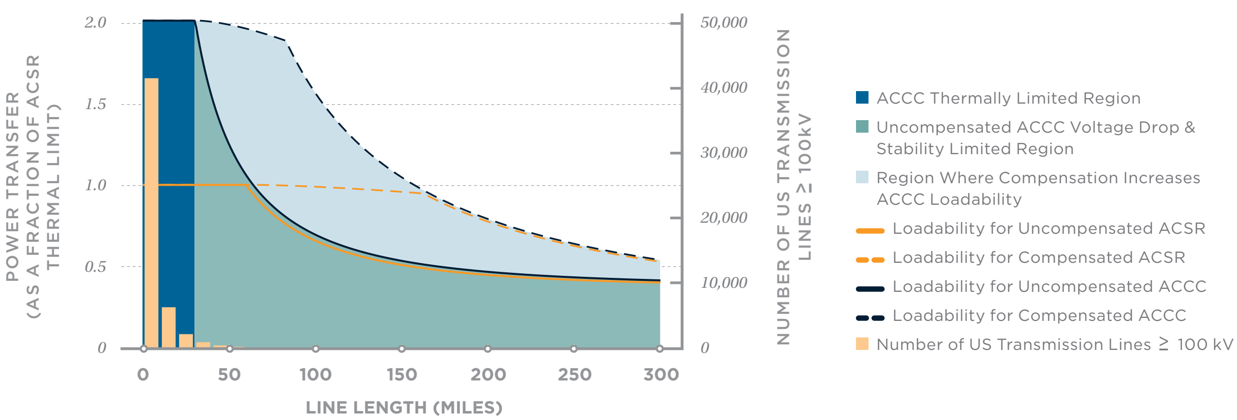


FIGURE 7.

Transmission line power transfer limits are determined by several factors including length. 98% of US Transmission lines are shorter than 50 miles and would be candidates for reconductoring with advanced conductors and voltage support to quickly increase capacity. Lines longer than 50 miles are typically limited by voltage stability which could be addressed with the novel approach of sectionalization.

While reconductoring with advanced composite-core conductors is commonly perceived as relevant only for short, thermally-limited lines, we find that reconductoring coupled with voltage support, or the novel concept of sectionalization, may provide similar capacity increases for longer lines that may not be thermally-limited. Sectionalization would involve the addition of new substation(s) with active and reactive power generation sources along the line, leveraging the benefits of advanced conductors while simultaneously creating new interconnection points for clean energy resources coupled with storage. As a result, advanced conductors can be utilized within existing ROW to double capacity both for the 98% of transmission lines in the U.S. that are shorter than 50 miles, with voltage support as needed, but also for the 2% of transmission lines in the U.S. that are longer than 50 miles, with simultaneous sectionalization (see Appendix III for more details).

2. Reconductoring projects typically cost less than half the price of new lines for similar capacity increases.

We estimate the bottom-up cost to increase transmission capacity through reconductoring projects versus new-build projects with ACSR. Although advanced conductors may currently cost two to four times the price of conventional conductors on a unit length basis, due to higher raw material costs and limited scale of production (Grid Strategies, 2022; EPRI, 2021), the total cost of reconductoring projects on a unit length basis is less than half—if not a third or even a fourth—that of new-build projects, due to the avoided costs of new ROW and structures. These findings are based on empirical cost data from reconductoring and new-build projects in Europe and the U.S.

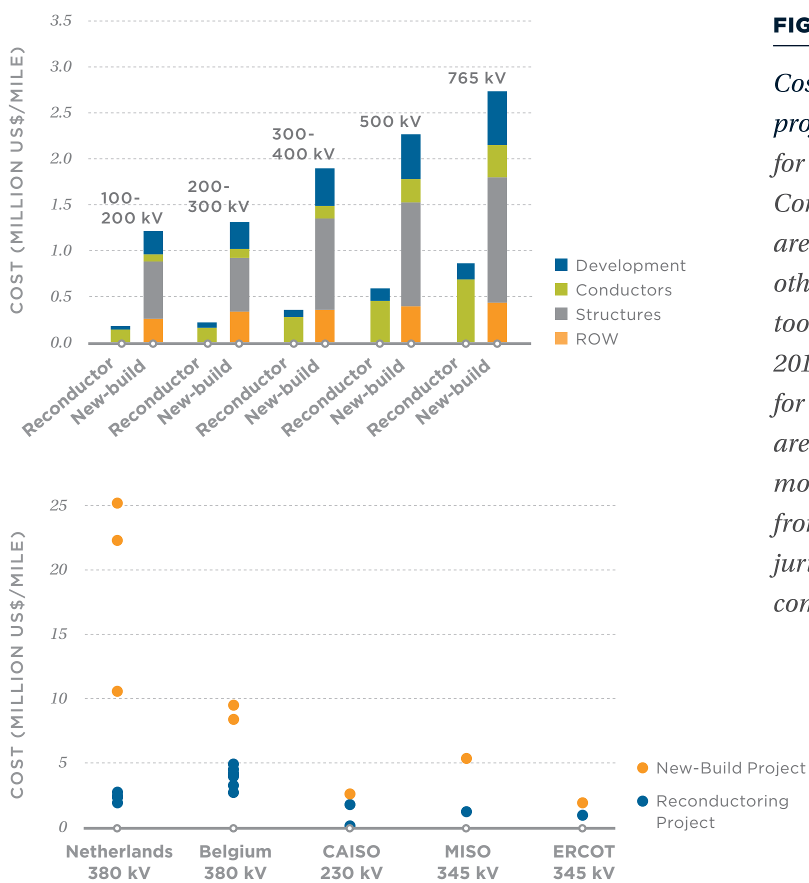


FIGURE 8.

Cost estimates for reconductoring projects vs new-build. Our estimates for new-build projects with Aluminum Conductor Steel Reinforced (ACSR) are in line with generic estimates from other popular transmission planning tools (Black & Veatch, 2014; NREL, 2013; MISO, 2022), falling within 20% for each voltage level. Terminal costs are accounted for separately in the modeling. Empirical project cost data from Europe and the U.S., presented by jurisdiction since cost definition and composition may vary.

3. **Reconductoring enables nearly four times (4x) the interzonal transmission capacity expansion by 2035 compared to new-build alone, given restrictions on greenfield transmission build-out.**

In the business-as-usual scenario without widespread reconductoring and with restricted new transmission build-out, only 16 TW-miles of interzonal transmission capacity are added by 2035, well short of the anticipated transmission capacity needed to support widespread decarbonization and electrification. However, if the build-out of new transmission lines remains at recent historical rates, large-scale reconductoring with advanced conductors can enable nearly four times the interzonal transmission capacity (i.e., across balancing areas of the Regional Energy Deployment System [ReEDS] model) by 2035 at only a 20% higher total transmission investment. These capacity additions through reconductoring account for nearly 90% of the new interzonal transmission capacity added in this scenario which reaches more than 90% clean electricity by 2035.

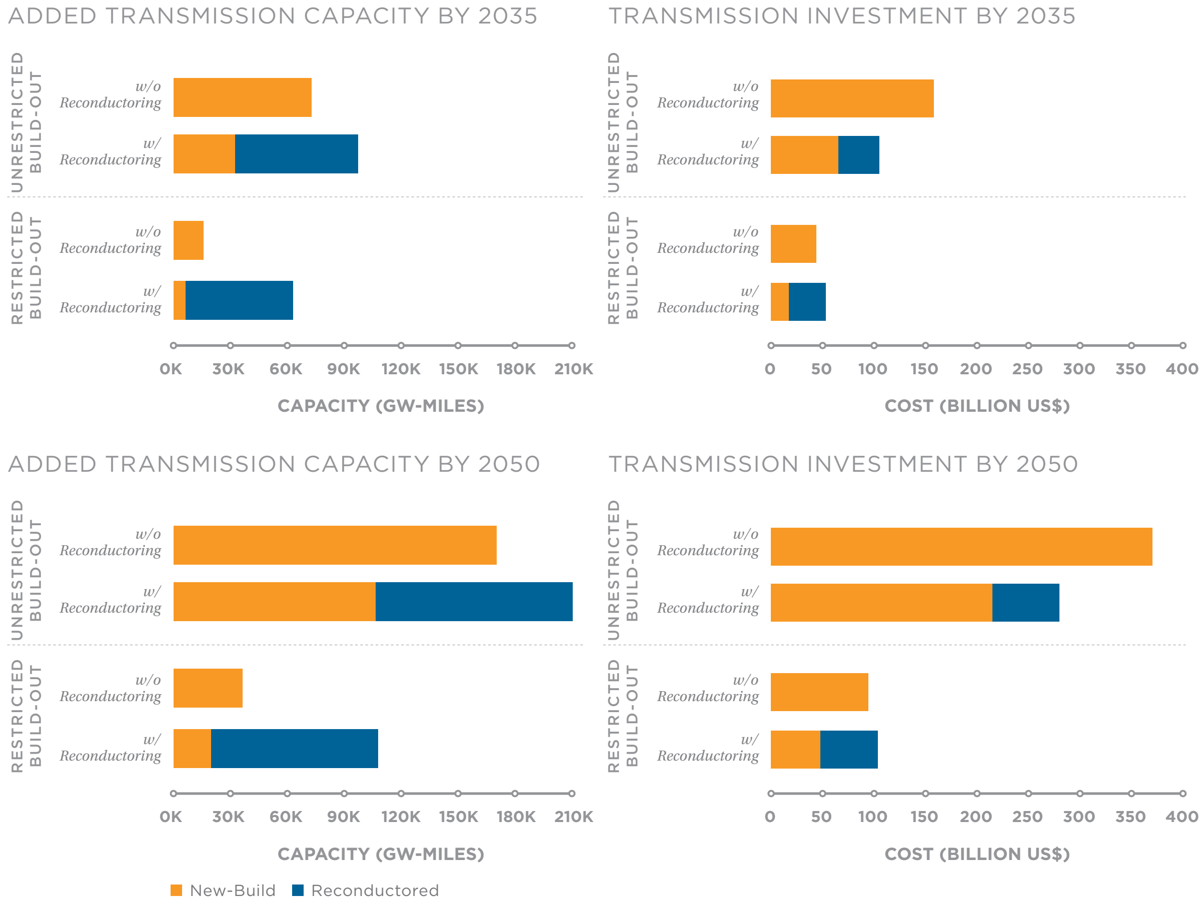
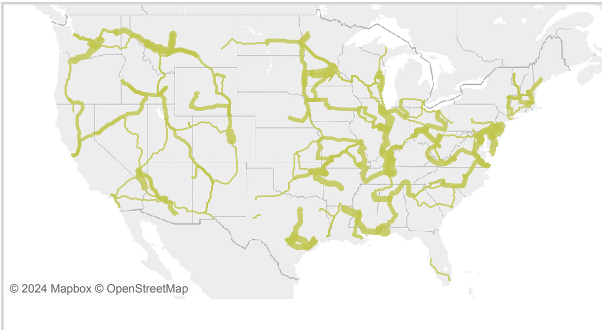


FIGURE 9.

Transmission capacity added (left) and associated investment (right) in 2035 (top) and 2050 (bottom). All four scenarios (with and without reconductoring, with and without build-out rate restrictions) are shown. When reconductoring with advanced conductors is allowed, significantly more transmission capacity is added in both restricted and unrestricted cases.

Given that reconductoring is a lower-cost option for increasing transmission capacity, it enables not only a larger total transmission capacity increase but also distributes the newly added interzonal transmission capacity over more transmission corridors (Figure 10).

ADDED CAPACITY: RESTRICTED BUILD-OUT, W/O RECONDUCTORING



ADDED CAPACITY: RESTRICTED BUILD-OUT, W/ RECONDUCTORING

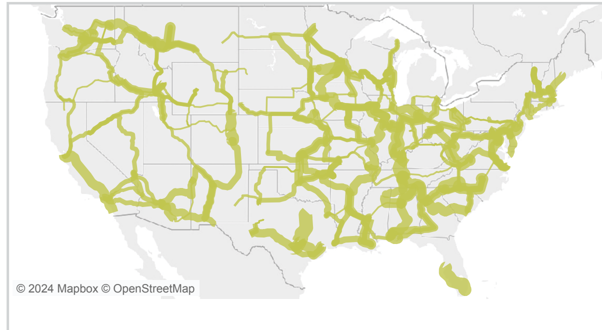


FIGURE 10.

Geographic distribution of added transmission capacity by 2035, without reconductoring (left) and with reconductoring (right).

The additional interzonal transmission capacity unlocked with an advanced conductor pathway provides access to lower-cost, higher-quality clean energy development in more locations across the country, lowering wholesale electricity costs by 3–4% and translating to $85 billion in system cost savings (the sum of generation and transmission costs) by 2035 and $180 billion by 2050, compared to business-as-usual.

It is worth noting that without changes to U.S. transmission siting and cost-allocation policy, it is unlikely that the unrestricted build-out scenarios for greenfield transmission are feasible.

4. Reconductoring with advanced conductors can help provide the majority of near-term interzonal transmission capacity needs, providing time for new lines to be developed for long-term needs.

As seen in Figure 11, the role of reconductoring is particularly relevant in the coming years, as reconductoring accounts for the vast majority of new interzonal transmission capacity that is added by 2035: nearly 90% in the restricted build-out scenario and 65% in the unrestricted build-out scenario. Without reconductoring, the rate of transmission build-out requiring new ROW would need to increase to around four times (~4x) the historical rate.

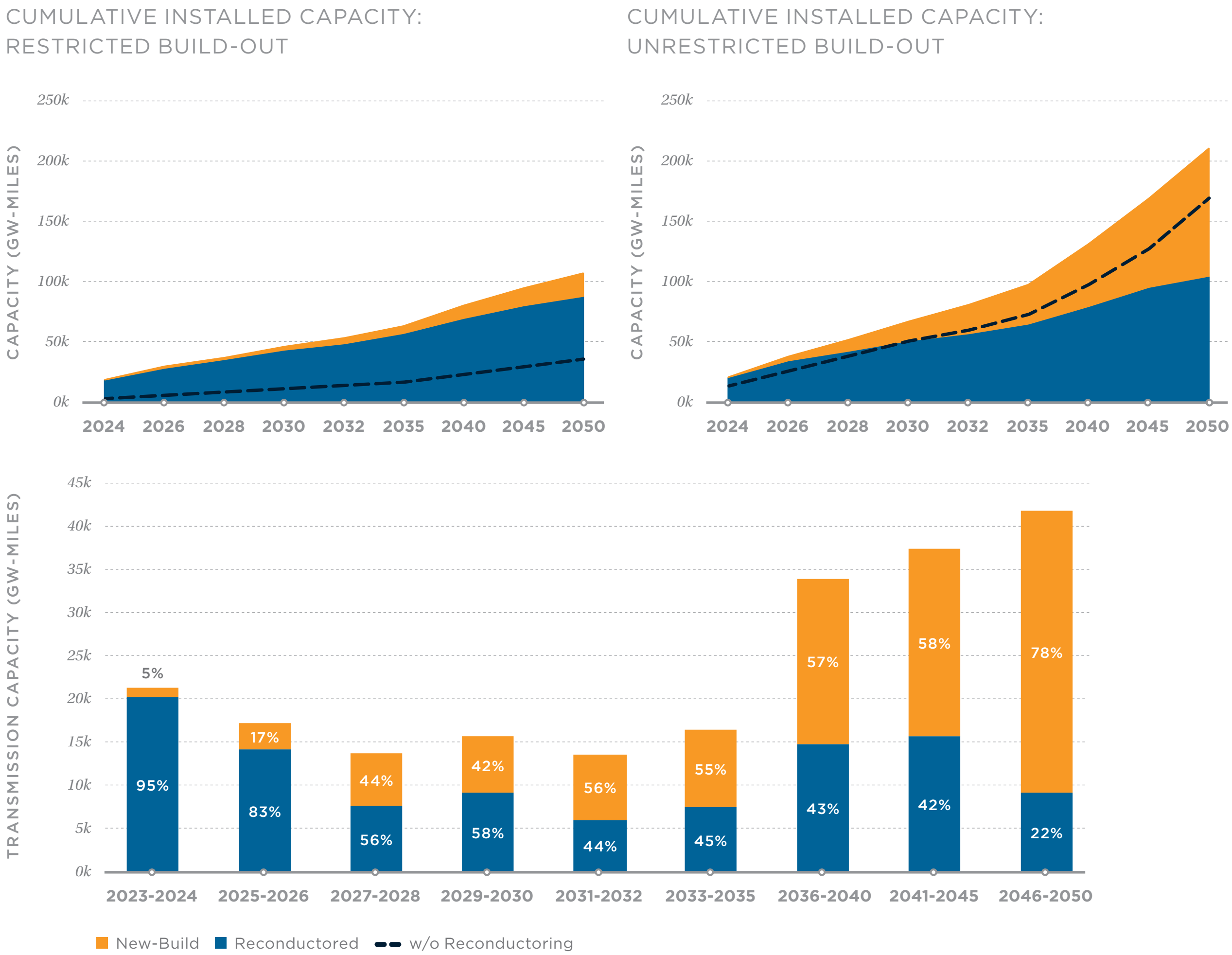


FIGURE 11.

Cumulative added transmission capacity, with restricted build-out (top left) and unrestricted build-out (top right). The scenario without reconductoring is shown as a dashed red line in each. (bottom) Added transmission capacity from new-build and reconductoring with advanced conductors in the unrestricted build-out case.

5. Pursuing a strategy of simultaneously reconductoring with advanced conductors and addressing barriers to new greenfield transmission provides the largest savings in total system costs of all considered scenarios, yielding cumulative savings of over $400 billion by 2050 compared to the business-as-usual case.

Reconductoring not only enables an increase new interzonal transmission capacity, but also distributes the new transmission capacity over more transmission corridors, compared to the business-as-usual case.

This unlocks access to lower-cost, higher-quality clean energy in more locations across the country, thereby lowering wholesale electricity costs and resulting in $85 billion in system cost savings by 2035 and $180 billion by 2050.

Meanwhile, simultaneously pursuing widespread reconductoring along with greenfield expansion, without restrictions on transmission build-out — shows how resolving permitting and cost allocation issues can further yield significant cost savings of over $400 billion by 2050, over the business-as-usual case as presented in Figure 11.

ELECTRIC ENERGY SYSTEM COST SAVINGS COMPARED TO BUSINESS-AS-USUAL INCLUDING FEDERAL AND STATE INCENTIVES

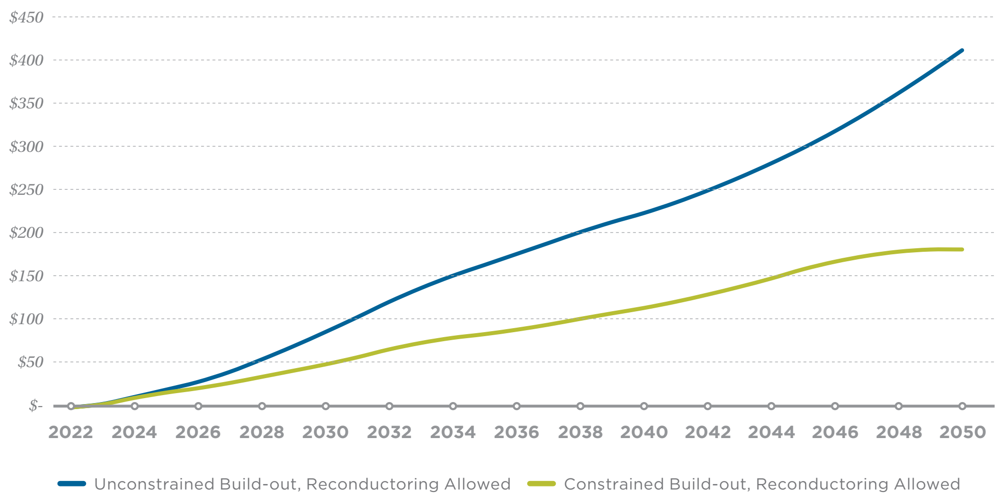


FIGURE 12.

Comparison of Cumulative Electric Energy System (Transmission and Generation) Cost Savings from Reconductoring with Advanced Conductors and New Greenfield Transmission Versus Business-as-usual. Reconductoring with advanced conductors offers approximately half of the available savings from 2022–2050. Pursuing both strategies in tandem resulted in the greatest savings. ReEDS savings included federal

6
CONCLUSION

The lagging pace of transmission development today threatens decarbonization goals, grid resiliency, and national economic growth. To avoid electricity shortfalls and continue the energy transition, transmission capacity must be increased multifold within the next few decades. This is an imperative and enormous challenge that is further compounded by increasingly aging grid infrastructure.

A number of technologies already on the market can be leveraged in the near term to increase the transmission capacity of the existing system rapidly and cost-effectively. **Of all strategies, reconductoring with advanced conductors offers the greatest potential to provide substantial capacity increases—up to double, within existing rights-of-way (ROW)—affordably and within a relatively short time-frame.** As new-build lines are planned, permitted, and

constructed to meet long-term system needs, large-scale reconductoring can unlock renewables near the existing network and contribute to rapid and cost-effective grid decarbonization.

In the face of unprecedented strain on the transmission system, grid planners increasingly recognize the need to pivot from decades of a least-cost development strategy to more holistic and proactive system planning. Accounting for future generation and load, such an approach would increasingly evaluate grid investments based not only on capital costs but also on the lifelong total cost of ownership, along with difficult-to-quantify advantages of different technologies. Acknowledging the uncertainty inherent in planning the highly decarbonized and electrified grid of the future, reflected in the varying estimates of required transmission capacity, a "least regrets" rather than a least-cost approach may reduce the risks and help address system needs more efficiently (Brattle, 2021). This includes pursuing near-term options to increase power density simultaneously with planning greenfield transmission with flexibility in mind. Reconductoring with advanced conductors fits this approach: it is not only the most promising near-term solution to deliver sorely needed capacity gains in the U.S. grid; it is also a "least regrets" option that leverages existing ROW while complements longer-term new-build development design.

This study has been conducted in tandem with the preparation of a companion report from Energy Innovation and GridLab, which describes real-world examples of reconductoring with advanced conductors, examines barriers to their deployment, and sets out recommendations at various legislative, regulatory, and planning levels.

7 ADDITIONAL RESOURCES

For more details, see the Working Paper published by the Energy Institute at Haas **HERE**.

See **renewable energy (solar and wind) resource potential** near existing transmission infrastructure **HERE**.

View **key modeling** results **HERE**.

Explore indicative transmission corridors that could benefit from capacity increases in order to unlock renewable energies **HERE**.

APPENDIX I

SURVEY OF TECHNOLOGIES THAT CAN INCREASE TRANSMISSION CAPACITY WITHIN EXISTING RIGHTS-OF-WAY (ROW)

Dynamic Line Rating (DLR)

A transmission line's loading limit is typically static—often with some seasonal variation—determined by the heat-tolerance of the equipment and very conservative assumptions about the ambient conditions, such as air temperature, wind speed and direction, solar insolation, etc. DLR monitors line conditions to determine the safe carrying capacity of the line in real time, with a variety of sensor-based technological solutions commercially available. This enables higher power flows, especially in cooler or windier conditions, while limiting power flows in extreme heat or other weather conditions to ensure safe and reliable operation.

Power Flow Controllers (PFCs)

PFCs include hardware and software that is used to push or pull power to help balance overloaded lines and underutilized corridors (DOE, 2022). Software solutions can identify congested or overloaded transmission elements and leverage the meshed nature of the grid to reroute power, typically by switching on/off existing high-voltage circuit breakers, to optimize power flow.

Flexible AC Transmission System (FACTS) devices

FACTS devices represent a collection of power electronic devices that can add significant operational flexibility by controlling either line impedance, phase angle, or voltage magnitude to provide improved network stability. This is often performed by controlling the active and reactive power flow of a particular circuit, or within a particular substation. FACTS devices are generally very fast-acting and finely controlled, making them well-suited to mitigation of dynamic problems that can limit power flow (and reduce power density). Specific technologies under the FACTS umbrella include series compensation systems, synchronous condensers, phase shifting transformers, static var compensators (SVCs), and static synchronous compensators (STATCOMs). Whereas FACTS devices are generally customized to the relevant applications, there are also other static flow-control devices that improve switching operations and are highly modular and typically movable, offering additional flexibility and cost-effectiveness.

Demand-Side Measures

In addition to traditional Grid-Enhancing Technologies (GETs) such as DLR and FACTS devices, demand-side measures can also offer significant flexibility in efficient grid operation, stability, and control. Broadly, demand-side measures refer to programs, policies, and technologies that adjust electricity consumption based on financial incentives. Specifically, this can include demand response programs, load shifting, and energy storage. Such measures can reduce congestion in certain nodes, reduce consumption during times of peak demand, and free up transmission capacity.

Voltage Uprating

Increasing a line's operating voltage can significantly increase the line capacity, often by more than 100% (EPRI, 2021). However, the desired increase in line capacity must be assessed relative to the project costs and budget. While a modest increase in system voltage can be made with limited physical adjustments, a larger increase in system voltage may require larger and more costly changes, such as increased phase spacing, longer insulator lengths, modifications to tower design, and substation upgrades. Further, large increases in system voltage may require right-of-way (ROW) width expansion conditional upon additional permitting. Generally, lines with more than two substations ("multiterminal lines") are prohibitively expensive to uprate as it requires more than two transformer changeouts.

Multi-Circuit and Advanced Towers

Economic and reliability considerations have historically tended to favor projects with a single circuit on each tower. However, well established industry practice allows two or even more circuits on a single tower. A number of tower designs support this, including monopole structures (a single tubular structure at the ground without guy wires) that tend to draw less landowner opposition due to being more compatible with surface activities (like farming) than older multipole (e.g., H-frame), guyed, or lattice tower designs. However, the addition of a second circuit on an existing tower, while ideally doubling the power density, may require ROW expansion conditional upon additional permitting.

A growing technique in transmission planning is "future-proofing": building lines that are designed to allow for future modifications. One example—seen especially in dense urban areas or environmentally sensitive areas where new ROW acquisition is untenable—is erecting structures that can support additional circuits over time, while initially using only one circuit. The minimally higher cost of installing a multi-circuit structure for initial single-circuit use is often an investment that pays for itself down the road, when the line can be double-circuited or serve in a separate circuit that may parallel the line in the future. Other tactics, such as designing AC lines and substation equipment capable of operating at higher voltages in the future or building AC circuits that could be converted to High Voltage Direct Current (HVDC) at a later point, are also under investigation in several regions.

While most transmission line designs are based on materials and industry practice established decades ago, improved structure designs have also been developed in recent years. These designs use novel conductor placements, enabled by improved insulator technology, to reduce surge impedance and increase the transfer capacity within existing ROW. Advanced structure designs, most notably the BOLD® designs, also typically have lower tower heights for the same voltage levels, as presented in Figure 12. With many transmission structures nearing their end of life, advanced structure design may be of particular relevance as a means of increasing power capacity through voltage uprating when old equipment is replaced. Further, recent advancements in software, drone technology and light detection and ranging (Lidar) can provide transmission line designers with highly accurate geospatial data that reduces clearance uncertainty and allows for greater power throughput.

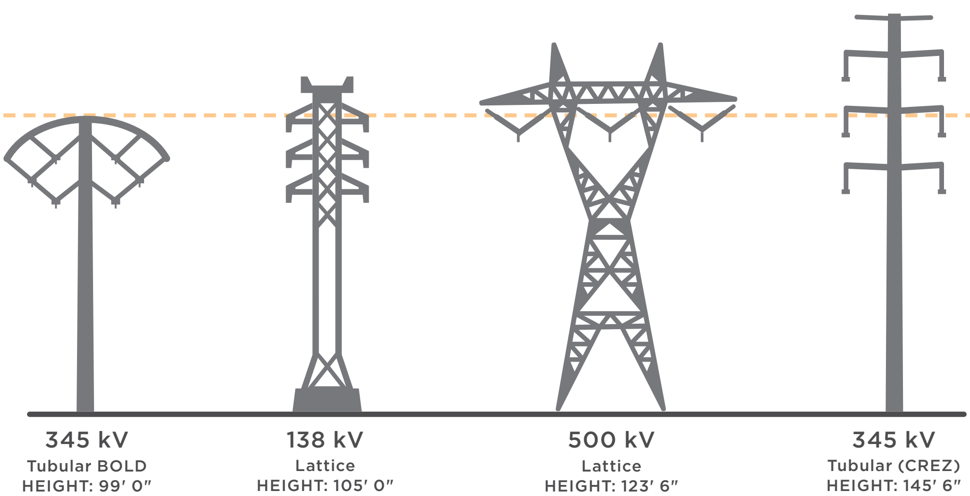


FIGURE 13.

Conventional vs advanced tower designs. The BOLD® Structure design allows for lower tower heights and increased power capacity.

Existing structures can also be retrofitted to increase capacity by raising the towers in place. One example of this is the Ampjack® Tower Lift System, which allows crews to use hydraulics to raise the existing tower in place while new structural members are installed to permanently extend the tower height. This option is particularly valuable on legacy towers that are due for structural remediation, and in areas where expanding the ROW to build new towers is untenable.

HVDC and AC-to-DC conversion

High Voltage Direct Current (HVDC) technology has been utilized for decades. However, the high costs related to AC-to-DC converter stations have conventionally limited its applications to power transmission between two unsynchronized AC networks or over very long distances, where HVDC transmission is more efficient for moving power at low losses, and not subject to the voltage and stability limitations of HVAC. However, recent advances in Voltage Source Conversion (VSC) HVDC technology have expanded the benefits to include reactive power control, synthetic inertia, black start capability, frequency response, reserve sharing, and more. The comprehensive evaluation of these benefits and the falling costs of converter stations may make HVDC technology increasingly cost competitive (Reed, 2019). Given their higher power densities, HVDC requires less space than HVAC, as seen in Figure 14, and when existing AC lines are converted to DC, the line capacity can be increased roughly twofold to threefold.

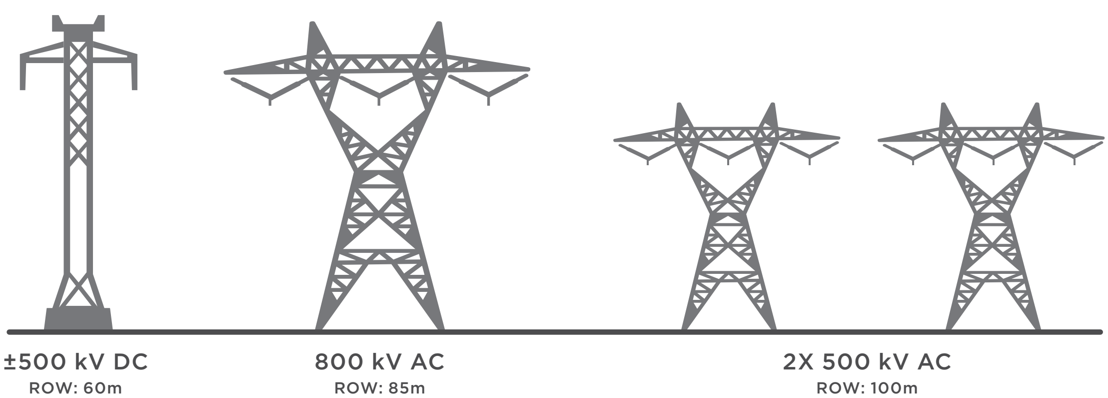


FIGURE 14.

Typical structures and required right-of-way. Despite different technologies, each design can carry approximately 2 GW of transfer capacity.Image credit: Power electronics handbook: devices, circuits, and applications handbook, edited by Muhammad H. Rashid., 3rd ed. (p. 826).

Leveraging AC-to-DC conversion to increase the transmission capacity of existing ROW, in turn unlocking renewable energy (RE) sources, requires careful evaluation as more complex multi-terminal HVDC control schemes would be needed. However, multi-circuit towers introduce the possibility of having load-serving AC circuits on one side of the towers and HVDC circuits on the other side. The system benefits can be substantial, including a 50–150% increase in power density and flow control from the DC circuits, while continuing to serve load at intermediate substations along the ROW from the AC circuits (EPRI, 2021). While this concept has been discussed for decades, operational and economic challenges have limited its development. As a result of recent advances in the industry, the Ultranet project in Germany is now piloting this solution, replacing one circuit in an existing 380 kV AC double-circuit line with a +/- 380 kV DC circuit on the same structures, and allowing for bulk power transfer from offshore wind farms in the north to load centers in the south.

Another example that is creatively leveraging HVDC technology is the Trans Bay Cable project in San Francisco, California. Rather than conventional solutions, like building a new AC line requiring new or uprated ROW, or an undergrounding project, it was decided to construct a 53-mile underwater HVDC line to inject power directly into the large-load center of San Francisco. This flexibility and reduced footprint made this project, which was far shorter than the generally accepted length for HVDC feasibility, much faster to complete than the conventional AC options. As a hallmark to the success of this project, and renewed urgency to achieve higher power densities in limited time-frames, this tactic is being replicated in the San Jose area.

APPENDIX II

EXAMPLES OF SUCCESSFUL ADVANCED CONDUCTOR DEPLOYMENT AT SCALE, FROM AROUND THE WORLD

Recognizing the benefits of advanced conductors to increase transmission capacity within a limited time-frame, a number of countries are pursuing large-scale reconductoring projects in their high-voltage networks. In some cases, advanced conductors are also being used in new transmission lines. Robust global deployment—including but not limited to the examples discussed here—has already produced a strong track record: In total, over 90,000 miles of advanced conductors have been deployed worldwide as of 2023.

Belgium

Belgium has pioneered reconductoring with advanced conductors in Europe. Since the first deployment in 2009, the country's Transmission System Operator (TSO) Elia has decided to boost power density along most of its 380 kV backbone by reconductoring with High Temperature Low Sag (HTLS) conductors by the mid-2030s (ENTSO-E, 2020; Elia, 2023). Beginning with the most congested lines, reconductoring will double the load transfer capacity from about 2,000 A to approximately 4000–5000 A, predominantly using Aluminum Conductor Composite Core (ACCC) conductors from CTC Global/Lamifil. Motivating factors for this grid reinforcement include the need to: integrate renewable energy and energy storage; accommodate the geo-spatial generational shift from retiring nuclear power plants to offshore wind resources in the North Sea; and support both domestic and industrial electrification. The main reasons for reconductoring with HTLS conductors over building new corridors are the cost and time savings—with reconductoring projects taking less than half as long and costing less than half as much as new-build projects. With the difficulty of securing new rights-of-way (ROW) exacerbated by high population density, the reduced permitting burden of reconductoring over new build is a significant advantage.

Given Belgium's location in the heart of Europe, and therefore frequent subjection to transiting power flows, reconductoring projects within and across its borders are also recognized for their potential to facilitate increased power trade and provide resiliency benefits to the greater continental grid. Interconnection projects in particular, given their increased cost-benefit ratios over building new corridors, may be prioritized by the European Commission as a Project of Common Interest (PCI), and thus eligible to receive public funds and accelerated permitting. Likewise, a supportive regulatory ecosystem has helped foster widespread adoption of advanced conductors, with Belgium's regulator CREG (Commission for Electricity and Gas Regulation) working closely with Elia to pursue the uptake of more efficiency-based technologies, provide incentives for innovation, and mitigate risks.

Netherlands

Like its Belgium counterpart, the Dutch TSO TenneT also plans to upgrade most of its 380 kV backbone to HTLS conductors, for a load transfer capacity increase from about 2500 A to 4000 A. This project, known as "Beter Benutten Bestaande 380 kV" (Making Better Use of the 380 kV Grid) involves two phases: first, upgrading 191 km (119 miles) of transmission lines between 2019 –2026, and second, upgrading an additional 165 km (103 miles) by 2035 (TenneT, 2023). Motivating factors include the difficulty of securing new ROW due to high population density; the need to address a growing interconnection queue and rapidly integrate more renewable energy (RE), especially offshore wind resources; the aim of increasing cross-border power trade; and the need to relieve congestion induced by rapid electrification, leaving no spare transmission capacity. Dutch plans have identified reconductoring with advanced composite-core conductors as a key strategy for alleviating congestion and increasing thermal transmission capacity in the near term, in tandem with additional solutions such as dynamic line ratings and improving dispatch coordination (MEACP, 2019).

With most reconductoring projects completed within a few years of conception, the replacement process is rooted in standardized practices shared by Elia and TenneT. Since the project mostly involves double-circuit lines, one circuit remains live while the other is de-energized and reconductored. Reconductoring is typically planned to coincide with lower-demand seasons, and is often combined with necessary maintenance work, such as replacing insulators, ground wires, and bird flight diverters, or reinforcing towers and mast foundations to bring them into line with the latest construction standards. Phase number optimization, to reduce or avoid expanding the magnetic field zone, can also be done concurrently with reconductoring.

Italy

Whereas reconductoring projects in Belgium and the Netherlands involve relatively short lines (< 90 km or 50 miles), Italy presents a case of transmission capacity expansion over significantly longer distances and at a larger scale. Motivating factors include the difficulty of securing new ROW due to high population density; the aim of strengthening network reliability and resilience; and the need to rapidly integrate more renewable energy in the face of a growing interconnection queue.

Terna, the Italian TSO, plans to invest 11 billion Euros in a Hypergrid network to double the exchange capacity between market zones in the country (from 16 GW to 30 GW) by the mid-2030s (Terna, 2023). In addition to reconductoring several 380 kV lines with advanced conductors with high temperature performance, the plan envisions a large, multi-terminal HVDC network running across the country. New north-south power lines are planned as undersea HVDC cables, as opposed to conventional AC overhead lines, due to "the impossibility of overhead lines or the need for synergy/efficiency with existing projects" (Terna, 2023). Several existing overhead AC lines are also set to be "modernized", i.e., converted to HVDC operation, raising the voltage from 220 or 380 kV AC to 500 kV DC, enabling the bulk transport of renewable energy from southern generation centers to northern load centers.

India

India, like other emerging economies where rapid electrification and load growth make increasing power transfer capacity a near-term priority, is also turning to reconductoring. In India, the transmission planning philosophy dictates the optimization of existing ROW and costs under a long-term perspective, particularly for constrained areas, including urban centers and difficult terrain. Guidelines explicitly outline the application of smart grid technologies (including FACTS devices and phase-shifting transformers); the upgrading of existing AC transmission lines to higher voltages; the reconductoring of existing AC transmission lines with higher ampacity conductors; and the use of multi-voltage levels, multi-circuit transmission lines, and HVDC transmission (CEA, 2023).

India's utilization of advanced conductors also highlights the technology's ability to increase the power transfer capacity of distribution systems. State utilities have also been prioritizing energy efficiency through the inclusion of an ohmic loss evaluation in their tenders, which favors advanced conductors due to their lower losses compared to conventional conductors. Large portions of the country's heavily populated, land-constrained cities like Delhi and Mumbai have been upgraded to advanced conductors to increase capacity and improve grid reliability and efficiency. Increasingly, the planning approach aims to evaluate conductor investments on a total cost of ownership basis, rather than a conventional cost estimation process, in order to more accurately capture conductor benefits.

China

China is also active in its adoption of advanced conductors, utilizing them in both reconductoring projects and new lines. This is strongly motivated by increased demand for electricity precipitated by the country's rapid economic growth, as advanced conductors offer an efficient and feasible means of reaching ambitious transmission growth objectives.

APPENDIX III

DETAILED DESCRIPTION OF METHODS AND SCENARIOS

Existing Lines

Our analysis is based on data on U.S. transmission lines from the U.S. Homeland Infrastructure Foundation-Level Data (HIFLD) (29), at 100 kV and above as per the methodology of the National Renewable Energy Laboratory (NREL) NREL Regional Energy Deployment System (ReEDS) model (HIFLD, 2023; NREL, 2021). For each voltage, we define the surge impedance in Ohms (taking the upper limit as a conservative value) to estimate the surge impedance loading (SIL). We use these SIL values to estimate the rated capacity for each line utilizing the standard St. Clair curve, defining line loadability as a function of distance to obtain a length-dependent SIL multiplier. This multiplier applies to all voltage levels except 765 kV, where the thermal limit is defined as 2.7*SIL for line lengths of up to 50 miles. As technical line configuration is unknown, we assume one circuit per line, no installed compensation, and that ratings are constant throughout the year (i.e., no seasonal ratings). The resulting total estimated transmission capacity of about 190 TW-miles aligns closely with the current GW-miles deployed in the U.S. (109 TW-miles of interregional capacity plus 86 TW-miles of within-region transmission, for a total of 195 TW-miles) (DOE, 2023).

Reconductored Lines

Given the limitations of the standard St. Clair curve for calculating line loadability as a function of distance with advanced conductors and/or varying compensation, we analytically derive St. Clair curves for an equivalent-diameter Aluminum Conductor Steel Reinforced (ACSR) cable and Aluminum Conductor Composite Core (ACCC) cable, given that the latter is the most widely deployed advanced conductor to date (Figure 14). We consider both zero and unlimited compensation at the receiving end and assume the ACCC® conductor's thermal limit is 2x and resistance is 0.75x that of the ACSR conductor (Lauria, 2017; Lauria, 2019; Gutman, 1979). We extend the St. Clair curves up to 300 miles, the length of the longest AC transmission line in the U.S. (HIFLD, 2023). From these curves, we quantify the capacity increase through reconductoring—based on the ratio of ACCC® loadability over uncompensated ACSR loadability—and determine the set of complementary strategies used, i.e., compensation and sectionalization—based on the line length. In line with previous derivations, we assume that the curves hold across varying voltage levels, although some minor differences may occur, e.g., due to conductor size and configuration.

POWER TRANSFER CAPABILITY AS A FRACTION OF THERMAL LIMIT BASED ON ST. CLAIR'S CURVES FOR LINE LOADABILITY

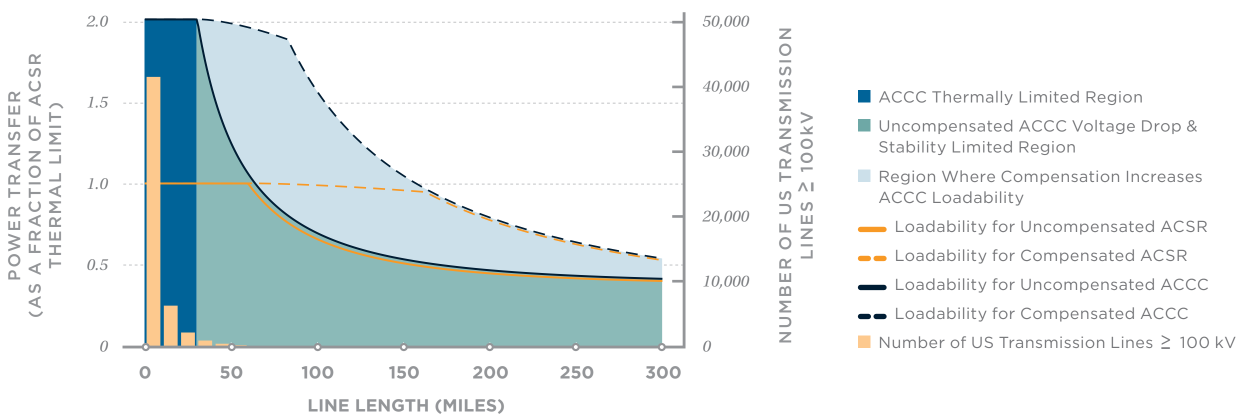


FIGURE 15.

St. Clair curves. Red lines represent Aluminum Conductor Steel Reinforced (ACSR), and blue lines represent Aluminum Conductor Composite Core (ACCC); solid lines indicate no reactive power compensation, and dashed lines indicate unlimited reactive power compensation. The yellow bars show a histogram of the number of U.S. transmission lines above 100 kV with a bin size of 10 miles (HIFLD, 2022). We also indicate the select strategies for doubling transmission capacity as a function of line length, although a full system study including load flow, contingency, and dynamic stability analyses should be conducted to verify these numbers in each real-world system. It should be noted that the St. Clair curve, while known as a single curve, is really a piecewise function for which the governing constraint—i.e., the thermal, voltage drop, and angular stability limits—defines each sub-interval.

Approximately 98% of the nation's 53,000 transmission lines at or above 100 kV are less than 50 miles long, i.e., typically short enough to avoid most voltage drop and stability limitations, and therefore are constrained primarily by thermal limitations (HIFLD, 2022). Reconductoring these lines with advanced composite-core conductors would raise the line conductor's thermal limit, improving its ability to withstand higher operating temperatures without compromising its structural integrity. We find that for lines under ~30 miles long, reconductoring simply doubles the line's thermal limit, while for lines of 30–50 miles, reconductoring with voltage support such as reactive power compensation, as necessary, can double the thermal limit.

The remaining 2% of transmission lines >50 miles are generally limited by voltage and angular stability constraints, which voltage support such as reactive power compensation can partially mitigate but not entirely assuage. To fully reap the benefit of increased thermal capacity offered by reconductoring, then, we find that the voltage and angular stability considerations can be improved with sectionalization, i.e., the addition of new substation(s) with active and reactive power generation sources along the line (CIGRE, 2022). This tactic, illustrated in Figure 15, leverages both the benefits of advanced conductors and simultaneously creates new interconnection points for renewable energy resources, coupled with storage.

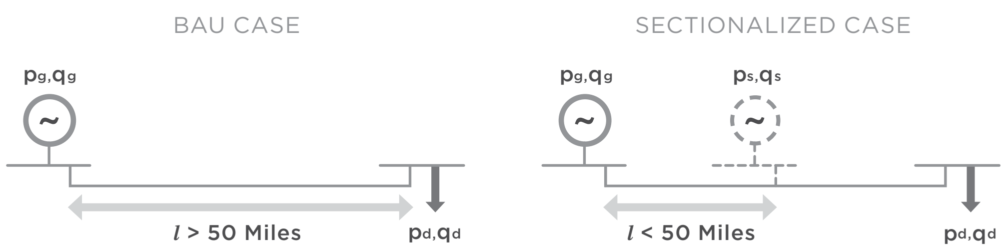


FIGURE 16.

The concept of sectionalization. Long lines can be sectionalized into segments at most 50 miles in length, to interconnect generation with grid-forming inverter technology. This enables greater transfer capacity across the entire line and the incorporation of new interconnection points for storage-backed renewable energy resources. pg is generator active power, qg is generator reactive power, l is line length, ls is sectionalized line length, pd is load active power, and qd is load reactive power.

The concept of sectionalization is demonstrated in a few ongoing real-world projects. For one, CAISO is constructing the new policy-driven 500/230 kV Manning Substation between Los Banos and Gates along Path 15 (the key transmission corridor between northern and southern California) in order to loop in renewable energy generation (primarily solar) from the San Joaquin Valley. Meanwhile, NV Energy is developing two new transmission lines—known as Greenlink West and Greenlink North—in Nevada, in order to improve grid reliability as conventional generation is phased out; these projects designate three "collector" substations, spaced evenly along these long lines at Esmeralda, Amargosa, and Lander, to collect nearby solar generation.

Reconductoring Costs

We build up the generic costs of expanding a line's transmission capacity through reconductoring and compare it with the conventional approach of building a new line parallel to an existing right-of-way (ROW), consisting of the ROW, structures, conductors, and development. For new lines, we do not include the additional financial risk, including the time value of money, associated with these projects which typically take a decade or more.

Right-of-way: Since reconductoring projects take place within existing ROW, no new land is required. For new lines, we utilize the U.S.-average cost of pastureland from the U.S. Department of Agriculture; although land costs may vary widely by state and be highly elevated, especially in urban or suburban areas (USDA, 2022; MISO, 2022). Although a new line that runs parallel to an existing ROW may be able to utilize some or all of an already-secured ROW, this may not always be the case, and we conservatively assume that an all-new ROW must be secured based on ROW width by voltage level. To the land costs, we add acquisition costs along with regulatory and permitting costs (MISO, 2022).

Structures: We assume all new structures are steel lattice towers and include the costs of materials, installation, hardware, and the structure foundation for the various structure types (tangent structures, running angle structures, non-angled deadend structures, and angled deadend structures) and their respective quantity-per-mile approximations (MISO, 2022). Reconductoring does not typically require any structure modification, so structure costs are assumed to be zero, although other necessary maintenance work is often performed concurrently with the reconductoring.

Conductors: We estimate the costs of the conductors based on the material, installation, and accessory costs of ACSR and equivalent-diameter ACCC® conductors (as the most widely-deployed advanced conductor to date) (MISO, 2022). For each voltage level, we establish a reference conductor size selection and bundle quantity (NREL, 2013; MISO, 2022). For sag and wastage, we assume an addition of 4% to the conductor material costs (MISO, 2022). For new lines, we assume that a shield wire is necessary for each circuit (MISO, 2022). For reconductoring, we assume that the aluminum from the former ACSR conductor can be recovered and recycled—at 50% the 5-year average price of new aluminum—which is then subtracted from the total costs (Business Insider, 2023).

Development: For development, we assume a contingency of 10% and an additional 5.5% for project management, 1.5% for administrative overhead, and 3% for engineering, testing, and commissioning, added to the sum of the ROW, structure, and conductor costs (MISO, 2022). We also assume an additional 7% allowance for funds used during construction (AFUDC), added to the sum of the ROW, structure, conductor, and contingency costs (MISO, 2022).

AC Terminals: The upgrades to AC terminal stations within a reconductoring project are heavily dependent on the ratings of the existing terminal equipment, especially the transformers and protection equipment. The ReEDS model accounts for terminal costs separate from line costs, so we use the terminal costs provided in ReEDS for both reconductoring and new-build lines, conservatively assuming that reconductoring projects require a full new substation. If the line length requires, we include in the reconductoring cost the cost of compensation, based on the cost of a static var compensator (SVC) (representing the median cost amongst various compensation technologies (MISO, 2022)), using the quantity of compensation determined by theory from the previous capacity estimates (Lauria, 2017; Lauria, 2019). If the line length requires, we also include in reconductoring cost the cost of sectionalization, reflecting a new 6-position (double-breaker bus) substation (MISO, 2022), although in practice these costs are typically allocated to the generators seeking access to the transmission system.

To this generic cost build-up, we add the cost of compensation and sectionalization, as a function of voltage level and line length, in order to estimate the total cost in US$/mile of reconductoring each of the ~53,000 transmission lines in the U.S. at 100 kV and above (HIFLD, 2022). We then incorporate the previously quantified delta capacity increase to obtain unit costs in US$/MW-mile.

Modeling Assumptions

We utilize the NREL ReEDS capacity expansion and dispatch model for the contiguous U.S. electric power system, in order to assess the impact of reconductoring on future-generation capacity additions, electricity costs, and new transmission development, etc. by 2050 (NREL, 2021). The ReEDS model utilizes a system-wide least-cost optimization approach to identify the most cost-effective mix of electricity generation, storage, and transmission technologies that can meet regional electric power demand. This optimization takes into account factors such as grid reliability, technology resource constraints, and policy constraints, and is performed in two-year intervals starting from 2010, with the capability to extend simulations up to the year 2100. The model yields a range of key outputs including generator capacity, annual generation from each technology, storage and transmission capacity expansion, total sector costs, and electricity prices, as well as fuel demand, prices, and CO_2 emissions. Although ReEDS can also simulate the power sectors of Canada and Mexico, it is primarily focused on the contiguous United States, which it divides into 134 model balancing areas that are interconnected by approximately 300 representative transmission paths, thereby providing a granular geographical and regulatory representation.

In this study, we use the 2022 version of ReEDS which includes all U.S. state and federal policies as of December 2022, including both the recently passed Inflation Reduction Act and the Infrastructure Investment and Jobs Act. We include stringent site exclusions in ReEDS. We model a high rate of electrification, with correspondingly high load and high zero-carbon generation build-out. To the base model, we also add additional constraints to retire coal capacity by 2035, implemented linearly with the oldest plants retiring first, and disallow new gas capacity post-2023, except plants that are already under construction—reflective of not only pending policy from the Environmental Protection Agency (EPA) but also the investment uncertainty regarding the construction of new fossil plants. No additional transmission capacity expansion is allowed between the three interconnects (East, West, ERCOT) nor across national borders (Canada, Mexico).

Scenario Design

The ReEDS model represents transmission via a synthetic network of 134 nodes connected by 300+ transmission paths, based on the real-world grid. The capacity of each path is determined from power flow analysis, incorporating individual line ratings. Meanwhile, the nodes are generally located in the center of each zone, also known as a balancing area. While this means that the ReEDS model inherently focuses on the build-out of interzonal transmission rather than intrazonal transmission or spur lines, power system planning studies generally must scale down the existing transmission system into a synthetic model for tractability and computational efficiency; however, despite these limitations, synthetic models can still be used to draw broad conclusions about transmission needs (NREL, 2022; Repeat Project, 2022; DOE, 2023).

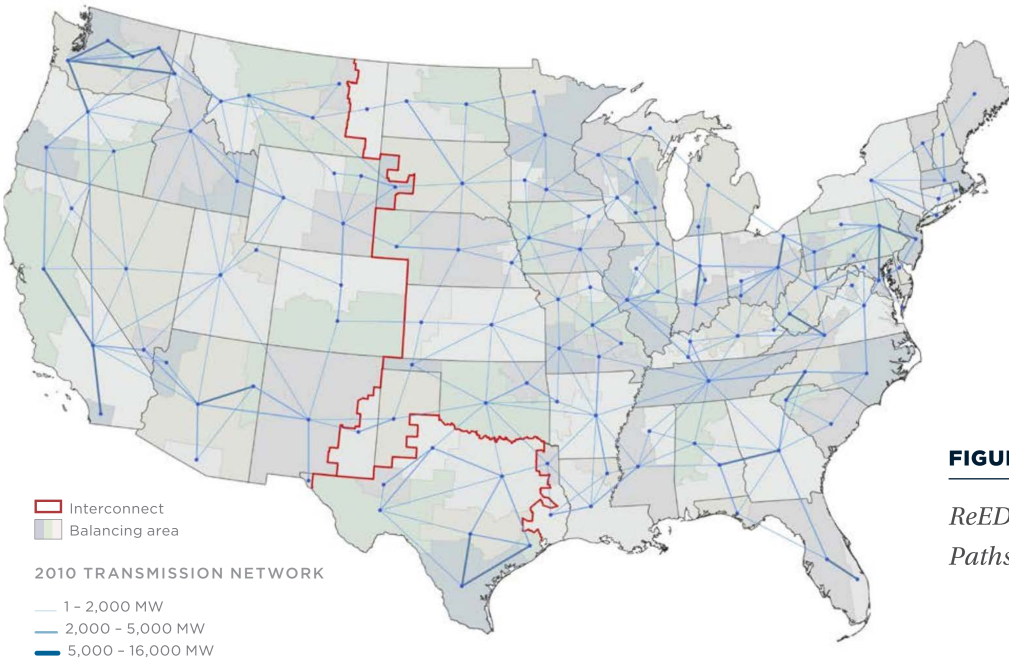


FIGURE 17.

ReEDS Transmission Paths (NREL, 2021).

We match every physical transmission line with a path in ReEDS and estimate its reconductoring cost by taking a GW-mile weighted average of the cost to reconductor each individual line that makes up the path.

By default, ReEDS only allows new-build transmission expansion, whose costs per MW-mile are calculated based on the voltage level of existing lines within the balancing area with regional multipliers. To simulate the reconductoring option in the ReEDS model, we provide it with a supply curve, composed of two bins with costs for each path—the first bin being reconductoring, capped at double the path's existing capacity in ReEDS; and the second bin being new-build capacity requiring new ROW, with unlimited build-out potential.

The four studied scenarios are summarized in Table 3. The scenario without reconductoring as an option and with a restricted build-out rate represents the business-as-usual (BAU) scenario.

TABLE 3.

Scenario summary.

Restricted build-out rate, Reconductoring not allowed (Business-as-usual)	**Restricted build-out rate, Reconductoring allowed**
Unrestricted build-out rate, Reconductoring not allowed	**Unrestricted build-out rate, Reconductoring allowed**

The four scenarios represent each combination of two variables: (1) whether build-out of new transmission is restricted to historical rates, and (2) whether the model is permitted to select reconductoring as an option for achieving the defined objective while fulfilling its function of minimizing cost.

Scenarios in which we restrict the build-out rate reflect permitting and cost allocation challenges through the addition of various constraints, as follows. For new-build lines that are potentially hindered by both issues, we limit the total nationwide expansion to 1400 GW-miles/year, the 2010–2021 average rate (Grid Strategies, 2022). For new-build lines, we also apply intraregional and interregional constraints, limiting annual expansion to the recent intraregional and interregional rates, respectively, for each region. For reconductoring, which may be hindered by interregional cost allocation issues, we similarly limit annual expansion of interregional capacity to the recent interregional rate. For the purposes of this study, transmission "region" refers to the Federal Energy Regulatory Commission (FERC) Order 1000 transmission planning regions, as presented in Figure 18.

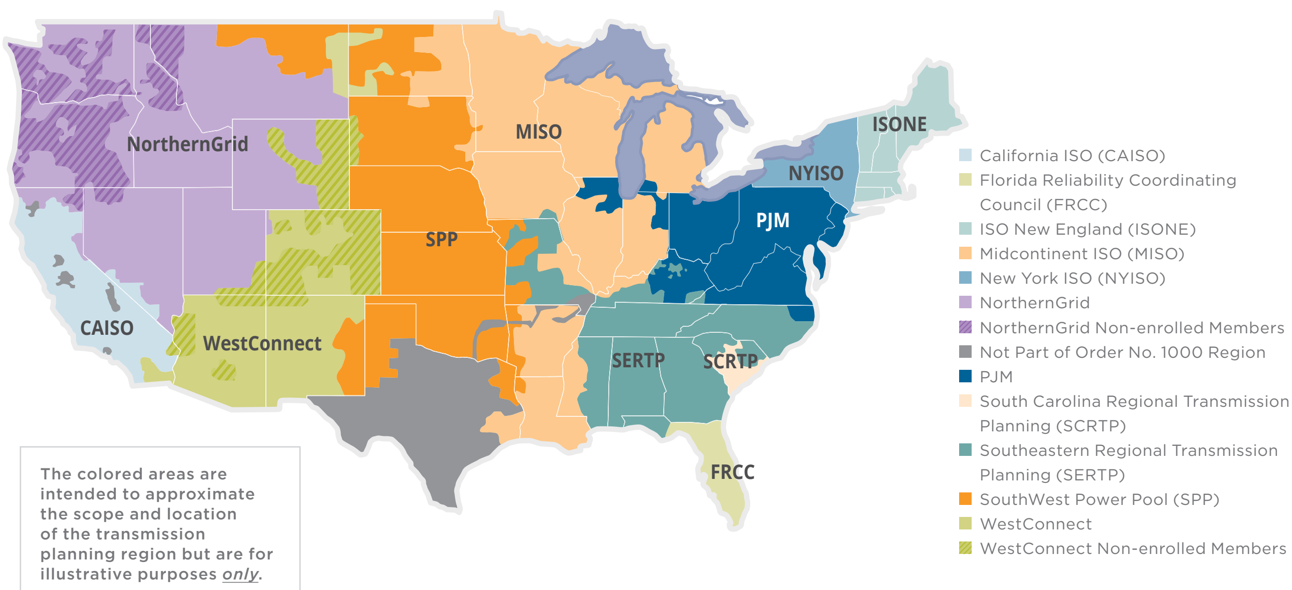


FIGURE 18.

Federal Energy Regulatory Commission (FERC) Order 1000 Regions including the California ISO (CAISO), Florida Reliability Coordinating Council (FRCC), ISO New England (ISONE), Midcontinent ISO (MISO), Northern Grid, New York ISO (NYISO), Pennsylvania-New Jersey-Maryland Interconnection (PJM), WestConnect, Southwest Power Pool (SPP), South Carolina Regional Transmission Planning (SCRTP), and Southeastern Regional Transmission Planning (SERTP). The Electric Reliability Council of Texas (ERCOT) is not FERC Jurisdictional, but it is included in this study as a "region."

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