Energy Institute WP 343R

Accelerating Transmission Expansion by Using Advanced Conductors in Existing Right-of-Way

Emilia Chojkiewicz, Umed Paliwal, Nikit Abhyankar,
Casey Baker, Ric O'Connell,
Duncan Callaway, and Amol Phadke

Revised February 2024

Energy Institute at Haas working papers are circulated for discussion and comment purposes. They have not been peer-reviewed or been subject to review by any editorial board. The Energy Institute acknowledges the generous support it has received from the organizations and individuals listed at https://haas.berkeley.edu/energy-institute/about/funders/.

Accelerating transmission expansion by using advanced conductors in existing right-of-way

Emilia Chojkiewicz[1], Umed Paliwal[1], Nikit Abhyankar[1], Casey Baker[2], Ric O'Connell[2], Duncan Callaway[1*], and Amol Phadke[1*]

Abstract

As countries pursue decarbonization goals, the rapid expansion of transmission capacity for renewable energy (RE) integration poses a significant challenge due to hurdles such as permitting and cost allocation. However, we find that large-scale reconductoring with advanced composite-core conductors can cost-effectively double transmission capacity within existing right-of-way (ROW), with limited additional permitting. This strategy unlocks a high availability of increasingly economically-viable RE resources in close proximity to the existing network. We implement reconductoring in a model of the United States power system, showing that reconductoring can help meet over 80% of the new interzonal transmission needed to reach over 90% clean electricity by 2035 given restrictions on greenfield transmission build-out. With $180 billion in system cost savings by 2050, reconductoring presents a cost-effective and time-efficient, yet underutilized, opportunity to accelerate global transmission expansion.

[1]University of California, Berkeley.
[2]GridLab
*Corresponding authors' emails: dcal@berkeley.edu, aaphadke@berkeley.edu
Funding for this study was provided under a grant from Breakthrough Energy and supported by GridLab. See solar & wind resource potential near existing transmission infrastructure here. View key modeling results here. Explore indicative transmission corridors that could benefit from capacity increases to unlock renewables here.
All data needed to evaluate the conclusions in the paper are included in the paper and/or the Supplementary Materials. All opinions, errors, and omissions are solely attributable to the authors.

1. Introduction

Increasingly, the energy transition discourse is focusing on electricity transmission: the need to build it and the challenges of doing so. The International Energy Agency (IEA) estimates that the global length of transmission lines must increase from 5.5 million to 15 million km - approximately 2.7 times - to reach net zero emissions by 2050, not including the eventual replacement of aging infrastructure *(1*). In the United States (US) and Europe, however, new overhead lines take an average of over 10 years to build (*1,2).* Grids are increasingly becoming the bottleneck of the energy transition, with over 1,200 GW of renewable energy (RE) projects in the US, and over 3,000 GW globally, awaiting connection to the grid *(3,4)*. Challenges related to permitting - such as securing new right-of-way (ROW), completing environmental impact assessments, and cost allocation - often result in project delays *(1,2)*. In the US, for example, the rate of transmission build-out has fallen by nearly 50 percent over the past decade, threatening decarbonization timelines *(5,6)*.

Recent rapid declines in the costs of solar, wind and batteries *(7)* along with incentives from the Inflation Reduction Act (IRA) have presented an opportunity for a paradigm shift in how transmission is planned and sited. Specifically, there is a narrowing gap in cost between RE sited at locations with the highest resource potential and RE sited at locations that are in close proximity to the existing transmission network and load. This RE capacity could be unlocked through a wide range of technological solutions that can increase the transmission capacity of the existing grid. Some strategies, known under the umbrella term of Grid-Enhancing Technologies (GETs) and including Power Flow Controllers (PFCs), Flexible AC Transmission Systems (FACTS) devices, Dynamic Line Ratings (DLR) and demand-side measures, can either enhance the physical capability of a transmission asset or the efficiency of power flow throughout the system. However, while these technologies are extremely important to expanding grid capacity, their potential is dependent on real-time operating conditions and thus typically limited and temporary. Other strategies can provide a larger and lasting increase of transmission capacity, such as reconductoring, voltage upgrades and AC-to-DC conversion. Yet whereas voltage upgrades may necessitate widening of the existing ROW and AC-to-DC conversion is generally most suitable for long lines, reconductoring - the replacement of a transmission line's existing conductors with either larger-diameter conductors or a different type of conductor - is a practice used by utilities to increase ampacity within existing ROW.

In recent decades, the development of advanced composite-core conductors has opened up new possibilities for rapid transmission capacity expansion through reconductoring *(14)*. While most of the high voltage grid today is wired with a century-old technology known as Aluminum Conductor Steel Reinforced (ACSR) featuring aluminum strands around a steel core *(8),* advanced conductors swap the steel for a stronger yet smaller composite-based core. This enables higher operating temperatures and more conductive aluminum to fit within an equivalent diameter, allowing advanced conductors to carry approximately twice as much power over ACSR (Fig. 1A). The composite-based core also reduces line sag, meaning the utilization of advanced conductors in reconductoring projects minimizes the need for and thus the costs of modifying structures to accommodate pre-existing clearances, as reconductoring with conventional high-ampacity conductors such as Aluminum Conductor Steel Supported (ACSS) may risk larger sags. Because reconductoring projects leverage existing transmission towers and ROW, the extensive land acquisition and permitting processes that impede the construction of new lines can be circumvented (Fig. 1B) *(8,14-16).*

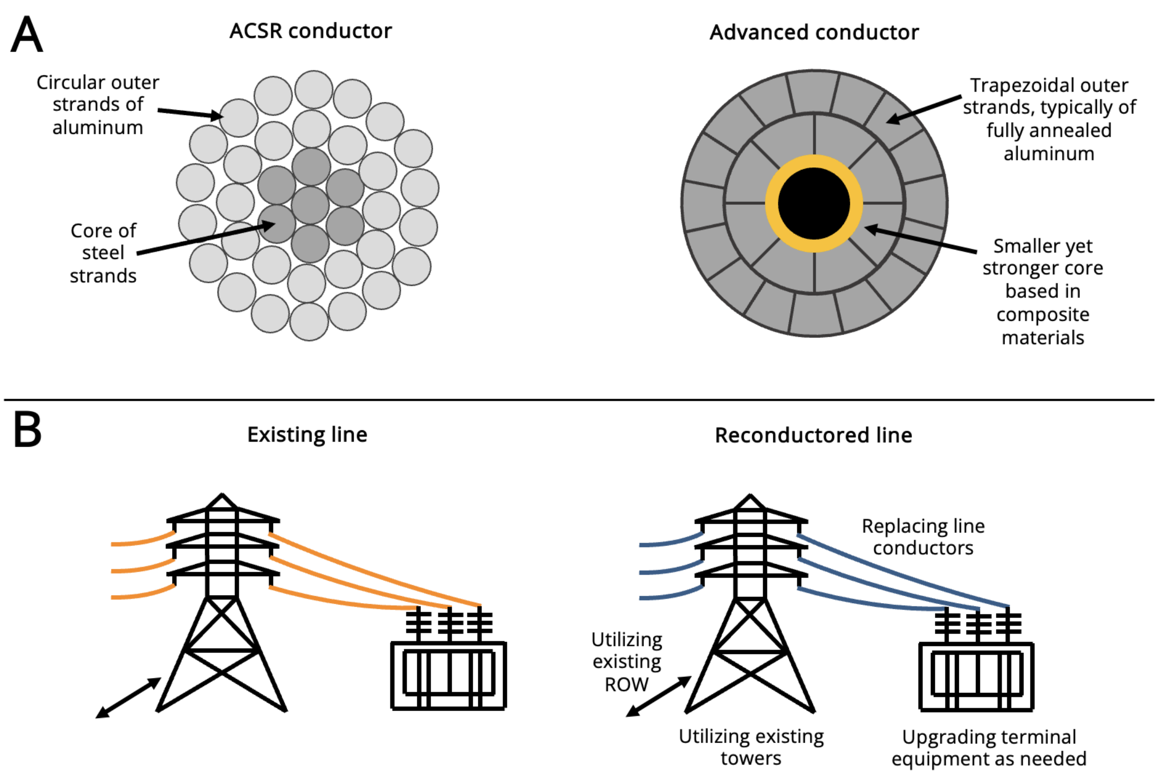

Fig. 1: Conventional conductor technology compared to lines reconductored with advanced composite-core conductors. (A) A comparison of a cross-section of a conventional ACSR conductor compared to an equivalent-diameter advanced composite-core conductor (for more details, see the supplementary text). While ACSR conductors can also be stranded with trapezoidal outer strands, the most commonly utilized conductor design features circular outer strands. (B) A schematic of an existing transmission line reconductored with advanced composite-core conductors.

Previous work has established that it is cost effective and time efficient to expand transmission capacity by reconductoring existing lines *(8,14-16)*. Further, advanced conductors may offer additional advantages such as reduced galvanic corrosion and lower line losses during certain operating conditions (see the supplementary text, Figs. S1 and S2, and Table S1). Over 90,000 miles of advanced conductors have been deployed globally (see the supplementary text for case studies), and manufacturing is widespread, including 3M, Southwire, CTC Global, TS Conductor, and Epsilon. However, in the US the technology is generally regarded as a niche solution for large spans such as river crossings *(9-13)*. Further, major US power system planning studies *(17-22)*, models *(23)* and existing planning tools *(24)* limit analysis to the construction of new lines only, or omit the most widely deployed composite-core conductor to date, CTC Global's Aluminum Conductor Composite Core (ACCC) *(15,25)*. While the selection of the technological solution to increase transmission capacity should be carefully evaluated based on project needs, technical parameters, costs, timeline constraints, grid topology and environmental conditions, these apparent advantages support the investigation of reconductoring with advanced conductors. However, no study has investigated the transmission capacity expansion potential of reconductoring at scale.

In this article, we show how recent developments have converged to present an opportunity for large-scale reconductoring to enable rapid transmission expansion US-wide. We first assess the transmission capacity increase and associated cost to reconductor all 53,000 US transmission lines. We select the most widely deployed composite-core conductor to date - CTC Global's ACCC - for evaluation, although many other advanced conductors with similar thermal capabilities are available. We implement the resulting unit cost estimates in a widely-used transmission and generation capacity expansion model, the Regional Energy Deployment System (ReEDs) *(23).* We apply constraints on the rate of transmission build-out to capture the permitting and cost allocation challenges that delay the development of transmission projects. Our modeling shows that reconductoring enables nearly four times as much transmission capacity to be added between the 134 ReEDS zones by 2035 at a marginally higher investment cost, compared to the case when only greenfield expansion is allowed at the recent historical rate. Reconductoring unlocks a high availability of cost-effective renewable resources in close proximity to the existing US transmission network and load, helping to meet over 80% of the new interzonal transmission needed to reach over 90% clean electricity given restrictions on greenfield transmission build-out. We also find that reconductoring can be a promising solution for intrazonal transmission capacity expansion, given that these lines tend to be shorter with lower unit costs to reconductor. These results indicate that reconductoring should constitute a key pillar in strategies to achieve grid decarbonization goals.

Advanced conductors enable a doubling of line capacity at less than half the cost of new lines

Reconductoring with advanced composite-core conductors raises the line conductor's thermal limit, improving its ability to withstand higher temperatures of operation without compromising its structural integrity. However, the rated transfer capacity of long alternating current (AC) lines may be constrained by non-thermal factors, such as voltage drop and/or angular stability limits. To fully reap the benefit of increased thermal capacity offered by reconductoring, voltage drop and stability limits can be improved with additional voltage support in the form of reactive power compensation and/or sectionalization (the addition of new substation(s) with active and reactive power generation sources along the line, see the supplementary text and Figs. S3 and S4). We show this in the St. Clair's curves in Fig. 2A, showing line loadability of ACCC and ACSR lines as a function of line length, with and without voltage support *(26-28)*. Assuming the base case line is wired with ACSR, and the reconductored line is wired with an equivalent-diameter ACCC, reconductoring with voltage support as needed can double transmission capacity for lines up to approximately 50 miles. For the 2% of US transmission lines above 50 miles, sectionalization at most every 50 miles can shorten the effective line length that with voltage support as needed can similarly up to double transmission capacity (see the supplementary text) *(29)*.

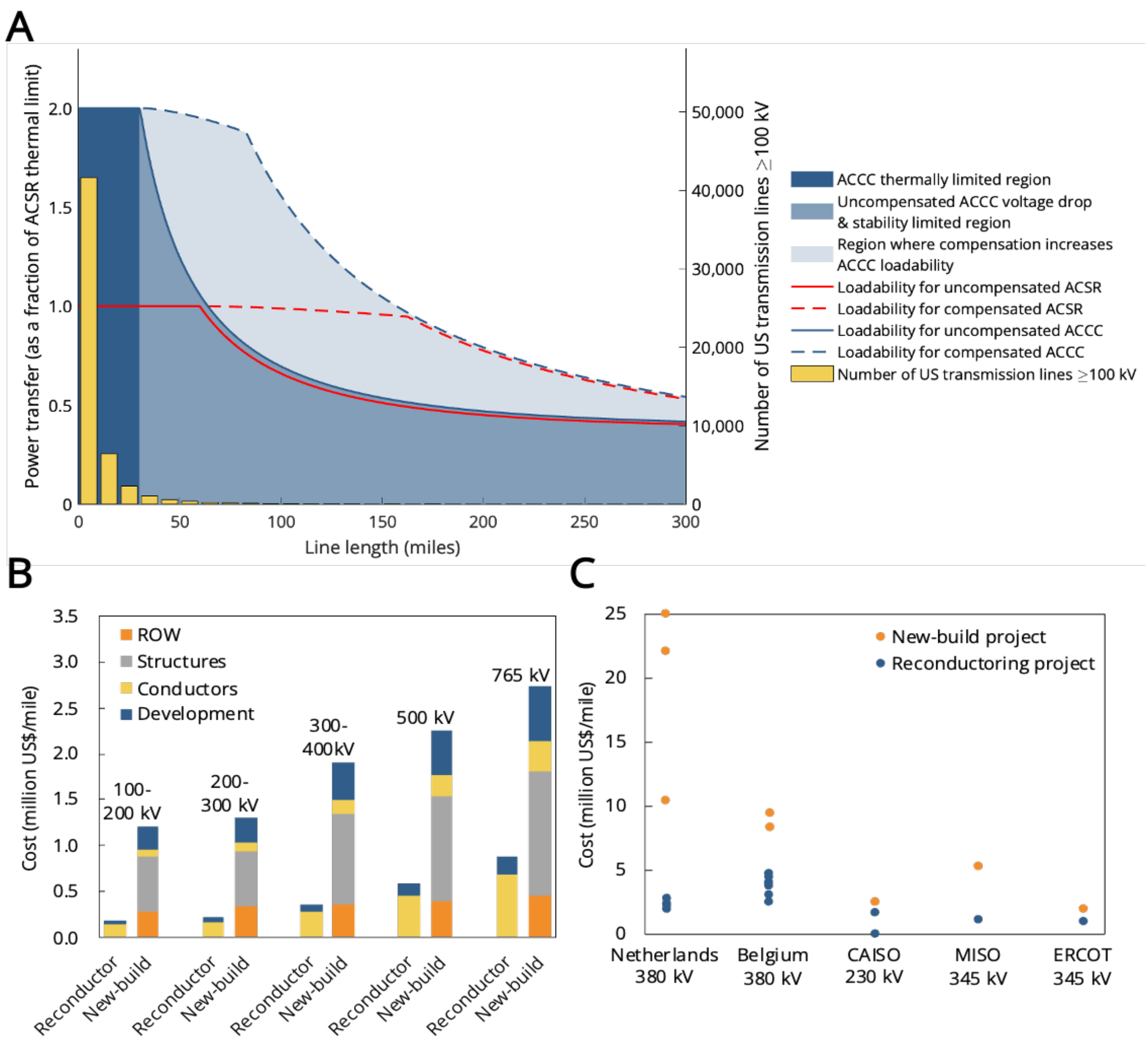

Fig. 2: Capacity increases and costs of reconductoring. (A) The St. Clair's curve for ACSR and ACCC conductors represents a piecewise measure of transmission line loadability as a function of line length, with the governing constraint - i.e., the thermal, voltage drop and angular stability limits - defining each interval of the curve. A full system study including load flow, contingency and dynamic stability analyses should be conducted to verify these numbers in each real-world system. Red lines represent ACSR and blue lines represent 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 US transmission lines above 100 kV with a bin size of 10 miles *(29)*. (B) Bottom-up cost estimates for reconductoring projects and new-build projects by voltage level (see Methods). Our estimates for new-build projects with ACSR are in line with generic estimates from other popular transmission planning tools *(23-25)*, falling within 20% for each voltage level. (C) Empirical project cost data from Europe and the US, presented by jurisdiction since cost definition and composition may vary (see Table S2) *(30-38)*.

We estimate the bottom-up cost to increase transmission capacity through reconductoring projects vis-a-vis new-build projects with ACSR (Fig. 2B). Although advanced conductors currently cost two to four times more than conventional conductors on a unit length basis due to higher raw material costs and limited scale of production *(8,16)*, the total cost of reconductoring projects on a unit length basis is less than half of new-build projects due to the avoided cost of new ROW and structures (see the supplementary text). These findings are reflected in empirical cost data from reconductoring and new-build projects in Europe and the US (Fig. 2C, Table S2).

Reconductoring can play a pivotal role in low-cost decarbonization of power systems

To demonstrate the utility of reconductoring to achieving decarbonization goals, we extend the ReEDS model to include reconductoring as a decision variable. We first calculate the cost to reconductor each of the 53,000 transmission lines in the US (defined as a segment at or above 100 kV) *(29)* based on voltage level and line length (see the methods and Table S3). Like other power system planning models that require tractability and computational efficiency to draw insights on transmission needs *(17-21)*, ReEDS simplifies the real-world system into 134 zones connected by 300+ transmission paths. We estimate the cost of reconductoring each ReEDS path by taking a GW-mile weighted average of the cost to reconductor each individual line that makes up the path, use these per-line costs to generate a supply curve for the path, then run a least-cost system optimization investigating system expansion under four scenarios: with and without reconductoring as an option, and with and without constraints on the rate of transmission build-out, on a time horizon up to 2050. We consider IRA incentives and increases in load due to high electrification. Furthermore, reflecting pending policy from the Environmental Protection Agency (EPA), and consistent with a net-zero pathway, we model the phase-out of coal generation by 2035, and we block the construction of new gas-fired capacity (for more details, see Methods). For new-build lines, build-out constraints reflect permitting and cost allocation challenges through nationwide, interregional and intraregional constraints based on recent historical rates; for reconductoring projects, build-out constraints reflect cost allocation challenges for interregional lines through a similar constraint based on recent historical rates (for more details, see Methods).

We find that when reconductoring is an option, it is favored over building new lines due to its lower cost, representing 66% of interzonal transmission capacity added by 2035 in the unrestricted build-out case (Fig. 3A). This indicates that even without factoring in the benefit of faster project realization resulting from leveraging existing ROW, reconductoring should be considered as a key strategy for expanding transmission capacity purely based on its cost competitiveness. The significance of reconductoring is even more pronounced in the case where build-out is restricted to the recent historical rate, enabling nearly four times as much new interzonal transmission capacity to be added by 2035 at only slightly higher cost (Fig. 3A and 3B). The resulting transmission capacity increase with reconductoring is therefore not only larger but also distributed over more transmission corridors (Fig. 3C and 3D). Further, regardless of build-out rate restrictions, reconductored capacity accounts for the majority of interzonal capacity added before 2030 (Fig. 3E and 3F). Although this trend is likely driven by the lower cost of reconductoring, considering that new lines often take 10-15 years to complete *(1,2,4)*, reconductoring presents a synergistic opportunity for expanding transmission capacity in the near-term while new lines are planned and permitted.

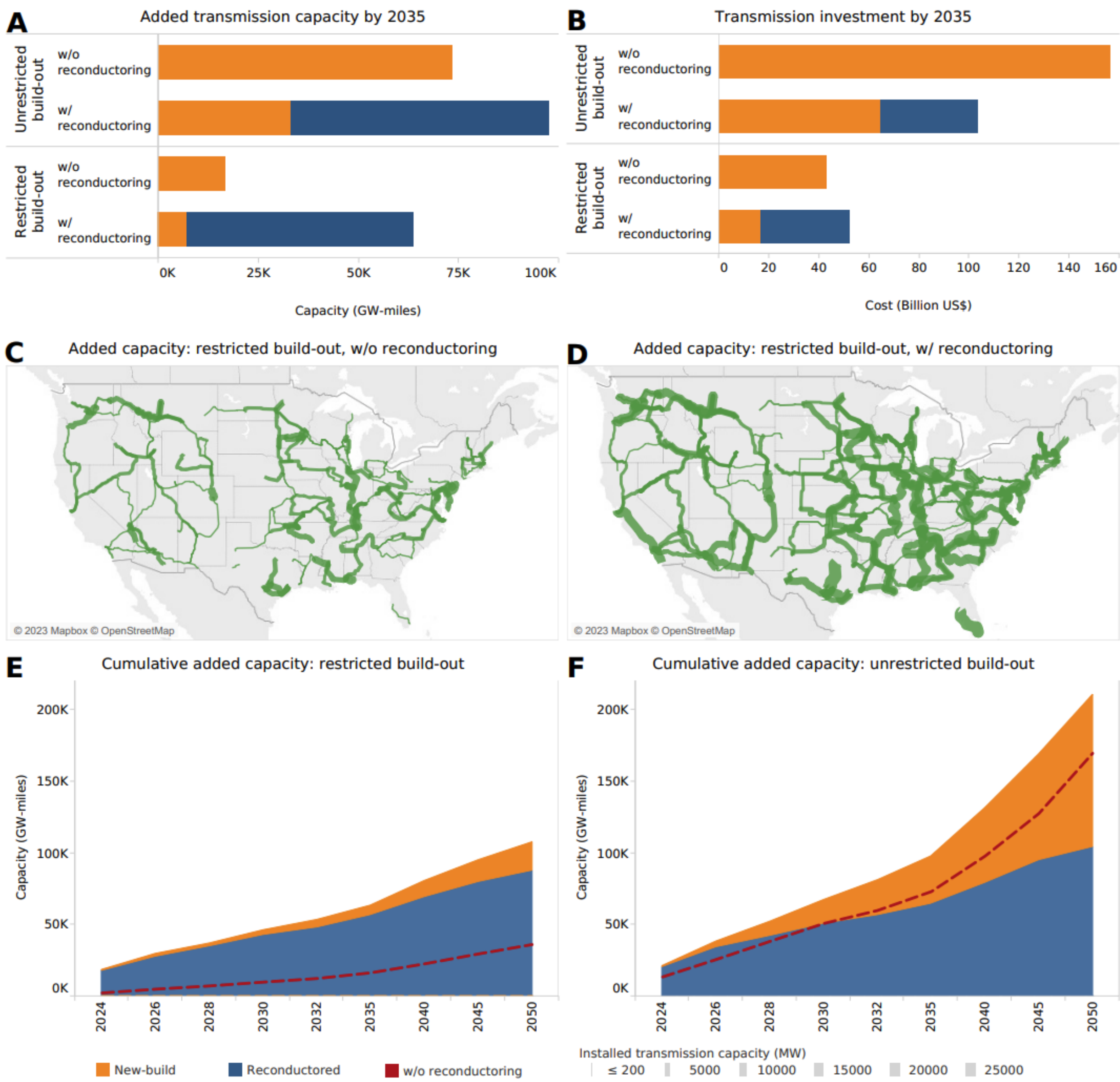

Fig. 3: Added interzonal transmission capacity and associated investment. (A) Added interzonal transmission capacity between 2022 and 2035, by scenario. (B) Total interzonal transmission investment between 2022 and 2035, in 2022 US$. Transmission investment includes both line as well as substation costs; reconductoring projects are assumed to require a new substation. (C and D) Added interzonal transmission capacity between 2022 and 2035 for the restricted build-out scenario by ReEDS path, without reconductoring as an option (C) and with reconductoring as an option (D). Bar width corresponds to the magnitude of added capacity. No additional expansion is allowed between the three interconnects (East, West, ERCOT) nor across national borders (Canada, Mexico). (E and F) Cumulative interzonal transmission capacity build-out with reconductoring for the restricted case (E) and the unrestricted case (F), with the total added interzonal transmission capacity build-out without reconductoring represented by a red dashed line.

While ReEDS' synthetic nature prompts the model to focus on the expansion of interzonal transmission capacity - which accounts for over half the ~200 TW-miles of existing transmission capacity in the contingent US today *(19)* - rather than intrazonal transmission or spur lines, we additionally find that the average intrazonal line length is considerably shorter (7 miles compared to 30 miles) and that the average unit cost of reconductoring intrazonal transmission lines is about 20% lower than interzonal lines, making a compelling case for the reconductoring of intrazonal transmission lines as well.

The larger and more distributed interzonal transmission capacity increase enabled by reconductoring simultaneously unlocks access to lower-cost, higher-quality RE in more locations (Fig. S5). The combined effect of lower transmission expansion costs and higher-quality RE lowers wholesale electricity costs by 3-4% (Fig. S6), translating to $85 billion in system cost savings by 2035 and $180 billion by 2050. This is notable considering the fact that although we do not impose a constraint to reach a certain clean energy share by a certain year, all four scenarios reach over 90% clean energy by 2035, and correspondingly commensurate greenhouse gas emissions, largely due to low clean energy costs resulting from IRA incentives and the absence of conventional fossil-fuel alternatives. The system cost savings unlocked by reconductoring are largely a result of the variation in which technologies are installed to meet load across the four scenarios (Fig. S7). In the restricted build-out case and without reconductoring as an option, the model relies more heavily on an expensive technology not currently available at scale - gas-fired generation with carbon capture and storage (CCS) - which is consistent with other studies *(5,18)*. This indicates that large-scale reconductoring can facilitate the cost-effective achievement of decarbonization goals while also mitigating the risk and uncertainty that comes with the development of transmission requiring new ROW, the siting of renewable projects and the commercialization of dispatchable zero-carbon technologies.

Given that transmission expansion needs and their respective barriers may vary widely by planning region, we analyze the added interzonal transmission capacity over time by transmission planning region (Fig. 4A and 5B, Fig. S8). In regions such as ERCOT, PJM and CAISO, a larger share of reconductoring is the least-cost strategy to increasing interzonal transmission capacity compared to regions such as MISO or SPP, where reconductoring plays a smaller role (Fig. 4A). For these latter regions, the increase of interzonal transmission capacity through reconductoring is incremental compared to new-build through 2050, indicating that the least-cost expansion strategy exhausts reconductoring options in these regions and requires the build-out of new lines. Comparing the unrestricted build-out case (Fig. 4A) with the restricted build-out case (Fig. 4B) also reveals that in the absence of permitting delays and cost allocation challenges, significantly more transmission capacity can be built to access prime onshore wind resources in MISO and SPP. This is key since onshore wind is the least-cost RE resource. However, even in the more realistic case with restricted build-out, reconductoring enables more wind capacity to be accessed and evacuated from wind-rich states, as demonstrated by Montana and Nebraska, and at higher capacity factors, as demonstrated by Oklahoma (Fig. 4C). The trend holds for other wind-rich states such as Idaho and Illinois, although notably does not hold for the wind-rich state of Texas, where high-quality wind resources cannot be evacuated due to limited cross-interconnect capacity with neighboring states.

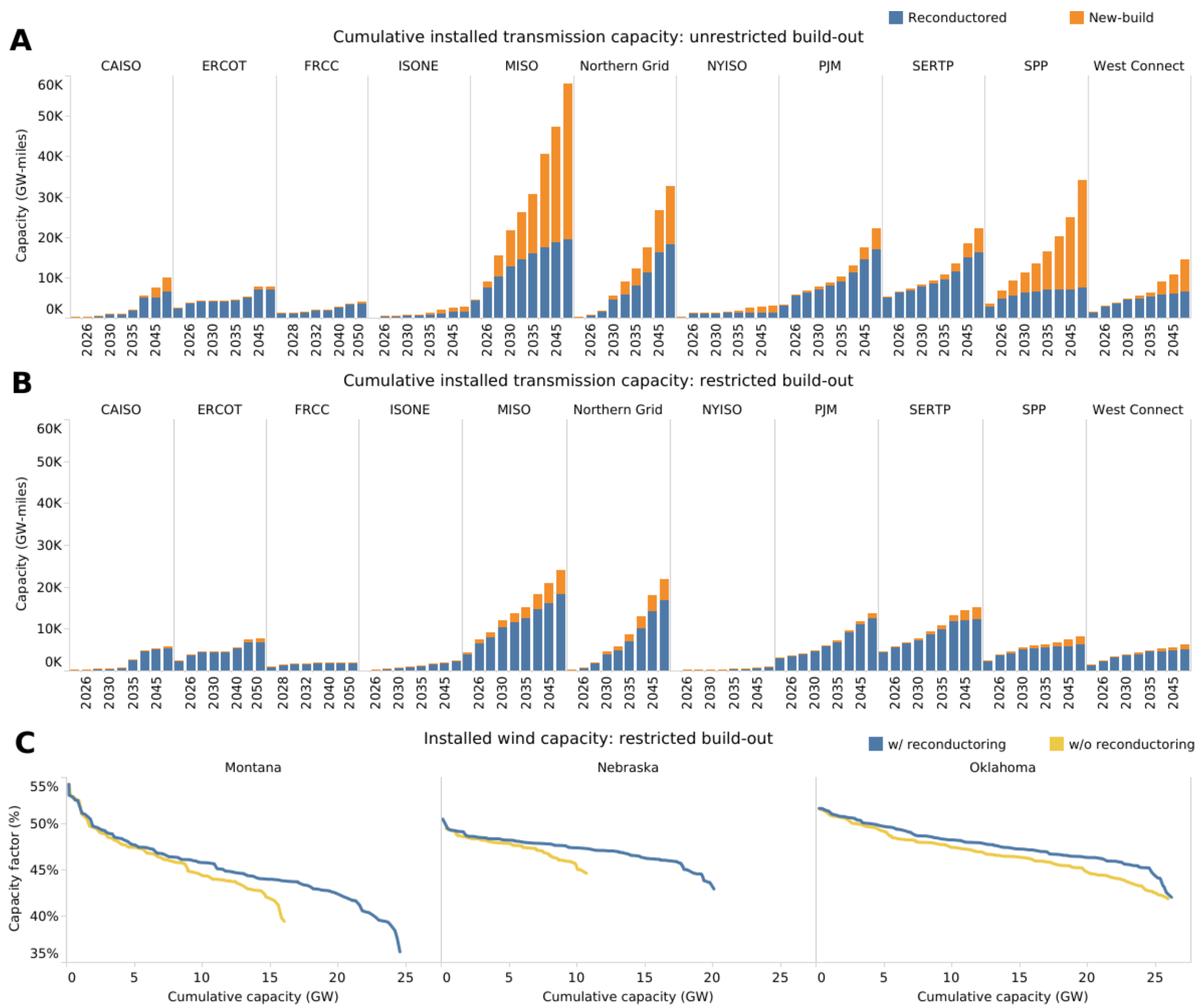

Fig. 4: Regional variation in transmission capacity expansion. (A) Cumulative interzonal transmission capacity for the unrestricted build-out scenario. (B) Cumulative interzonal capacity for the restricted build-out scenario. (C) The capacity factor of installed wind farms as a function of the cumulative installed wind capacity for the restricted build-out case, with reconductoring in blue and without reconductoring in yellow.

Policy considerations to spur uptake

The timely build-out of transmission capacity is key to integrating the RE resources necessary for meeting decarbonization goals. However, the commercial availability of composite-based advanced conductors with high-temperature and low-sag capabilities, as well as low-cost high-quality renewable resources in close proximity to the existing US transmission network, have created an opportunity to meet a majority of near-term transmission needs through leveraging existing ROW. Our results indicate that reconductoring can rapidly and cost-effectively increase transmission capacity and unlock RE on a US-wide scale, contributing to over 80% of the new interzonal transmission needed to reach over 90% clean electricity by 2035 given restrictions on greenfield transmission build-out. This informs optimal investment decisions and demonstrates the importance of a holistic system planning approach that jointly considers generation and transmission investments.

Increasing transmission capacity may offer additional notable yet difficult-to-quantify advantages. Previous work has noted that although today's approach to transmission planning focuses primarily on reliability benefits *(39)*, transmission build-out also importantly helps reduce congestion and mitigate extreme grid conditions through improved resiliency and interregional trade *(40-43)*. Reconductoring can help support these benefits - especially in light of the clogged interconnection queue *(3,4)*, high uncertainty about load and variable generation forecasts *(44)* and the increasing frequency and severity of extreme weather events *(45,46)* - given that it enables a larger and more distributed increase of transmission capacity. While the reconductoring process may involve taking the line out of service while work is completed, which can pose a challenge in already-congested networks, the work can be performed circuit-by-circuit in seasons of low demand and in applicable cases while the line remains energized (see the supplementary text for case studies). Further, from an operational perspective, the elimination of the steel core in composite-core conductors has been demonstrated to significantly improve corrosion resistance compared to conventional ACSR *(47)*, and a reconductoring project can enable real-time monitoring, dynamic line ratings as well as improve wildfire protection through the inclusion of a fiber-optic cable within the conductor. The evaluation of these many potential benefits should be incorporated into transmission planning processes.

Some regions are capitalizing on this opportunity more than others. For example, both the Netherlands and Belgium are reconductoring most of their high-voltage backbone by 2035, prompted by the need to rapidly integrate more RE, reduce congestion and overcome difficulties in securing new ROW *(30-32)*. The adoption of innovative, efficiency-based solutions - like advanced conductors, but also dynamic line ratings and topology control, among others -

has been encouraged by the European Union (EU) as well as on a national level through a variety of policies, that authorize public funding, accelerate project permitting and offer innovation incentives *(48-52)*. Similarly, the transmission planning philosophy in India - where demands of rapid load growth necessitate strategies that increase the capacity of both transmission and distribution systems in a limited time frame - dictates the optimization of ROW utilization, specifying reconductoring of existing AC transmission lines with higher ampacity conductors as one example *(53)*. Projects are increasingly evaluated on a total cost of ownership basis rather than the conventional capex estimation, with the inclusion of an ohmic loss evaluation in many project tenders that favors advanced conductors' lower resistance, resulting in India boasting some of the largest deployment rates of advanced conductors in the world *(54,55)*.

Policymakers and regulators in the United States need to consider similar options. The Montana State Legislature recently passed a law establishing cost-effectiveness criteria for advanced conductors *(56),* and other states should follow suit. Meanwhile, the DOE or IEEE could consider a national conductor efficiency and/or resistance-based standard - similar to the energy conservation standards for distribution transformers - to ensure that advanced conductors make their way into widespread use *(57)*. Further, because reconductoring has the potential to unlock RE capacity and accelerate transmission capacity expansion on a large scale, the strategy's benefits cannot be fully captured by evaluating its merits solely on a line-by-line basis, motivating the consideration of reconductoring within system planning processes. FERC's proposed reform of transmission planning could mandate the evaluation of advanced conductors and reconductoring practices as alternatives to new lines within long-term regional transmission planning, ensuring reconductoring is considered in ways similar to dynamic line ratings and advanced power flow control devices *(58)*. The DOE's Grid Deployment Office could also identify opportunities for reconductoring within the National Transmission Needs Study *(19)*, while the Loan Programs Office could conduct outreach with utilities to garner proposals for reconductoring projects. Utilities themselves can solicit grant proposals under the Bipartisan Infrastructure Law's Smart Grid Grants program. Meanwhile, outreach to ISOs/RTOs, state regulators, and other advocates can help quantify the opportunity and compel transmission builders and owners to embrace this technological solution.

Transmission networks are complex, and the actual increase in power transfer capacity offered by reconductoring is determined by a multitude of factors beyond the scope of this analysis. We recommend that transmission owners, ISOs, and RTOs perform more detailed studies - including load flow, contingency and dynamic stability analyses - to evaluate the wide-scale deployment of advanced conductors and more broadly consider the array of commercially-available solutions that can increase power density in their existing networks with regard to their technical parameters, costs, project needs, timeline constraints, grid topology and environmental conditions. While we study reconductoring with an equivalent-diameter advanced conductor, even higher capacity increases are possible by reconductoring with an equivalent-weight advanced conductor and/or including different coatings. Further, the reconductoring of lower-voltage lines may simultaneously increase the rated capacity of neighboring higher-voltage lines that may be constrained by stability or contingency limits. A reconductoring project may also provide an opportunity to simultaneously reinforce existing towers, replace insulators or perform other necessary maintenance work, depending on the line's age and state. Moreover, sectionalization with inverter-based resources and grid-forming inverters appears to be an emerging and promising strategy (59) to integrating renewable generation and support system stability through reactive power support, inertia, frequency response, and black start capability (60), yet additional technical assessment is needed to realize mass deployment in bulk power systems. Future work is planned to explore the potential transmission capacity increase of other technological solutions that can increase the transmission capacity of the existing grid (like AC-to-DC conversion and DLR); conduct power flow analysis and investigate system stability implications of reconductoring and sectionalization to understand the benefits of coordinated transmission and resource planning; and investigate the potential for large-scale reconductoring in other global regions.

Methods

Estimate the capacity of existing lines

We obtain data on US transmission lines from the US Homeland Infrastructure Foundation-Level Data (HIFLD) *(29)*, at 100 kV and above as per the methodology of NREL's ReEDS model *(23)*. 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), which aligns with other estimates *(28,61,62)*:

$$SIL\ [MW]\ =\frac{(Voltage\ [kV])^2}{Surge\ Impedance\ [Ohms]}$$

We use these SIL values to estimate the rated capacity for each line utilizing the standard St. Clair's curve defining line loadability as a function of distance to obtain a length-dependent SIL multiplier *(28)*. This multiplier applies to all voltage levels except for 765 kV, where the thermal limit is defined as 2.7*SIL for line lengths up to 50 miles as per MISO's safe loading limits *(61)*. 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 (~190 TW-miles) falls within other estimates of the current TW-miles deployed in the US (150-200 TW-miles) *(5,20,23)*.

Estimate the capacity of reconductored lines

Given the limitations of the standard St. Clair's curve for calculating loadability with advanced conductors and/or varying compensation, we analytically derive St. Clair's curves for an equivalent-diameter ACSR and ACCC line; 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 *(9,12,26,27).* We extend the St. Clair's curves up to 300 miles, the length of the longest AC transmission line in the US *(29)*. 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 that is used based on the line length. Lines between 0-30 miles do not require any other complementary strategy as they fall within the thermal limit; lines between 30-50 miles can leverage voltage support to enable a doubling of line capacity with reconductoring, with the quantity of reactive power compensation determined by theory from *(26,27)*; and for the 2% of US transmission lines above 50 miles, sectionalization (the addition of new substation(s) with active and reactive power generation sources along the line, likely with a grid-forming inverter) at most every 50 miles can shorten the effective line length that with voltage support as needed can similarly up to double transmission capacity. In line with previous St. Clair's curve derivations, we assume the curves hold across varying voltage levels, though some minor differences may occur for example due to conductor size and configuration *(28)*. However, with the exception of resistance, conductor properties like reactance and susceptance remain the same across different types of conductors with the same diameter *(63)*.

Estimate the cost to reconductor existing lines

In Figure 2B, 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 the existing ROW, consisting of the ROW, structures, conductors, and development.

ROW

Since reconductoring projects take place within existing ROW, no new land is required. For new lines, we utilize the US-average cost of pasture land from the US Department of Agriculture; although land costs may vary widely by state and be significantly elevated especially in urban or suburban areas *(38,64)*. 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 entirely new ROW must be secured based on ROW width by voltage level (see Table S3) *(24)*. To the land costs, we add acquisition costs along with regulatory and permitting costs *(38)*.

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 *(38)*. 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 accessories costs of ACSR and equivalent-diameter ACCC® conductors *(38)*. For each voltage level, we establish a reference conductor size selection and bundle quantity (see Table S3) *(24,38)*. We assume a sag and wastage adder of 4% to the conductor material costs *(38)*. For new lines, we assume that a shield wire is necessary for each circuit *(38)*. 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 *(65)*.

Development

For development, we assume a contingency of 10%, a 5.5% project management adder, a 1.5% administrative overhead adder, and a 3% engineering, testing and commissioning adder, added to the sum of the ROW, structure and conductor costs *(38)*. We also assume a 7% adder for the allowance for funds used during construction (AFUDC), added to the sum of the ROW, structure, conductor, and contingency costs *(38)*. We do not include terrain multipliers because the HIFLD dataset of US transmission lines do not contain sufficient information on the terrain for each segment *(29)*, and there is no concrete evidence on the varying labor/installation costs resulting from varying terrain.

AC Terminals

The upgrades to AC terminal stations within a reconductoring project are heavily dependent on the ratings of the existing terminal equipment, most notably the transformers and protection equipment. The ReEDS model accounts for terminal costs separate from line costs, so we use the provided terminal costs in ReEDS for both reconductoring and new-build lines, conservatively assuming reconductoring projects require entirely a new substation. For lines with an effective length of 30-50 miles, we do include the cost of voltage support within the reconductoring line cost based on the costs of a static var compensator (SVC), representing the median cost amongst various compensation technologies *(38)*, with the quantity of compensation determined by theory from *(26,27)*. For lines above 50 miles, we also include the cost of sectionalization at most every 50 miles within the reconductoring line cost - reflecting a new 6-position (double-breaker bus) substation *(38)* - although these costs are typically allocated to the generators that are 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, to estimate the total cost in US$/mile to reconductor each of the ~53,000 transmission lines in the US at 100 kV and above *(29)*. We then incorporate the previously quantified delta capacity increase to obtain unit costs in US$/MW-mile.

ReEDS model set-up

We utilize the Regional Energy Deployment System (ReEDS) capacity expansion and dispatch model from the National Renewable Energy Laboratory (NREL) for the contiguous US electric power system, in order to assess the impact of reconductoring on future generation capacity additions, electricity costs, new transmission development, etc. by 2050 *(23)*. It 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, electricity prices, as well as fuel demand, prices, and CO2 emissions. Although ReEDS can also simulate the power sectors of Canada and Mexico, it is primarily focused on the contiguous United States, dividing it into 134 model balancing areas that are interconnected by approximately 300 representative transmission paths, thereby providing a granular geographical and regulatory representation.

We use the 2022 version of ReEDS in this study which includes all the 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 as per the reV model *(66)*. 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 for plants that are already under construction. This reflects pending policy from the Environmental Protection Agency (EPA) that seeks to strengthen emission limits and guidelines for carbon dioxide from fossil fuel-fired power plants, along with the investment uncertainty regarding the construction of new fossil fuel-fired power plants. No additional transmission capacity expansion is allowed between the three interconnects (East, West, ERCOT) nor across national borders (Canada, Mexico).

Implementing reconductoring in ReEDS

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, these studies still draw broader conclusions about transmission needs *(17-21)*. We match every physical transmission line with a path in ReEDS and estimate its cost of reconductoring by taking a GW-mile weighted average of the cost to reconductor each individual line that makes up the path, and use these per-line costs to generate a supply curve for 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 model the option of reconductoring in the ReEDS model we provide 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.

Modeling transmission constraints in ReEDS

For the restricted build-out scenarios, we represent permitting and cost allocation challenges through the addition of several constraints. For new-build lines that are potentially hindered by both these issues, we limit the total nationwide expansion to 1400 GW-miles/yr, the 2010-2021 average rate *(6,23)*. 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's (FERC) Order No. 1000 transmission planning regions and includes the California ISO (CAISO), ColumbiaGrid, 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), Electric Reliability Council of Texas (ERCOT), South Carolina Regional Transmission Planning (SCRTP), and Southeastern Regional Transmission Planning (SERTP).

References

1. "Energy Technology Perspectives 2023" (International Energy Agency, 2023); https://iea.blob.core.windows.net/assets/a86b480e-2b03-4e25-bae1-da1395e0b620/EnergyTechnologyPerspectives2023.pdf
2. J. Moch, H. Lee, "The Challenges of Decarbonizing the U.S. Electric Grid by 2035" (Harvard Kennedy School Belfer Center Policy Brief, 2022); https://www.belfercenter.org/publication/challenges-decarbonizing-us-electric-grid-2035#:~:text=A%20review%20of%20over%2030,over%2010%20years%20to%20complete.&text=The%20quickest%20line%20reviewed%20was,ongoing%20for%20over%2016%20years
3. J. Rand, R. Strauss, W. Gorman, Joachim Seel, J. Mulvaney Kemp, S. Jeong, D. Robson, R. Wiser, "Queued Up: Characteristics of Power Plants Seeking Transmission Interconnection As of the End of 2022" (LBNL, 2023); https://emp.lbl.gov/queues
4. "Electricity Grids and Secure Energy Transitions" (International Energy Agency, 2023); https://iea.blob.core.windows.net/assets/70f2de45-6d84-4e07-bfd0-93833e205c81/ElectricityGridsandSecureEnergyTransitions.pdf
5. J. Jenkins, J. Farbes, R. Jones, N. Patankar, G. Schivley, "Electricity Transmission is Key to Unlock the Full Potential of the Inflation Reduction Act" (REPEAT Project, Princeton, 2022); https://zenodo.org/record/7106176
6. J. Caspary, M. Goggin, R. Gramlich, J. Selker, "Fewer New Miles: The US Transmission Grid in the 2010s" (Grid Strategies LLC, 2022); https://gridprogress.files.wordpress.com/2022/08/grid-strategies_fewer-new-miles.pdf
7. A. Phadke, U. Paliwal, N. Abhyankar, T. McNair, B. Paulos, D. Wooley, R. O'Connell, "2035 The Report: Plummeting Solar, Wind, and Battery Costs Can Accelerate Our Clean Electricity Future" (UC Berkeley Goldman School of Public Policy and GridLab, 2020); https://www.2035report.com/electricity/
8. J. Caspary, J. Schneider, "Advanced Conductors on Existing Transmission Corridors to Accelerate Low Cost Decarbonization" (Grid Strategies LLC, 2022); https://acore.org/wp-content/uploads/2022/03/Advanced_Conductors_to_Accelerate_Grid_Decarbonization.pdf
9. "ACSR" (Southwire, 2019); https://www.southwire.com/wire-cable/bare-aluminum-overhead-transmission-distribution/acsr/p/ALBARE6
10. "3M Aluminum Conductor Composite Reinforced (ACCR): High-capacity transmission conductor" (3M, 2014); https://multimedia.3m.com/mws/media/478270O/3mtm-accr-high-capacity-transmission-conductor.pdf
11. "3M ACCR: More Amps, More Confidence" (3M, 2014); https://www.ieee.hr/_download/repository/Allan_Russell_3M_ACCR_%28Aluminum_Conductor_Composite_Reinforced%29_-_Proven_Solutions_to_Increase_Capacity.pdf
12. "ACCC Conductor Data Sheets" (CTC Global, n.d.); https://ctcglobal.com/accc-conductor-data-sheets/
13. "TS Conductor" (TS Conductor, 2023); https://tsconductor.com/products/
14. L. Reed, M. Dworkin, P. Vaishnav, M. G. Morgan, Expanding Transmission Capacity: Examples of Regulatory Paths for Five Alternative Strategies. *The Electricity Journal* **33** (6), 106770 (2020). https://doi.org/10.1016/j.tej.2020.106770
15. L. Reed, M. G. Morgan, P. Vaishnav, D. E. Armanios, Converting existing transmission corridors to HVDC is an overlooked option for increasing transmission capacity. *PNAS* **116** (28), 13879-13884 (2019). https://doi.org/10.1073/pnas.1905656116

16. “Leveraging Existing Infrastructure: Increasing the Capacity of Transmission Lines and Rights of Way” (Electric Power Research Institute, 2021); https://www.epri.com/research/products/000000003002023004
17. P. Denholm, P. Brown, W. Cole, T. Mai, B. Sergi et al. “Examining Supply-Side Options to Achieve 100% Clean Electricity by 2035” (National Renewable Energy Laboratory, 2022); https://www.nrel.gov/docs/fy22osti/81644.pdf
18. E. Larson, C. Greig, J. Jenkins, E. Mayfield, A. Pascale, C. Zhang, J. Drossman, R. Williams, S. Pacala, R. Socolow, E. Baik, R. Birdsey, R. Duke, R. Jones, B. Haley, E. Leslie, K. Paustian, and A. Swan, “Net-Zero America: Potential Pathways, Infrastructure, and Impacts” (Final Report, Princeton University, 2021); https://netzeroamerica.princeton.edu/the-report
19. “National Transmission Needs Study: Draft for Public Comment” (Department of Energy, 2023); https://www.energy.gov/sites/default/files/2023-02/022423-DRAFTNeedsStudyforPublicComment.pdf
20. P. Brown, A. Botterud, The Value of Inter-Regional Coordination and Transmission in Decarbonizing the US Electricity System. *Joule* **5**, Issue 1, 115-134 (2021). https://doi.org/10.1016/j.joule.2020.11.013
21. C. T. M. Clack, “The role of transmission in deep decarbonization” (Vibrant Clean Energy LLC, 2021); https://vibrantcleanenergy.com/wp-content/uploads/2021/03/VCE-COPUC03292021.pdf
22. “A 2030 United States Macro Grid” (Breakthrough Energy Sciences, 2021); https://bescdn.breakthroughenergy.org/publications/MacroGridReport.pdf
23. “Regional Energy Deployment System (ReEDS) Model Documentation: Version 2020” (National Renewable Energy Laboratory, 2021); https://www.nrel.gov/docs/fy21osti/78195.pdf
24. M. Goldberg, D. Keyser, “Transmission Line Jobs and Economic Development Impact (JEDI) Model User Reference Guide” (National Renewable Energy Laboratory, 2013); https://www.nrel.gov/docs/fy14osti/60250.pdf
25. R. Pletka, J. Khangura, A. Rawlins, E. Waldren, D. Wilson, “Capital Costs for Transmission and Substations: Updated Recommendations for WECC Transmission Expansion Planning” (Black and Veatch, 2014); https://efis.psc.mo.gov/mpsc/commoncomponents/viewdocument.asp?DocId=936076825
26. D. Lauria, F. Mottola, S. Quaia, Analytical Description of Overhead Transmission Lines Loadability. *Energies* **12**, 3119 (2019). https://doi.org/10.3390/en12163119
27. D. Lauria, S. Quaia, “An investigation on line loadability increase with high temperature conductors” in *2017 6th International Conference on Clean Electrical Power (ICCEP), Santa Margherita Ligure, Italy,* 645-649 (IEEE, 2017). https://doi.org/10.1109/ICCEP.2017.8004757
28. R. Gutman, P.P. Marchenko, R.D. Dunlop, Analytical Development of Loadability Characteristics for EHV and UHV Transmission Lines. *IEEE Transactions on Power Apparatus and Systems* **PAS-98** (2) (1979). https://doi.org/10.1109/TPAS.1979.319410
29. “Transmission Lines” (United States Homeland Infrastructure Foundation Level Database (HIFLD), 2022); https://hifld-geoplatform.opendata.arcgis.com/datasets/geoplatform::transmission-lines/about
30. “TYNDP 2020 Project Sheets” (ENTSO-E, 2020); https://tyndp2020-project-platform.azurewebsites.net/projectsheets
31. “Beter Benutten Bestaande hoogspanningsverbindingen (380 kV) opwaarderen” (TenneT, 2022); https://www.tennet.eu/nl/projecten/beter-benutten-bestaande-380kv
32. “Federal Development Plan 2024-2034” (Elia, 2023); https://www.elia.be/en/infrastructure-and-projects/investment-plan/federal-development-plan-2024-2034
33. “Big Creek Corridor Rating Increase” (Southern California Edison, 2016); https://www.caiso.com/Documents/SCEPresenation-2016-2017TransmissionPlanningProcess.pdf
34. “Board-Approved 2017-2018 Transmission Plan” (CAISO, 2018); https://efiling.energy.ca.gov/GetDocument.aspx?tn=223248&DocumentContentId=20064

35. "Appendix F: Detailed Policy Assessment of the 2022-2023 Transmission Plan" (CAISO, 2023); http://www.caiso.com/InitiativeDocuments/Appendix-F-Revised-Draft-2022-2023-Transmission-Plan.pdf
36. J. Warren, "Texas Million-Dollar Miles" (Concept Elemental, 2023); https://www.conceptelemental.com/commentary/2023/1/21/texas-million-dollar-miles
37. "Transmission line approval recommended by ERCOT board" (Power Engineering, 2011); https://www.power-eng.com/news/transmission-line-approval-recommended-by-ercot-board/#gref
38. "Transmission Cost Estimation Guide" (MISO, 2022). https://cdn.misoenergy.org/20220208%20PSC%20Item%2005c%20Transmission%20Cost%20Estimation%20Guide%20for%20MTEP22_Draft622733.pdf
39. W. Gorman, A. Mills, R. Wiser, Improving estimates of transmission capital costs for utility-scale wind and solar projects to inform renewable energy policy. *Energy Policy* **135**, 110994 (2019). https://doi.org/10.1016/j.enpol.2019.110994
40. D. Millstein, R. Wiser, W. Gorman, S. Jeong, J. Kim, A. Ancell, "Empirical Estimates of Transmission Value using Locational Marginal Prices" (LBNL, 2022); https://eta-publications.lbl.gov/sites/default/files/lbnl-empirical_transmission_value_study-august_2022.pdf
41. D. Millstein, R. Wiser, A. D. Mills, M. Bolinger, J. Seel, S. Jeong, Solar and wind grid system value in the United States: The effect of transmission congestion, generation profiles, and curtailment. *Joule* **5**, Issue 7, 1749-1775 (2021). https://doi.org/10.1016/j.joule.2021.05.009
42. J. Pfeifenberger, J. Chang, A. Sheilendranath, "Toward More Effective Transmission Planning: Addressing the Costs and Risks of an Insufficiently Flexible Electricity Grid" (The Brattle Group, 2015); https://www.brattle.com/wp-content/uploads/2017/10/5950_toward_more_effective_transmission_planning_addressing_the_costs_and_risks_of_an_insufficiently_flexible_electricity_grid.pdf
43. J. Pfeifenberger, K. Spokas, J. M. Hagerty, J. Tsoukalis, "A Roadmap to Improved Interregional Transmission Planning" (The Brattle Group, 2021); https://www.brattle.com/wp-content/uploads/2021/11/A-Roadmap-to-Improved-Interregional-Transmission-Planning_V4.pdf
44. K. V. Horn, J. Pfeifenberger, P. Ruiz, "The value of diversifying uncertain renewable generation through the transmission system" (Boston University Institute for Sustainable Energy, 2020); https://open.bu.edu/bitstream/handle/2144/41451/value-of-diversifying-uncertain-renewable-generation-through-the-transmission-system-093020-final.pdf?sequence=1&isAllowed=y
45. M. Panteli, P. Mancarella, Influence of extreme weather and climate change on the resilience of power systems: Impacts and possible mitigation strategies. *Electric Power Systems Research* **127**, 259-270 (2015). https://doi.org/10.1016/j.epsr.2015.06.012
46. M. Goggin, "Transmission Makes the Power System Resilient to Extreme Weather" (Grid Strategies LLC, 2021); https://acore.org/wp-content/uploads/2021/07/GS_Resilient-Transmission_proof.pdf
47. E. Håkansson, P. Predecki, M. S. Kumosa, Galvanic Corrosion of High Temperature Low Sag Aluminum Conductor Composite Core and Conventional Aluminum Conductor Steel Reinforced Overhead High Voltage Conductors. *IEEE Transactions on Reliability* **64**, no. 3, 928-934 (2015). doi: 10.1109/TR.2015.2427894
48. "Directive 2009/72/EC of the European Parliament and of the Council concerning common rules for the internal market of electricity" (Official Journal of the European Union, 2009); https://faolex.fao.org/docs/pdf/eur124471.pdf
49. "Beyond State-of-the-Art Technologies for Power AC Corridors and Multi-terminal HVDC Systems" (CORDIS, 2014); https://cordis.europa.eu/project/id/612748
50. "Projects of Common Interest" (European Commission, nd); https://energy.ec.europa.eu/topics/infrastructure/projects-common-interest_en

51. “Besluit tot vaststelling van de tariefmethodologie voor het elektriciteitstransmissienet en voor de elektriciteitsnetten met een transmissiefunctie voor de regulatoire periode 2024-2027” (CREG, 2022); https://www.creg.be/sites/default/files/assets/Publications/Others/Z1109-11NL.pdf
52. “Innovation incentive 2020-2023 plan update” (Elia, 2020); https://www.creg.be/sites/default/files/assets/Publications/Decisions/B658E69Annex1.pdf
53. “Manual on Transmission Planning Criteria” (Central Electricity Authority, 2023); https://cea.nic.in/wp-content/uploads/psp___a_ii/2023/03/Manual_on_Transmission_Planning_Criteria_2023.pdf
54. V. Pillai, “Our Outlook For India Remains Bullish: CTC Global” (T&D India, 2021); https://www.tndindia.com/our-outlook-for-india-remains-bullish-ctc-global/
55. “ACCC Conductor Installations: Project Map” (CTC Global, nd); https://ctcglobal.com/project-map/
56. “House Bill 729: Providing for advanced conductor cost-effectiveness criteria” (Montana Free Press, 2023); https://apps.montanafreepress.org/capitol-tracker-2023/bills/hb-729/
57. “Energy Conservation Program: Energy Conservation Standards for Distribution Transformers” (Federal Register, 2022); https://www.federalregister.gov/documents/2023/01/11/2022-28590/energy-conservation-program-energy-conservation-standards-for-distribution-transformers
58. “FERC Issues Transmission NOPR Addressing Planning, Cost Allocation” (FERC, 2022); https://www.ferc.gov/news-events/news/ferc-issues-transmission-nopr-addressing-planning-cost-allocation
59. D. S. Carvalho Jr., D. J. T. Souza, F. Schmidt, M. Cury Jr., M. V. G. S. Farinha, R. R. Ferreira, R. T. A. Mello, S. F. F. Lima, “Sectionalizing transmission lines, an expansion planning challenge, amplified by unexpected emerging variable renewable generation and environmental restrictions” (CIGRE, 2022); https://www.epe.gov.br/sites-pt/publicacoes-dados-abertos/publicacoes/PublicacoesArquivos/publicacao-725/topico-670/C1_-_Full_Papers_PS1_10156_2022.pdf
60. Y. Lin, J. H. Eto, B. B. Johnson, J. D. Flicker, R. H. Lasseter, H. N. Villegas Pico, G. Seo, B. J. Pierre, A. Ellis, “Research Roadmap on Grid-Forming Inverters” (National Renewable Energy Laboratory, 2020); https://www.nrel.gov/docs/fy21osti/73476.pdf
61. “Discussion of Legacy, 765 kV, and HVDC Bulk Transmission” (MISO, 2023); https://www.ercot.com/files/docs/2023/06/27/2_ERCOT%20Discussion%20of%20EHV%20and%20HVDC_MISO_Tackett_20230626.pdf
62. R. Caola, D. Durbak, J. Laforest. “Typical EHV-UHV Transmission Line Characteristics” (GE, 1987). https://www.spp.org/documents/15079/typical%20line%20characteristics%20-%20data%20source%20for%20reactive%20compensation.pdf
63. L. Henriksen, J. Leman, S. Panigrahi, “Conductor Performance White Paper” (CTC Global, 2013); https://www.ctcglobal.com/wp-content/uploads/2016/05/ACCC_Conductor_Performance_by_Power_Engineers.pdf
64. “Land Values 2022 Summary” (USDA National Agricultural Statistics Service, 2022); https://www.nass.usda.gov/Publications/Todays_Reports/reports/land0822.pdf
65. “Aluminum Price” (Business Insider, 2023); https://markets.businessinsider.com/commodities/aluminum-price
66. G. Maclaurin, N. Grue, A. Lopez, D. Heimiller, M. Rossol, G. Buster, T. Williams, “The Renewable Energy Potential (reV) Model: A Geospatial Platform for Technical Potential and Supply Curve Modeling” (National Renewable Energy Laboratory, 2021); https://www.nrel.gov/docs/fy19osti/73067.pdf
67. “ACSS” (Southwire, 2015); https://www.southwire.com/wire-cable/bare-aluminum-overhead-transmission-distribution/acss/p/ALBARE7

68. D. Bryant, "Why High-Capacity, Low-Sag ACCC Conductor Offers a Better Solution than ACSS" (CTC Global, 2018); https://ctcglobal.com/high-capacity-low-sag-accc-conductor-offers-better-solution-acss/
69. "Engineering Transmission Lines with High Capacity Low Sag ACCC Conductors" (CTC Global, 2011); https://documents.dps.ny.gov/search/Home/ViewDoc/Find?id=%7B4B3A8A12-3090-40E7-841F-EC1BEED0C95B%7D&ext=pdf
70. "IEEE Standard 738-2006 for Calculating the Current-Temperature of Bare Overhead Conductors" (IEEE, 2007); doi: 10.1109/IEEESTD.2007.301349
71. J.F. Goffinet, "Elia Addresses the Need for More Capacity in Belgium" (T&D World, 2017); https://www.tdworld.com/overhead-transmission/article/20970140/elia-addresses-the-need-for-more-capacity-in-belgium
72. "Project at Belgian TSO Navigated Challenges Facing New Power Infrastructure" (INMR, 2020); https://www.inmr.com/project-belgian-tso-navigated-challenges-facing-new-power-infrastructure-2/
73. J.F Goffinet, "Elia Tackles Grid Reliability Through New Technologies" (T&D World, 2022); https://www.tdworld.com/transmission-reliability/article/21247687/elia-tackles-grid-reliability-through-new-technologies
74. "Studies on congestion management" (TenneT, 2022); https://www.tennet.eu/de-elektriciteitsmarkt/congestiemanagement/studies-congestion-management
75. "Regulation (EU) 2019/943 of the European Parliament and of the Council of 5 June 2019 on the internal market for electricity" (Official Journal of the European Union, 2019); https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32019R0943
76. "Action plan of the Netherlands: Implementation of Articles 14, 15 & 16 of Regulation (EU) 2019/943" (Ministry of Economic Affairs and Climate Policy of the Netherlands, 2019); https://energeia-binary-external-prod.imgix.net/BBN6GLBKKXz_lH4ydtunYPfcpgc.pdf?dl=Actieplan+zone-overschrijdende+transportcapaciteit+elektriciteitshandel.pdf
77. "Terna: 2023 Development Plan for the National Electricity Grid Presented" (Terna, 2023); https://www.terna.it/en/media/press-releases/detail/2023-development-plan
78. "2023: The Hypergrid Project and Development Requirements" (Terna, 2023); https://download.terna.it/terna/2023_Hypergrid_project_and_development_requirements_8db79602cedc732.pdf
79. "Record Energized Reconductor Project Brings Reliable Power to South Texas" (EEI Energy Biz, 2016); https://www.quantaenergized.com/wp-content/uploads/2015/05/EEI-Energy-Biz_pages.pdf
80. "Board of Directors Meeting: September 20, 2011" (ERCOT, 2011); https://www.ercot.com/calendar/09202011-Board-of-Directors-Meeting
81. V. Pillai, "In conversation with J.D. Sitton, CEO of CTC Global Corporation" (T&D India, 2019); https://ctcglobal.com/wp-content/uploads/T-and-D-India-March-2019.pdf
82. "An Evolving Market: Trends and growth drivers in the cables and conductors industry" (Powerline, 2018); https://powerline.net.in/2018/01/06/an-evolving-market/
83. "ACCR Should Be A Solution Of Choice To Transmission Utilities: 3M India" (T&D India, 2020); https://www.tndindia.com/accr-solution-choice-transmission-utilities-3m-india/
84. "CTC Global Joins Forces with World's Largest Electric Utility to Produce ACCC Conductor Core in China" (Business Wire, 2013); https://www.businesswire.com/news/home/20130814005174/en/CTC-Global-Joins-Forces-with-World%E2%80%99s-Largest-Electric-Utility-to-Produce-ACCC-Conductor-Core-in-China
85. "The Will to Power" (Global Trade Magazine, 2014); https://www.globaltrademag.com/the-will-to-power
86. D. Bryant, "ACCC Conductor Installed on Milestone 1100 kV DC Project in China" (CTC Global, 2020); https://ctcglobal.com/accc-conductor-installed-on-milestone-1100-kv-dc-project-in-china/

87. 2022-2023 Transmission Plan. (California Independent System Operator, 2023); http://www.caiso.com/InitiativeDocuments/ISO-Board-Approved-2022-2023-Transmission-Plan.pdf
88. "Greenlink Nevada" (NV Energy, 2021); https://lands.nv.gov/uploads/meeting_minutes/E2021-098.pdf
89. "Power Flow Test Systems Repository" (Al-Roomi, 2015); http://www.al-roomi.org/power-flow/3-bus-systems/system-iii
90. R. D. Zimmerman, C. E. Murillo-Sanchez, "Matpower User's Manual, Version 7.1" (Power Systems Engineering Research Center, 2020). https://matpower.org/docs/MATPOWER-manual.pdf
91. "C7 overhead conductor" (Southwire, 2017); https://overheadtransmission.southwire.com/wp-content/uploads/2017/06/1904_C7-Brochure_IMPERIAL_WEB_SPREADS.pdf

Supplementary Text

1: Background information on advanced conductors

The most common conductor utilized for overhead high voltage power transmission in the US today is the Aluminum Conductor Steel Reinforced (ACSR), featuring conductive aluminum strands around a supporting steel core *(8,9)*. Its many advantages like good conductivity, low weight, low cost, utilization of common materials and resistance to corrosion cemented its place as the industry standard since it was invented in the early 1900s to this day. However, lines wired with ACSR are typically technically limited to normal operating temperatures of approximately 75°C *(9)*, above which the tensile strength decreases over time, weakening the conductor and increasing susceptibility to failure.

Despite numerous efforts to improve conductor design over ensuing decades, enhancements in one aspect of conductor design often led to trade-offs with other features. This is reflected by the example of the Aluminum Conductor Steel Supported (ACSS), first introduced in the 1970s. By utilizing aluminum strands that were fully annealed, the conductor could withstand higher operating temperatures and thus increased power transfer capacity. 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 and/or under-rating reconductored lines below their thermal capacity to abide by the pre-existing sag restriction *(67,68)*.

In recent years, advancements in materials science have given rise to advanced conductors which can carry approximately up to twice the current, and thus double the power, of conventional conductors. Also known as high temperature low sag (HTLS) conductors, they swap the conventional steel core for a smaller and lighter composite core (typically ceramic, glass or carbon fibers) without compromising structural strength. Therefore, more aluminum - typically annealed aluminum, as it has the highest temperature capabilities - can fit within an equivalent diameter and higher operating temperatures can be achieved, all while abiding by the sag restrictions that often limit a line's rated capacity (*10-13,68*). In contrast to conventional conductors, the technology behind composite-based conductor cores is typically proprietary, with several US companies leading the market: examples include the Aluminum Conductor Composite Reinforced (ACCR) made by 3M, the Aluminum Conductor Composite Core (ACCC) made by CTC Global, and the Aluminum Encapsulated Carbon Core (AECC) made by TS Conductor *(10-13)*. These manufacturers typically produce the conductor cores in-house, then packaged on reels and shipped to vendors which strand the aluminum strands around the core and supply the ready conductor to end-users. Table S1 compares the technical characteristics of these advanced conductors with ACSR and ACSS.

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, UV waves, galvanic corrosion, and general environmental damage, varying by conductor model *(8,13,16,69)*. Some advanced conductors also embed an optical fiber to monitor line temperature and elongation in real time, enabling validation testing after installation, dynamic line ratings, and/or insulation-based wildfire protection. Furthermore, their installation typically follows similar procedures and tools as for ACSR, avoiding the need for special training and/or equipment.
Another result of advanced conductors' higher aluminum content and/or use of annealed aluminum, their electrical resistance is about 20-30% lower than ACSR conductors; this improved conductivity in turn reduces I^2R or "copper" losses, with advanced conductors manufacturers claiming loss reductions of up to 50% (9-13). For a utility, this can translate into considerable operational savings as well as emissions reductions through the offset of fossil fuel generation and/or increased savings of renewable generation, depending on the local resource mix (*66*). However, these claims are typically made under the assumption that the line loading stays the same, which would likely not apply to a reconductoring project where lines are upgraded with advanced conductors in order to increase their thermal carrying capacity.

We evaluate these claims by considering a "Drake"-size ACSR and ACCC conductor. The ACCC conductor operates at lower temperatures for equivalent current (Fig. S1A) due to the lower thermal conductivity of its composite-based, rather than steel-based, core. Likewise, although conductor resistance varies linearly with operating temperature (Fig. S1B), the ACCC conductor's resistance increases at a lower rate than the ACSR conductor for increasing operating temperature.

We next consider a double-circuit 345 kV line with 3 phases and 2 "Drake"-size conductors per phase. In the base case, the line is wired with ACSR. Grid planners have two options for increasing capacity through the corridor: reconductor with ACCC or build a new line with ACSR parallel to the existing one. We calculate line losses for the original case and the two upgraded cases via

$$Line\ losses\ = \left[\frac{I_\varphi}{N_{cond}}\right]^2 \cdot R \cdot N_{cond} \cdot N_{circ} \cdot N_\varphi \cdot FLA$$

and calculate line load via

$$Line\ load\ =\sqrt{3}\cdot I_{\varphi}\cdot N_{circ}\cdot V$$

where I_{φ} is the phase current, N_{cond} is the number of conductors per phase, R is the resistance per unit length, N_{circ} is the number of circuits per line, N_{φ} is the number of phases, FLA is the full load adjustment, V is the line voltage *(25)*. Losses increase exponentially with the line loading, yet for equivalent amps an ACCC reconductoring project would lower losses by up to ~30% compared to the original line (Fig. S2). After the line is upgraded and loaded above the thermal limit of the original line, losses are still lower when reconductoring with ACCC rather than building a new parallel line with ACSR up to approximately the point of emergency operation. However, since losses are heavily dependent on the utilization of a line, the overall change in annual losses before and after upgrading will depend on how frequently the line is lightly vs heavily loaded.

2: Real-world reconductoring project case studies

Belgium

In Europe, where advanced conductors are often referred to as high temperature low sag (HTLS) conductors, Belgium has pioneered deployment. Since the first installation in 2009, the country's Transmission System Operator (TSO) Elia has undertaken a wide-scale project to reinforce the majority of their 380 kV backbone with HTLS conductors by the mid-2030s *(71)*. Most of the existing backbone consists of double-circuit lines wired with All Aluminum Alloy Conductor (AAAC), rated at approximately 2000 A *(72,73)*. Beginning with the most congested lines, reconductoring will double the load transfer capacity to approximately 4000-5000 A, predominantly using the Aluminum Conductor Composite Core (ACCC) from CTC Global/Lamifil *(71-73)*. Motivating factors for grid reinforcement include the need to integrate renewables and energy storage, accommodate the geo-spatial shift of generation from retiring nuclear power plants to offshore wind resources in the North Sea, and support both domestic and industrial electrification (Elia predicts annual consumption to increase by up to 50%, from 80 to 120 TWh, between 2022-2032) *(32)*. The main reasons for using HTLS conductors over new corridors is their significantly faster realization, bypassing permitting delays and difficulties to secure new rights-of-way (ROW) due to high population density, as well as significantly lower capex; reconductoring projects take less than half the time and are less than half the cost of new-build projects.

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 out 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 *(50).* They are then coordinated by the European Network of Transmission System Operators for Electricity (ENTSO-E) under the Ten Year Network Development Plan (TYNDP) framework, ensuring harmonized transmission planning across the continent *(50)*. Elia was also a key contributor of the European Commission's BEST PATHS project (Beyond State-of-the-art Technologies for rePowering AC Corridors and Multi-Terminal HVDC Systems), which from 2014 to 2019 expanded European TSOs' knowledge around the safe construction with and operation of HTLS conductors *(49)*.

A supportive regulatory ecosystem has likewise helped foster the widespread adoption of advanced conductors. The EU electricity market directive of 2009 directed regulators to grant system operators “appropriate incentive over both the short and long term, to increase efficiencies, foster market integration… and support the related research activities” *(48)*. In its implementation of this EU directive, Belgium expressly recognized the strategic importance of technical innovation in the electricity sector in their own law, and the Belgian regulator CREG (Commission for Electricity and Gas Regulation) worked closely with Elia to pursue the uptake of more innovative technologies *(51)*. The first reconductoring projects in the early 2010s took several steps to mitigate risks, which included demonstrating to authorities that safe clearances would be maintained under different operating conditions as well as the utilization of different advanced conductors, complete with each supplier’s corresponding accessories, on separate circuits in case of unforeseen technical problems *(71-73)*. Beginning in the 2016, CREG also introduced an “innovation incentive”, which has led Elia to pursue other innovation and efficiency-based solutions, like digitalization, dynamic line ratings for overhead lines, and the installation of phase shifting transformers to better regulate power flows *(52)*. HTLS conductors are also viewed as a more sustainable solution over conventional conductors, given their composite-based cores do not use steel and thus have lower resistances, translating to lower line losses and improved efficiencies.

Netherlands

Like Belgium, Dutch TSO TenneT also plans to upgrade most of their 380 kV backbone to HTLS conductors for a load transfer capacity increase from about 2500 A to 4000 A *(30,31)*. Known as the “Beter Benutten Bestaande 380 kV” (Making Better Use of the 380 kV Grid) project, the first phase involves upgrading 191 km (119 miles) of transmission lines between 2019-2026 and the second phase plans to upgrade an additional 165 km (103 miles) by 2035 *(30,31)*. Motivating factors include difficulty to secure new rights-of-way (ROW) due to high population density, the need to rapidly integrate more renewable energy (RE) and in particular offshore wind resources, and the reduction of congestion enabling increased cross-border power trade.

In the Netherlands, the challenge of structural congestion in the high voltage transmission grid is particularly acute. Some areas of the grid have seen rapid electrification of industrial processes saturating spare transmission capacity, while other areas have seen explosive growth in interconnection requests from renewable energy generators *(74)*. The latest EU electricity market regulation in 2019 recognized these issues, impelling Member States to review bidding zones and address capacity allocation and congestion management with efficient market-based solutions; it also directed TSOs to ensure that at least 70% of cross-border transmission capacity is offered for cross-zonal trade *(75)*. In response, the Dutch action plan identified reconductoring with HTLS conductors as a key strategy to alleviate congestion and increase thermal transmission capacity in the near-term, along with exploring dynamic line ratings and improving dispatch coordination *(76)*.

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 most of the pertinent lines are double-circuit, one circuit remains live while the other is de-energized and reconductored, typically planned to coincide with seasons of lower demand. Other necessary maintenance work - such as the replacement of insulators, ground wires, bird flight diverters or strengthening of towers and mast foundations to bring them to the latest construction standards - is often combined and performed concurrently with the reconductoring *(30,71-73)*. Furthermore, the reconductoring may be combined with phase number optimization, in order to avoid expanding the magnetic field zone.

Italy

Whereas reconductoring projects in Belgium and the Netherlands pertain to relatively short line lengths (i.e., <90 km or <50 miles), Italy presents a case of transmission capacity expansion over significantly longer distances and larger scale. Motivating factors include difficulty to secure new rights-of-way (ROW) due to high population density, strengthening network reliability and resilience, and the need to rapidly integrate more renewable energy (RE). At the end of January 2023, requests from renewable generators to connect to the high voltage grid had reached 340 GW; in comparison, Italy had 32 GW of installed capacity of wind and solar in 2019 and forecasts an installed capacity of 102 GW in 2030 *(77,78)*.

Terna, the Italian TSO, plans to invest 11 billion Euros in a Hypergrid network in order to double the exchange capacity between market zones in the country (from 16 GW to 30 GW) by the mid-2030s *(77,78)*. In addition to reconductoring several 380 kV lines with advanced conductors capable of high-temperature operation, the plan notably envisions a large, multi-terminal HVDC network across the country. New north-south power lines are planned as undersea HVDC cables, rather than conventional AC overhead lines, due to “the impossibility of overhead lines or the need for synergy/efficiency with existing projects” *(77)*. Several existing overhead AC lines are also set to be “modernized” and thereby converted to HVDC operation, raising the voltage to 500 kV DC from either 220 or 380 kV AC, enabling the bulk transport of renewable energy from southern generation centers to northern load centers *(78)*.

Texas

While mass deployment of advanced conductors and reconductoring practices in transmission planning is commonplace in several European countries, at the time that it was completed, 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) *(79,80)*. 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. Although the local utility - American Electric Power (AEP) - considered conventional solutions such as the construction of new lines, the risks of permitting delays associated with ROW acquisition was seen as a serious deterrent to this time-sensitive project *(79)*.

Given the need to meet reliability demands within a constrained timeframe, an energized reconductoring of the line emerged as the only option. Although this required the construction of temporary poles, the poles were placed within the existing right-of-way. Therefore the project did not require time-intensive permitting for new land acquisition and was approved the same day it was presented to ERCOT's Board of Directors in 2011 *(79,80)*. Ultimately, the $225 million project was completed in 2016, several months ahead of schedule and millions of dollars under-budget (*36,37,79*).

India

Many emerging economies - where the demands of rapid electrification and load growth necessitate the consideration of strategies that increase power transfer capacity in a limited timeframe - are 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), upgrade of existing AC transmission lines to higher voltages, reconductoring of existing AC transmission lines with higher ampacity conductors, the use of multi-voltage level and multi-circuit transmission lines, as well as the use of HVDC transmission *(53)*.

As the manufacturer of the most widely deployed advanced conductor, as of 2021 CTC Global had completed over 180 projects in India, accounting for approximately 16% of the company's 1,100 total projects with ACCC *(54)*. The projects have spanned 23 Indian states, deploying 15,000 km (~9,300 miles) of conductor to over 30 customers, on voltage levels ranging from 22 kV to 400 kV *(54,55,81)*. India's utilization of advanced conductors also highlights the technology's ability to increase capacity of distribution systems, as advanced conductors played an important role in the Saubhagya Scheme to bring electricity to every household, particularly in rural areas (*81,82*). State utilities have also been prioritizing energy efficiency through the inclusion of an ohmic loss evaluation in their tenders, which favors advanced conductors like ACCC due to their lower losses over conventional conductors *(53)*. Nearly ⅓ of the capital city of Delhi has been upgraded to ACCC conductors to increase capacity and improve grid reliability and efficiency *(54)*.

India also has seen the widespread deployment of 3M's Aluminum Conductor Composite Reinforced (ACCR), for example, around the land-constrained city of Mumbai *(83)*. Increasingly, the planning approach aims to evaluate conductor investments on a total cost of ownership basis, rather than a conventional cost estimation process, to more accurately capture conductor benefits.

China

China is also active in its adoption of advanced conductors, where they are utilized both in reconductoring projects as well as new lines. Motivated by rapid economic growth that has precipitated increased demand for electricity, advanced conductors offer an opportunity to efficiently reach transmission growth objectives. As previously described, CTC Global is one of the most active advanced conductor manufacturers. Alongside its core production facilities in the United States, Paraguay and Indonesia, CTC Global partnered with the NARI group (a wholly-owned subsidiary of the State Grid Corporation of China, the largest electricity utility in the world) to open a manufacturing plant in China in 2014 *(84)*. The primary objective of the new plant is to produce core exclusively for the Chinese market, which sees approximately 50 billion US$ in transmission investment each year *(85)*. For example, the plant supplied 291 km (180 miles) of ACCC conductor for a critical grounding line at one of the AC/DC converter stations of the 3,300 km (2,050 miles) 1100 kV Zhundong-Huainan HVDC project, set to deliver 66 TWh annually to eastern China *(86)*.

3: Impacts of sectionalization on power system stability

Recent work *(59)* and ongoing real-world projects like CAISO's new Manning substation *(87)* and NV Energy's new Greenlink transmission line *(88)* suggest that sectionalization - the addition of a new substation(s) with active and reactive power generation sources along the transmission line, likely with a grid-forming inverter - can help enhance transmission performance while incorporating the necessary renewable resources along existing right-of-way (ROW). Here, we investigate the impacts of sectionalization on power system stability using a simple 3-bus, 230 kV system based on *(89)* with a few changes. We select branch 1-3, as the branch from primary generation source to load, for investigation. We assign bus 1 to be the slack bus, remove the load and generation source at bus 2 to better isolate the performance on branch 1-3, add a new generation source at bus 3 and make the impedance on each line the equivalent, forming the business-as-usual (BAU) case. If the length of branch 1-3 l_{13} is over 50 miles, i.e., past the thermally-limited region, we sectionalize the branch by adding new buses n with active and/or reactive power generation sources p_n and q_n at evenly spaced intervals. These intervals, at most, are 50 miles long ($50<l_{13}\leq100$ results in 1 new bus and 2 sections, $100<l_{13}\leq150$ results in 2 new buses and 3 sections, and so on). The costs of generation sources p_n and q_n are set to zero so that they are preferred by the model, representing renewable resources that are increasingly the most cost-effective source of electricity generation. Single line diagrams of these systems are shown in Figure S3.

Since sectionalizing may affect bus voltages and voltage drops, we employ a continuation power flow in Matpower *(90)* to determine steady state stability limits. The base case starts at a load of p^d_3=100 MW, increasing to a target case load of p^d_3=1000 MW; generation at bus 3 is not scaled, so that the increasing load comes from the slack bus. The continuation power flow uses a step size of 0.05, pseudo arc length parametrization, and is set to enforce active and reactive power generation limits. The process terminates when a branch flow limit is reached. We investigate cases with and without bisection, with and without reconductoring all lines of the system with advanced conductors, and with and without different amounts of active and reactive power injection at the load bus 3 as well as the new sectionalized buses. For each case, the branch flow limit is calculated based on theory from *(26-28)* based on the voltage level, line length, conductor type, and availability of compensation. In Figure S4, we show results in the form of load bus 3 voltages over continuation parameter λ, which is proportional to the bus 3 active power demand.

For short lines, reconductoring enables higher power transfers over branch 1-3 and thus higher active power consumption at bus 3. Due to the lower resistance of ACCC over conventional ACSR, the PV curve shifts to the right for an equivalent bus 3 voltage. For long lines, which are not thermally limited, reconductoring alone offers minimal benefit to the system. However, the utilization of the existing transmission system may be enhanced through the sectionalization of very long lines with appropriate quantities of active and/or reactive power injection, especially when combined with reconductoring with advanced conductors which raise the thermal limit of operation. As seen in Figure S4, sectionalization of long lines with reactive power support at both the load bus 3 and the new sectionalized buses improves voltage stability at the load bus 3 and increases power transfer over branch 1-3. For very long lines with several sections, the amount of reactive power injection at each new sectionalized bus increases with increased distance from the slack bus 1. In these cases, sectionalization and the injection of active and reactive power can boost power flow on branch 1-3 and thus enable higher demand at bus 3, which is directly proportional to the continuation parameter λ. While here we only consider a small 3-bus system, preliminary findings indicate that sectionalization may help integrate this required renewable capacity, along with storage, while simultaneously enhancing the utilization of the existing transmission system.

Supplementary Figures

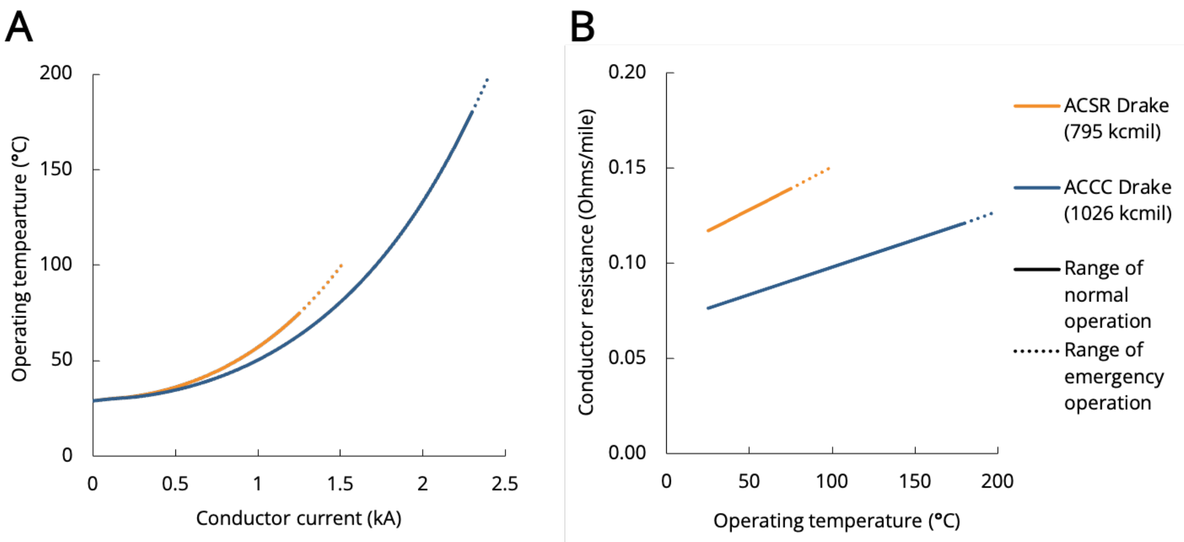

Figure S1: The relationship between conductor properties and operating temperature. (A) Conductor operating temperature as a function of current through the conductor. (B) Conductor resistance as a function of conductor operating temperature. Solid lines refer to the conductor's normal range of operation, while dotted lines indicate the conductor's range of emergency operation. Calculations performed at 25.0°C Ambient Temperature, 1028.7 (W/m²) Sun Radiation, 2.00 (m/s) Wind, 90 Wind angle, 0 (m) Elevation, 0.50 Solar Absorptivity, 0.50 Emissivity based on IEEE Standard 738-2006 for Calculating the Current-Temperature of Bare Overhead Conductors for a single "Drake"-size conductor *(69)*.

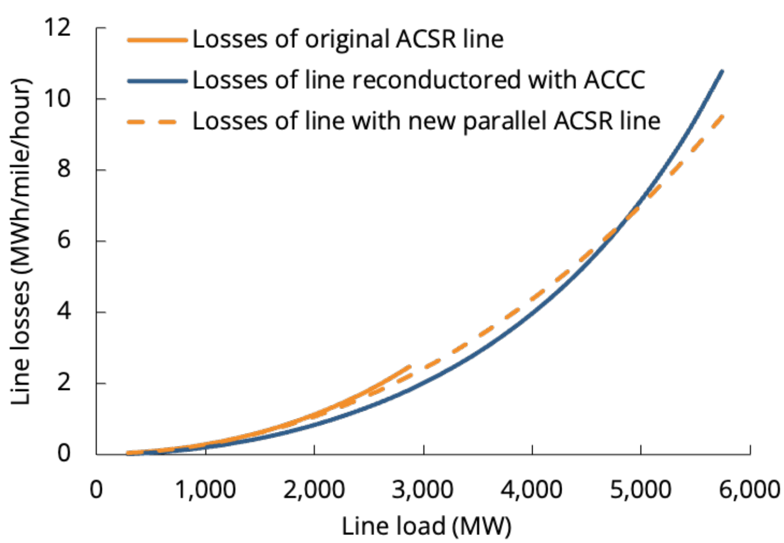

Figure S2: Line losses as a function of line load. The figure shows how the losses would change as a function of line loading for a double-circuit 345 kV line with 3 phases and 2 "Drake"-size conductors per phase, originally wired with ACSR, either through reconductoring or the building of a new parallel ACSR line.

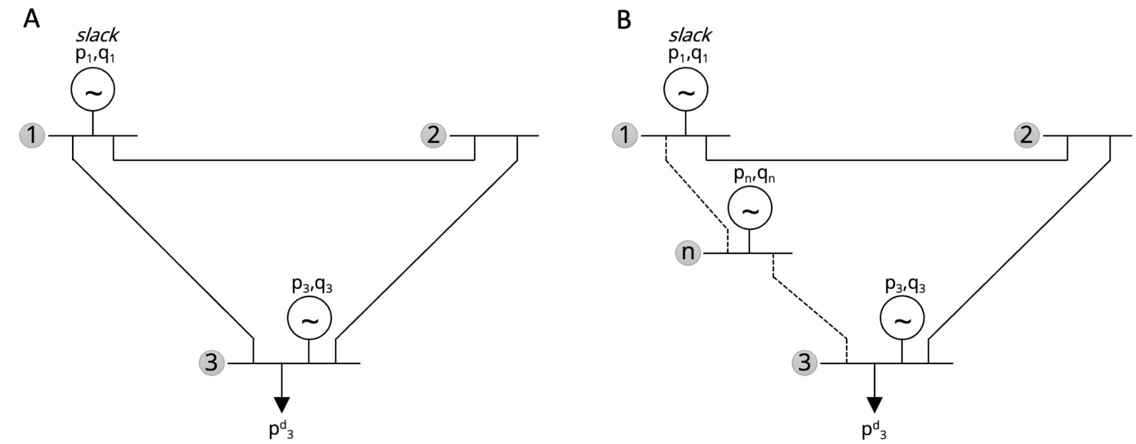

Fig. S3: Single line diagram of the three-bus test system. (A) The Business-As-Usual (BAU) case. (B) The sectionalized case, featuring a new substation between bus 1 and bus 3. In both cases, bus 1 serves as the slack bus while bus 3 serves as the load bus. The variables p_1 and q_1 refer to the active and reactive power at bus 1, respectively; p_3 and q_3 refer to the active and reactive power at bus 3, respectively; p_n and q_n refer to the active and reactive power at bus n (the sectionalized bus), respectively.

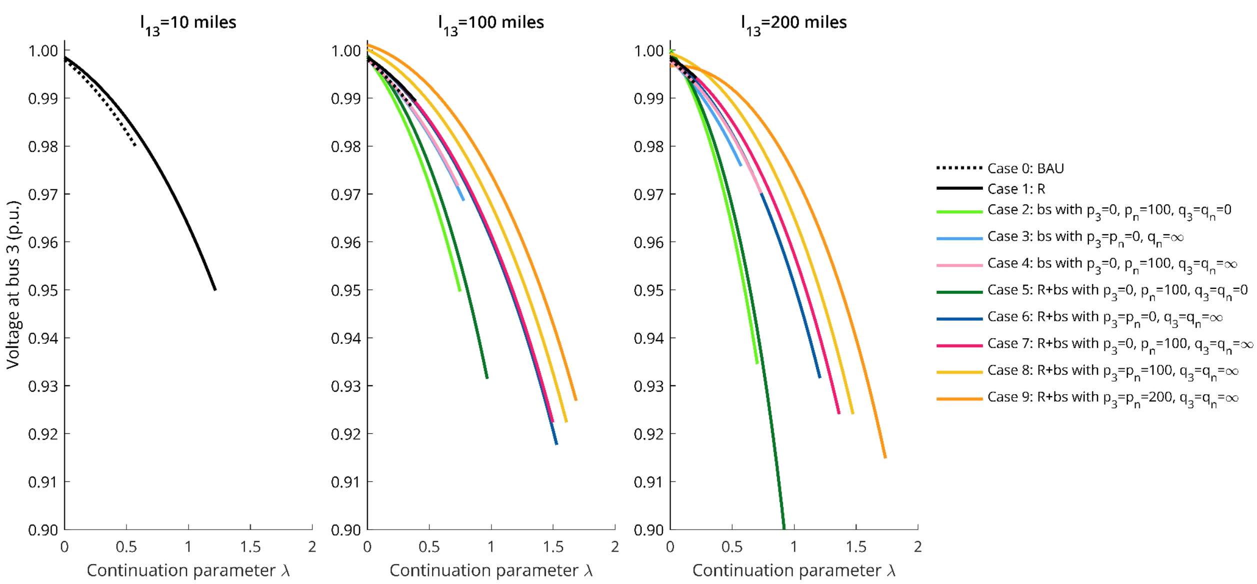

Fig. S4: PV curves of bus 3 for different lengths of branch 1-3. These PV curves show the results of the continuation power flow on various cases of reconductoring (R), bisection (bs), and reconductoring with bisection (R+bs) of the three-bus test system compared to Case 0, the Business-As-Usual (BAU) case. In long lines, sectionalization and the injection of active and reactive power can boost power flow on branch 1-3 and thus enable higher demand at bus 3, which is directly proportional to the continuation parameter λ. The variables in the legend refer to Fig. S3: p_3 and q_3 refer to the active and reactive power at bus 3, respectively; p_n and q_n refer to the active and reactive power at bus n (the sectionalized bus), respectively.

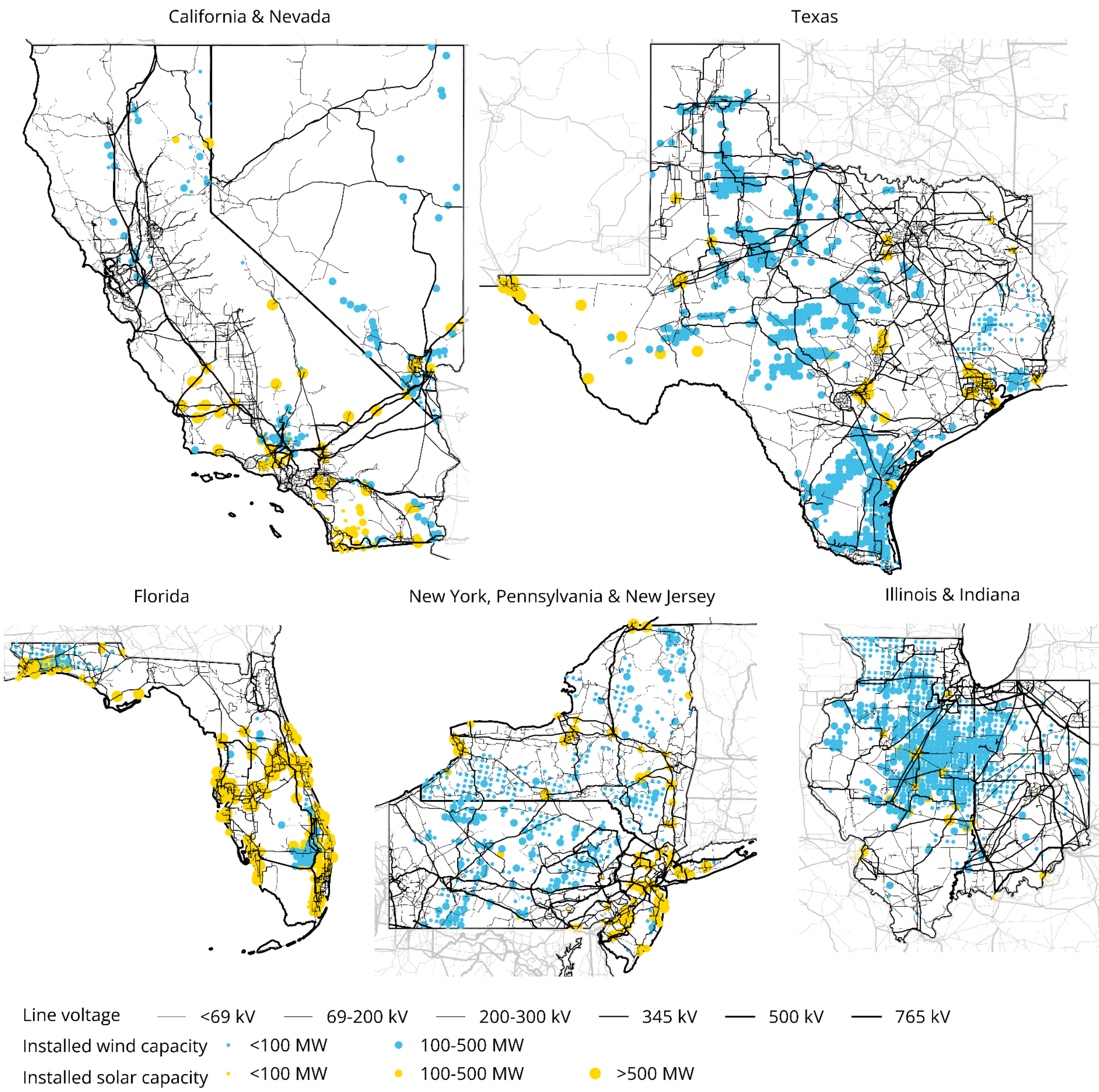

Fig. S5: Selected sites of solar and wind plants by the ReEDS model for the restricted build-out scenario with reconductoring are in close proximity to the existing US transmission network. Dots denote the locations of solar plants (in yellow) and wind farms (in blue) installed by 2035 for the restricted build-out scenario with reconductoring, underlaid with the existing US transmission network *(29)* for select states. Dot size and transmission line width correspond to capacity.

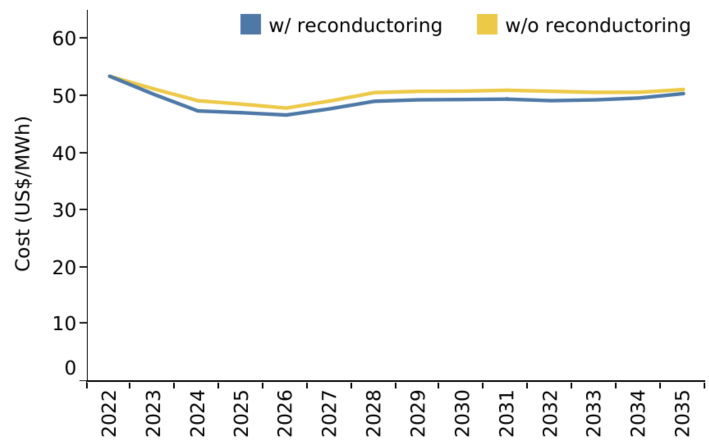

Fig. S6: Progression of wholesale electricity costs for the restricted build-out scenario. The combined effect of lower transmission expansion costs and higher-quality RE lowers wholesale electricity costs (the sum of transmission and generation costs, in US$/MWh) by 3-4% versus when reconductoring is not offered as an option.

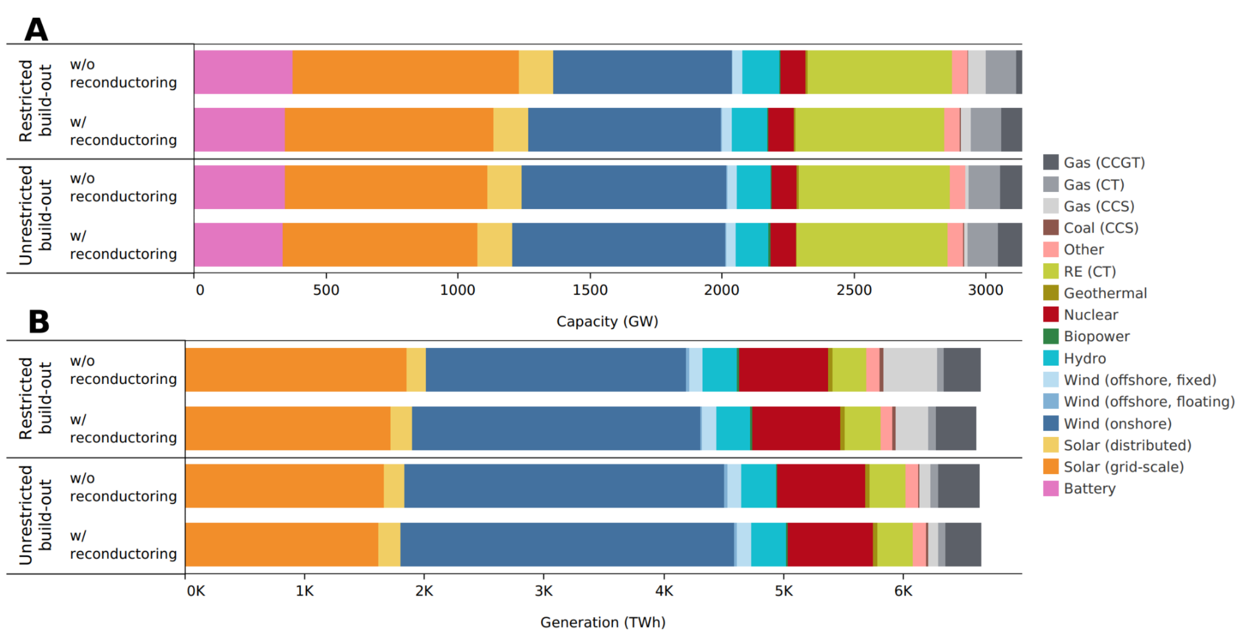

Fig. S7: Technological breakdown of installed capacity and annual generation US-wide in 2035. (A) Installed capacity. (B) Annual generation. The generation of battery capacity is included within the battery charging technology.

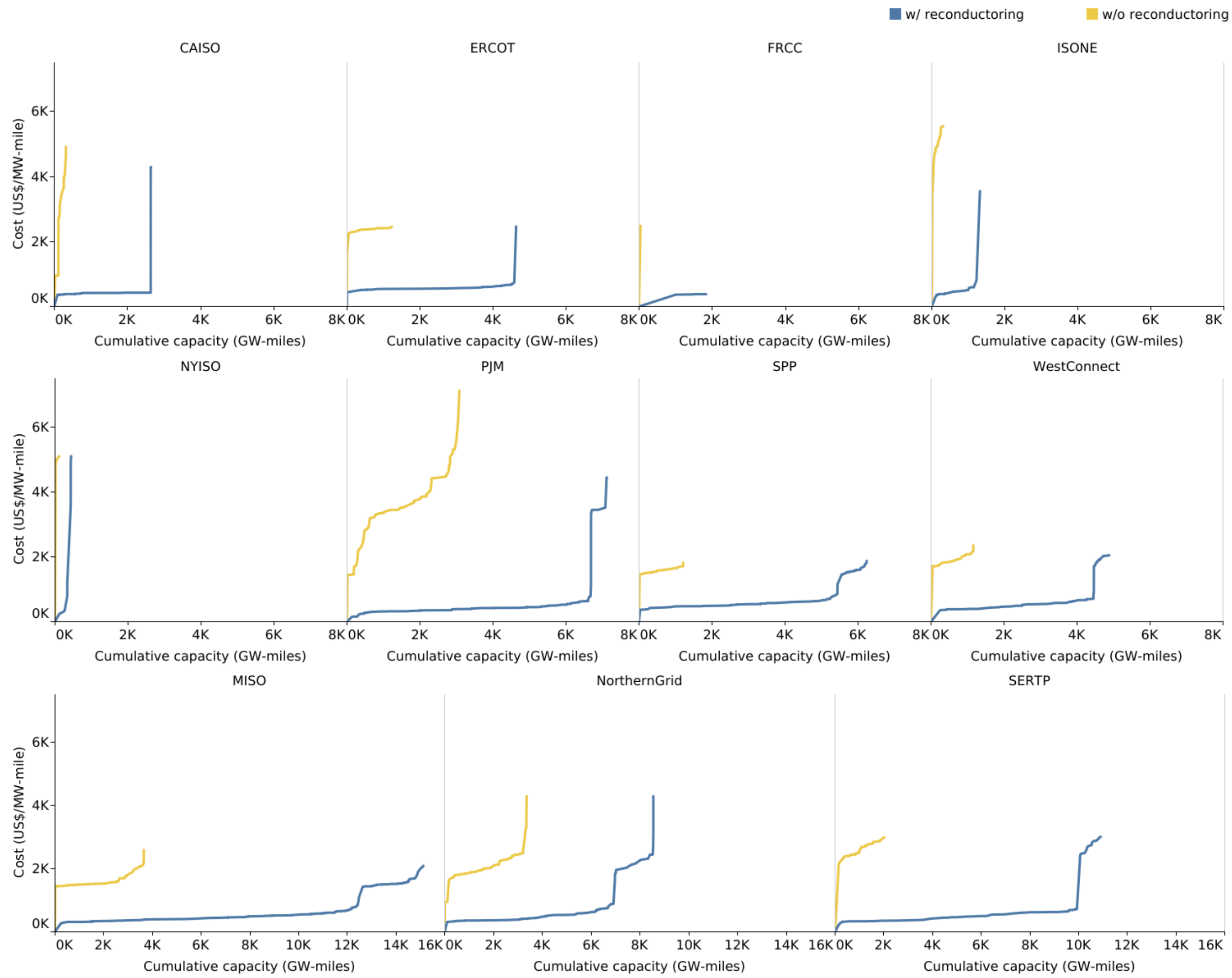

Fig. S8: Supply curves for adding transmission capacity by transmission region for the restricted build-out scenario. When reconductoring is offered as an option, the model builds more transmission capacity and at lower unit costs in both the unrestricted and restricted build-out scenarios. Supply curves were created by sorting the ReEDS paths' unit costs of reconductoring in ascending order and plotted as a function of cumulative GW-miles.

Supplementary Tables

Table S1. Comparison of conventional conductors with different types of advanced conductors[1].

Abbr.	Full name	Year invented	Composition	Ampacity increase over ACSR	Operating temperature	"Drake"-size area[2]	"Drake"-size strength[3]	"Drake"-size weight[3]	"Drake"-size AC resistance at 75°C	Proprietary?	Deployment	Source(s)
ACSR	Aluminum Conductor Steel Reinforced	1900s	1350-H19 aluminum round strands around a galvanized steel core	1x	75°C cont., 100°C emerg.	795 kcmil	31,500 lbs	1093 lbs/kft	0.0263 Ohms/kft	no	En masse	*(9)*
ACSS	Aluminum Conductor Steel Supported	1970s	1350-O fully annealed aluminum round strands around a galvanized steel core	<1.7x	250°C cont./emerg.	795 kcmil	25,900 lbs	1093 lbs/kft[4]	0.0257 Ohms/kft	no	En masse	*(67)*
ACCR	Aluminum Conductor Composite Reinforced	2000s	Zirconium-doped aluminum trapezoidal strands around a core of aluminum oxide fibers embedded in an aluminum matrix	~2x	210°C cont., 240°C emerg.	795 kcmil	37,000 lbs	1075 lbs/kft	0.0213 Ohms/kft	yes: 3M	>6,000 miles installed on >325 projects	*(10,11)*
ACCS	Aluminum Conductor Composite Supported[5]	2000s	1350-O fully annealed aluminum trapezoidal strands around a composite core of carbon fiber in a polymer matrix	~2x	180°C cont., 225°C emerg.	995 kcmil	33,500 lbs	1001 lbs/kft	0.0290 Ohms/kft[6]	yes: Southwire	n/a	*(91)*
ACCC	Aluminum Conductor Composite Core[7]	2000s	1350-O fully annealed aluminum trapezoidal strands around a composite core of carbon fiber encased in a fiberglass tube	~2x	180°C cont., 200°C emerg.	1026 kcmil	41,200 lbs	1052 lbs/kft	0.0202 Ohms/kft	yes: CTC Global	>81,000 miles installed on >1,100 projects in 60+ countries	*(12)*
AECC	Aluminum Encapsulated Carbon Core	2000s	1350-O fully annealed aluminum trapezoidal strands around a composite core of carbon fiber encapsulated in aluminum	~2-3x	180°C cont., 200°C emerg.	1051 kcmil	42,200 lbs	1050 lbs/kft	0.0199 Ohms/kft	yes: TS Conductor	>300 miles	*(13)*

[1] Technical conductor specifications are taken from manufacturers' data sheets and may vary slightly as a result of different environmental parameters at which measurements were taken. 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 "Drake"-size conductor, similar trends hold across different conductor sizes.

[3] Advanced 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 ACCR, ACCC and AECC may be slightly elevated compared to ACSR and ACSS.

[4] Standard strength, although high strength options are also available (*67*).

[5] Also known as the C[7] 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).

Table S2. Empirical project data.

Line	Transmission region	Project type	Commissioning year	Voltage	Line length	Original capacity	New capacity	Capex[1,2] (million US$)	Cost (million US$/mile)	Cost (million US$/GW-mile)	Source(s)
Avelin-Avelgem-Horta	Belgium	Reconductor	2022	380 kV	48 miles	3 GW	6 GW	193	4.0	1.3	*(30)*
Massenhoven-Van Eyck			2026		56 miles	3 GW	6 GW	140	2.5	0.8	*(30)*
Van Eyck-Gramme			2029		54 miles	3 GW	6 GW	164	3.0	1.0	*(30)*
Gramme-Courcelles			2033		43 miles	3 GW	6 GW	175	4.1	1.4	*(30)*
Courcelles-Bruegel			2035		29 miles	3 GW	6 GW	129	4.4	1.5	*(30)*
Bruegel-Mercator			2025		20 miles	3 GW	6 GW	93	4.7	1.6	*(30)*
Mercator-Massenhoven			2030		22 miles	3 GW	6 GW	82	3.8	1.3	*(30)*
Avelgem-Courcelles ("Boucle de Hainaut")[3]		New-build	2028		62 miles	-	6 GW	584	9.4	1.6	*(30)*
Stevin-Avelgem ("Ventilus")[3]			2028		56 miles	-	6 GW	467	8.4	1.4	*(30)*
Diemen-Lelystad-Ens	Netherlands	Reconductor	2022	380 kV	45 miles	3.3 GW[4]	5.3 GW[4]	123	2.8	1.4	*(30)*
Ens-Zwolle			2024		20 miles	3.3 GW[4]	5.3 GW[4]	48	2.4	1.2	*(30)*
Krimpen-Geertruidenberg			2023		21 miles	3.3 GW[4]	5.3 GW[4]	48	2.3	1.2	*(30)*
Eindhoven-Maasbracht			2025		30 miles	3.3 GW[4]	5.3 GW[4]	58	1.9	1.0	*(30)*
Zwolle-Hengelo-Doetinchem-Dodewaard			2040		102 miles	3.3 GW[4]	5.3 GW[4]	245	2.4	1.2	*(30)*
Borssele-Rilland ("ZuidWest380 West")		New	n/a		30 miles	-	-	659	22.1	-	*(30)*
Rilland-Tilburg ("ZuidWest380 Oost")			n/a		50 miles	-	-	1273	25.0	-	*(30)*
Zandvliet-Lillo-Liefkenshoek ("Brabo II")			2025		11 miles	-	-	117	10.5	-	*(30)*
Lower Rio Grande Valley	ERCOT	Reconductor	2016	345 kV	240 miles	1.2 GW[5]	2.4 GW[5]	225	0.9	0.7	*(37)*
CREZ lines		New	2013		3600 miles	-	-	6900	1.9[3]	2.5[3]	*(36)*
Bob-Mead	CAISO	Reconductor	n/a	230 kV	15 miles	-	n/a	25	1.7	-	*(34)*
Big Creek Corridor			2018		69 miles	-	n/a	6	0.1	-	*(33)*
Beatty		New	n/a		62 miles	-	-	155	2.5	-	*(35)*
Generic double circuit	MISO	Reconductor	-	345 kV	-	-	n/a	-	1.1	-	*(38)*
Generic double circuit		New	-		-	-	-	-	5.4	-	*(38)*

[1] Where applicable, Euros are converted to US$ with a conversion rate of 1.168 US$/EUR, the 10-year average between 2013-2022.

[2] Costs for new-build projects may be overly optimistic as they reflect planning costs for lines that were master planned and part of a larger transmission planning package.

[3] In Belgium, the costs of new-build projects reflect new lines which will be wired with ACCC.

[4] Capacity estimated based on provided current rating, voltage, number of circuits and other known information.

[5] CREZ lines' cost in US$/mile is calculated as the total capex over the summed line lengths, while the cost in US$/GW-mile is an average over all voltage level.

Table S3. Reference conductor selection[1].

AC voltage range	ROW width	Surge Impedance (SI)	Surge Impedance Loading (SIL)	Bundle quantity[2]	Original conductor[3]	Upgraded conductor[3]
100-161 kV	120 ft	380 Ohms	26-68 MW	1	ACSR “Drake” (795 kcmil)	ACCC “Drake” (1026 kcmil)
220-287 kV	150 ft	375 Ohms	129-220 MW	1	ACSR “Bittern” (1272 kcmil)	ACCC “Bittern” (1582 kcmil)
345 kV	160 ft	366 Ohms	325 MW	2	ACSR “Drake” (795 kcmil)	ACCC “Drake” (1026 kcmil)
500 kV	180 ft	294 Ohms	850 MW	3	ACSR “Cardinal” (954 kcmil)	ACCC “Cardinal” (1222 kcmil)
765 kV	200 ft	266 Ohms	2200 MW	5	ACSR “Drake” (795 kcmil)	ACCC “Drake” (1026 kcmil)

[1] Based on *(24,38)*. Actual line configurations may vary by transmission planning region, the age of the line, etc.
[2] Bundle quantity is assumed to be the same for the original and upgraded conductor, yet bundle quantity may be modified within a reconductoring project depending on the project needs, structure capabilities, etc.
[3] 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).