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

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

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## Abstract

*As countries pursue decarbonization goals, the rapid expansion of transmission capacity for renewable energy (RE) integration poses a significant challenge due to hurdles like permitting and cost allocation. However, declining RE costs have increased their competitiveness in more locations, presenting an opportunity to cost-effectively double transmission capacity within existing right-of-way (ROW) via large-scale reconductoring with advanced composite-core conductors, requiring limited additional permitting. We implement reconductoring in a model of the United States power system, finding that the consideration of reconductoring enables four times more transmission capacity by 2035 - representing over 80% of the transmission needed to reach over 90% clean energy. With \$180 billion in system cost savings by 2050, reconductoring presents a cost-effective and time-efficient, yet underutilized, opportunity to accelerate transmission expansion globally.*

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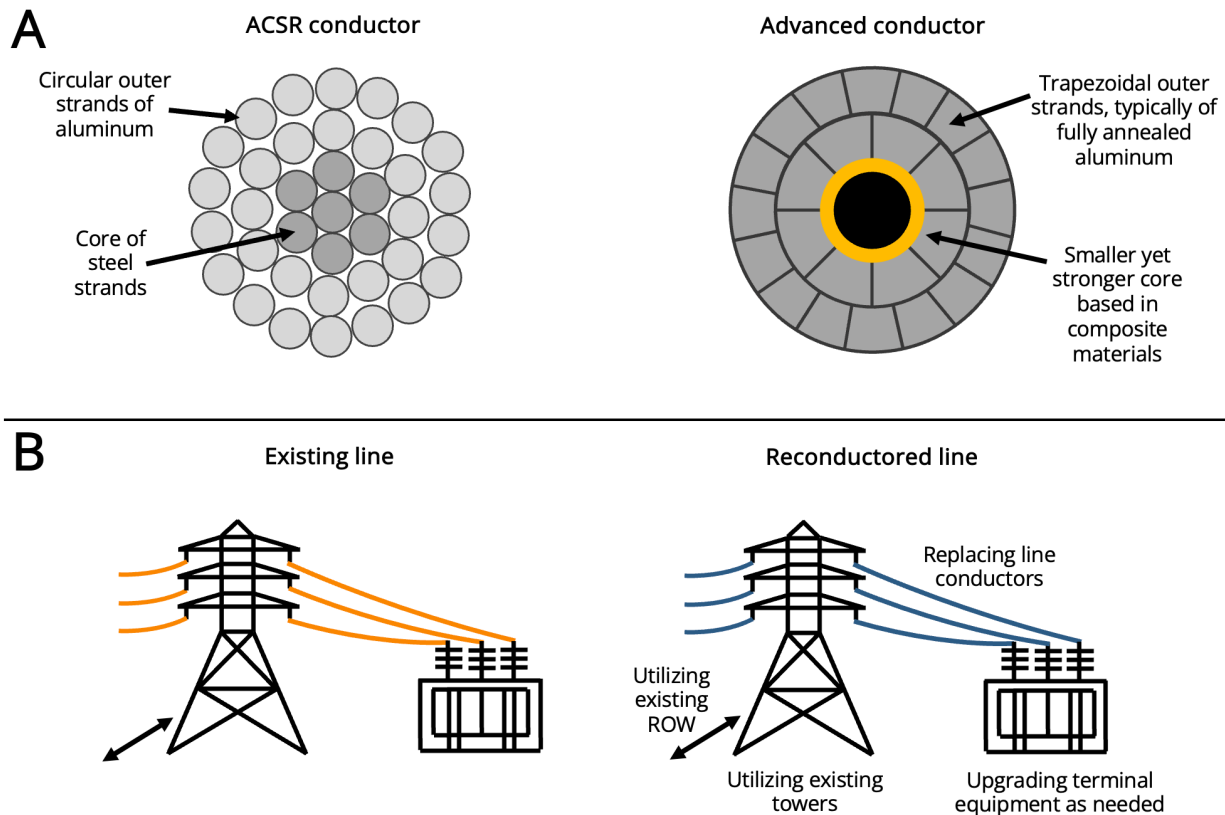
Funding for this study was provided under a grant from Breakthrough Energy and supported by GridLab. Modeling results are available in a GIS dashboard [here](#). All data needed to evaluate the conclusions in the paper are included in the paper and/or the Supplementary Materials. All opinions, errors, 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 estimates that the global length of transmission lines must increase by approximately 2.7 times to reach net zero emissions by 2050 - from 5.5 million to 15 million km, 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 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. Expanding the capacity of the existing transmission system, rather than building new long distance lines, can unlock this increasingly economically viable RE capacity.

Reconductoring - the replacement of a transmission line's existing conductors with advanced conductors - holds significant potential for rapid transmission expansion (14). While most of the high voltage grid today is wired with a century-old technology known as Aluminum Conductor Steel Reinforced (ACSR) (8), advanced conductors swap the steel for a similarly strong yet smaller composite core, enabling higher operating temperatures and allowing more conductive aluminum to fit within an equivalent diameter (Fig. 1A). As a result, these advanced composite-core conductors can carry approximately twice as much power as conventional conductors, while lowering losses during certain operating conditions as well (see the supplementary text and Table S1) (9-13). Because reconductoring leverages existing transmission towers and rights of way, 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 conductors and transmission lines compared to lines reconducted 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). (B) A schematic of an existing transmission line reconducted with advanced composite-core conductors.

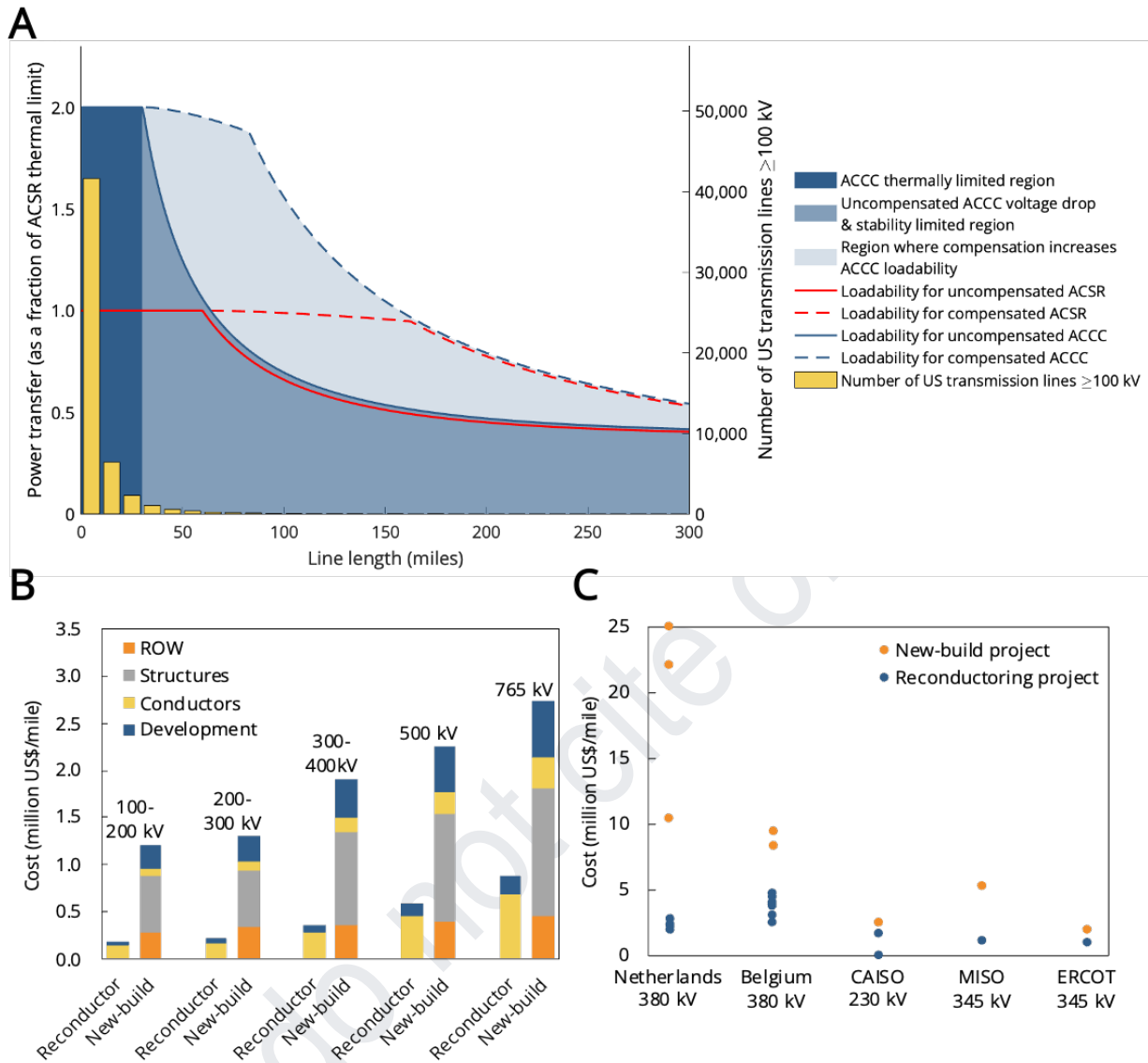
Previous work has established that it is cost effective and time efficient to expand transmission capacity by reconductoring existing lines (8,14-16). Although there is robust global deployment of advanced conductors (see the supplementary text for case studies), the technology has seen only limited uptake in the US. However, major 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, the Aluminum Conductor Composite Core (ACCC) (15,25). 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, which can contribute to the cost-effective achievement of decarbonization goals. We first evaluate the transmission capacity increase and associated cost to reconductor all 53,000 US transmission lines. While advanced conductors refer to a range of available conductor technologies with increased thermal ratings, we specifically evaluate the proprietary ACCC manufactured by CTC Global

given it is the most widely deployed composite-core conductor to date, although we do not endorse nor investigate differences amongst other advanced conductors with similar qualities. We include the resulting unit cost estimates in a widely-used transmission and generation co-optimization 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 more transmission capacity at only slightly higher cost than a business as usual case, unlocking a high availability of cost-effective renewable resources in close proximity to the existing US transmission network and load. These results indicate that reconductoring should constitute a key pillar in strategies to achieve grid decarbonization goals.

## **2. 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. The rated transfer capacity of long alternating current (AC) lines may additionally 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 reactive power compensation or sectionalization (the addition of new substation(s) with active and reactive power generation sources along the line). We show this in the St. Clair's curves in Fig. 2A, which plot the line loadability of ACCC and ACSR lines as a function of line length, with and without reactive power compensation and sectionalization (26-28). Assuming the base case line is wired with ACSR, and the reconducted line is wired with an equivalent-diameter ACCC, reconductoring with compensation can up to double transmission capacity for lines up to approximately 50 miles, and for the 2% of US transmission lines above 50 miles, with sectionalization and compensation at most every 50 miles (see the supplementary text) (29).



**Fig. 2: Capacity increases and costs of reconductoring.** (A) 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). We also indicate the select strategies for doubling transmission capacity as a function of line length, although a full system study including load flow, contingency and dynamic stability analyses should be conducted to verify these numbers in each real-world system. It should be noted that the St. Clair's curve, while known as a single curve, is really a piecewise function for which the governing constraint - i.e., the thermal, voltage drop and angular stability limits - defines each sub-interval. (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).

To expand the ReEDs model to include reconductoring as a decision variable, we calculate the bottom-up cost to increase transmission capacity through reconductoring projects vis-a-vis new-build projects with ACSR (Fig. 2B). Although advanced conductors 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).

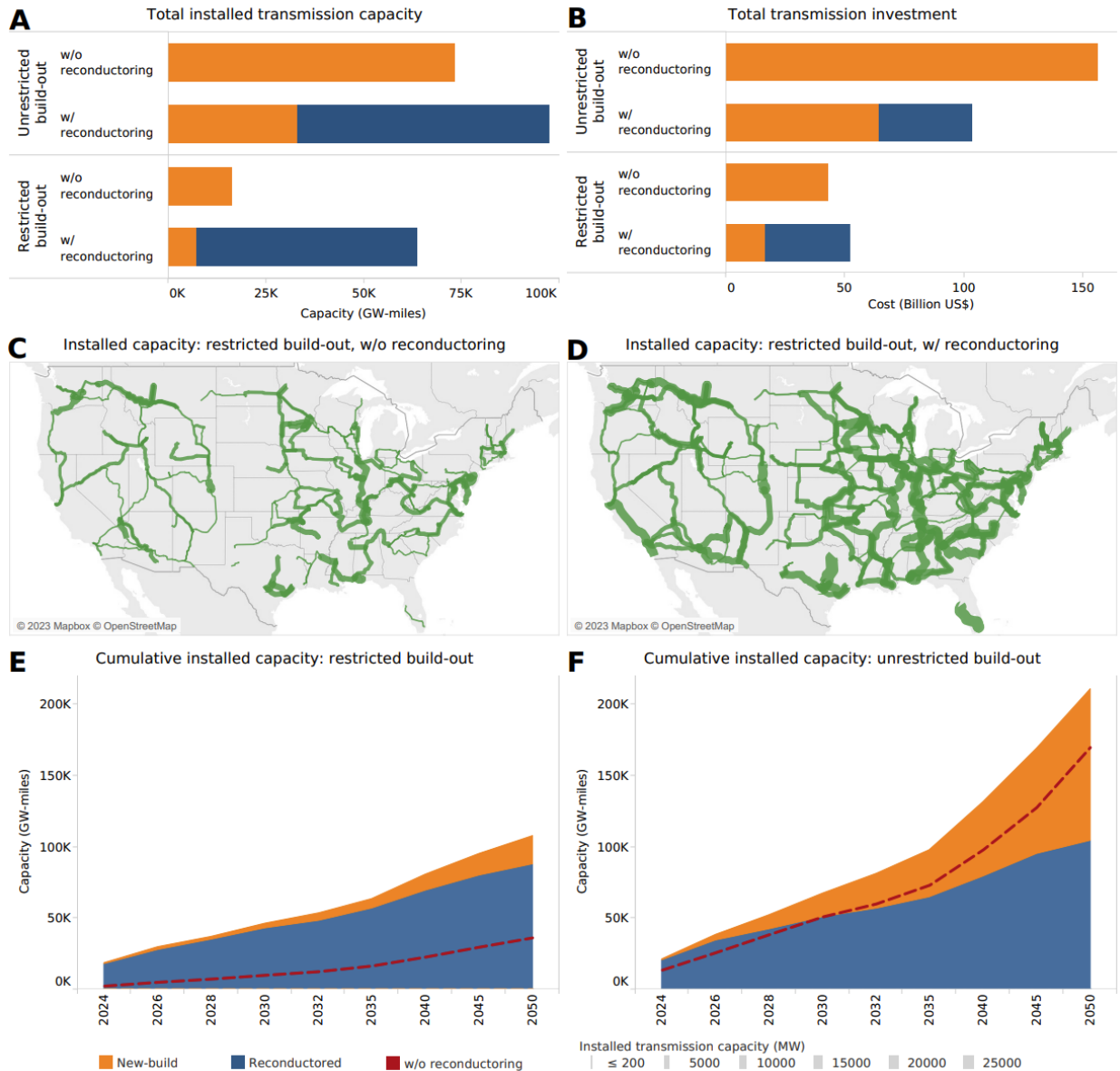
We estimate the capacity increase and cost to reductor each of the 53,000 transmission lines in the US (defined as a segment at or above 100 kV) (29) based on voltage level and line length (see the supplementary text). Voltage indicates the conductor size, number of conductors per phase and spacing arrangement, while line length determines if a complementary set of strategies - i.e., compensation and/or sectionalization - is used in conjunction with reductoring. Although typical reductoring projects do not entail sectionalization, and substation upgrades including compensation may be considered separately, we include these costs in our reductoring cost estimates to comprehensively account for the upgrades that enable a doubling of capacity. The resulting unit costs in US\$/MW-mile are inversely related with voltage, with the highest voltage lines bearing the lowest costs per unit of transmission capacity increase.

### **3. Reconductoring can play a pivotal role in low-cost decarbonization of power systems**

To demonstrate the utility of reductoring to achieving decarbonization goals, the resulting cost estimates are implemented in ReEDS. We run a least-cost system optimization considering IRA incentives as well as increases in load due to high electrification. Further, we assume that coal generation is phased out by 2035 and no new gas-fired capacity can be built after 2023, reflecting pending policy that is consistent with a net-zero pathway (for more details, see Methods). We investigate four primary scenarios: with and without reductoring as an option, and with and without constraints on the rate of transmission build-out, on a time horizon up to 2050. 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 reductoring 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).

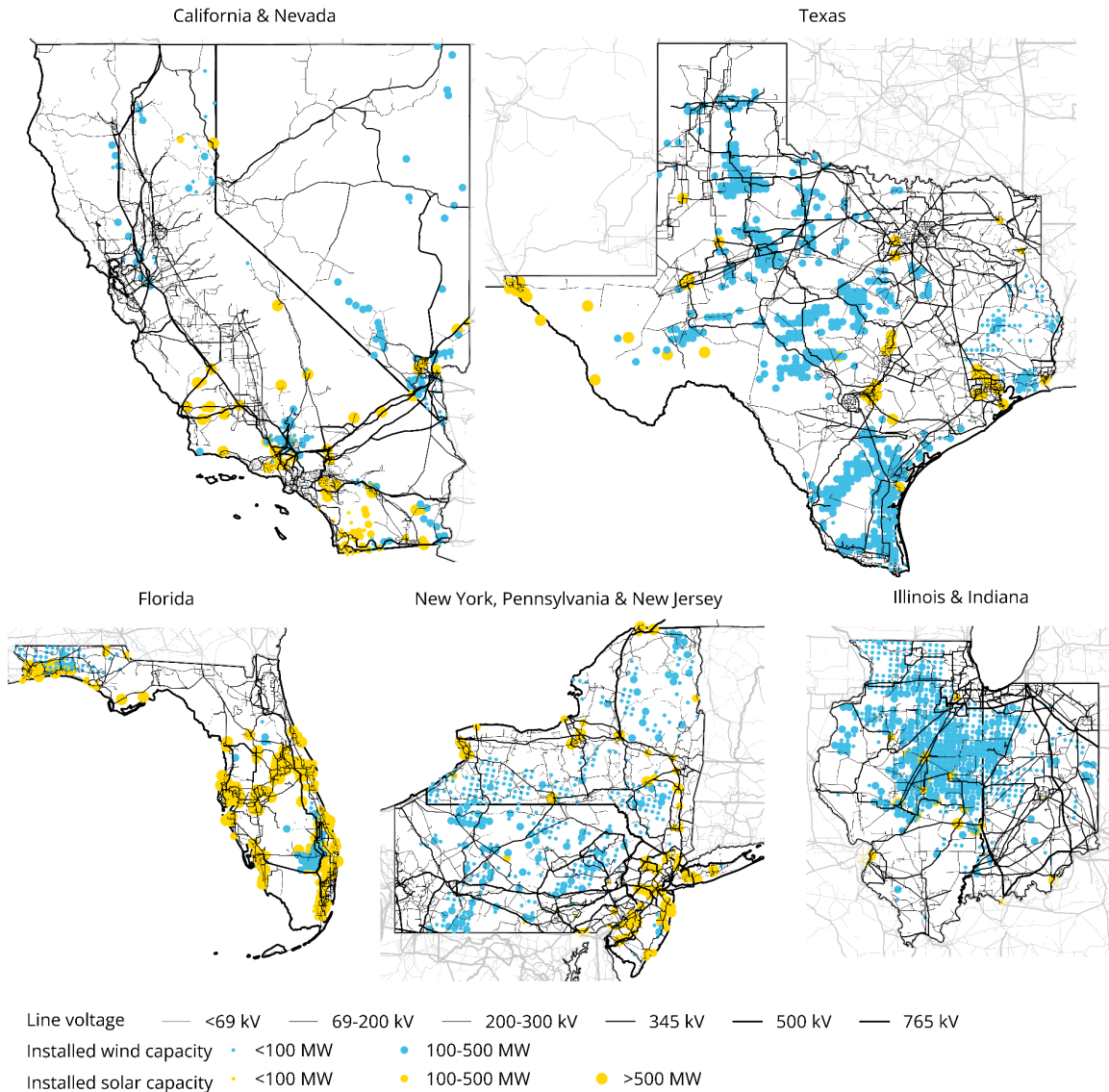
We find that when reconductoring is an option, it is favored over building new lines due to its lower cost, representing 66% of total installed transmission capacity by 2035 in the unrestricted build-out case (Fig. 3A). This indicates that even without factoring in the benefit of faster project realization 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 restricted build-out case, where it represents 89% of the total capacity installed by 2035. Compared to the case without reconductoring as an option, reconductoring enables nearly four times as much transmission capacity to be added at only slightly higher total transmission cost (Fig. 3A and 3B) because it circumvents the extensive planning and permitting processes that impede new lines which require new ROW and cross regional boundaries. 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 capacity installed 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 next few years while new lines are planned and permitted.





**Fig. 3: Installed transmission capacity and associated investment.** (A) Total installed transmission capacity between 2022 and 2035, by scenario. (B) Total transmission investment between 2022 and 2035, in 2022 US\$. Transmission investment includes both line as well as terminal station costs. (C and D) Installed transmission capacity between 2022 and 2035 for the restricted build-out scenario by ReEDS path, without reductoring as an option (C) and with reductoring as an option (D). Bar width corresponds to the magnitude of installed capacity. (E and F) Cumulative installed transmission capacity build-out with reductoring for the restricted case (E) and the unrestricted case (F), with the total installed transmission capacity build-out without reductoring represented by a red dashed line.

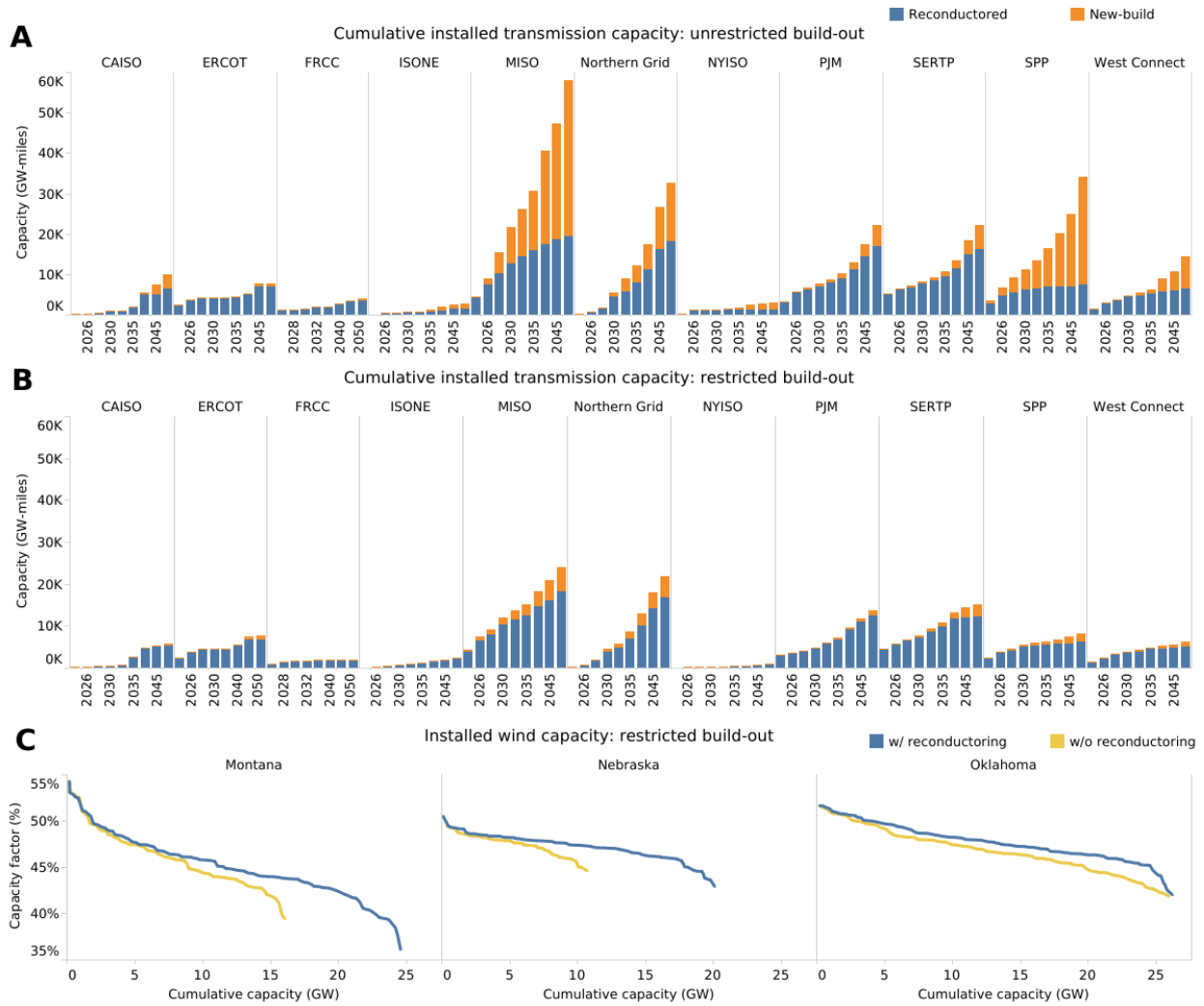
The larger and more distributed transmission capacity increase enabled by reconductoring simultaneously unlocks access to lower-cost, higher-quality RE in more locations. The ReEDS model identifies specific sites with cost-effective, high-quality renewable resources that are located near the existing transmission network (Fig. 4).



**Fig. 4: High availability of cost-effective renewable resources 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.

With reconductoring, the combined effect of lower transmission expansion costs and higher-quality RE lowers wholesale electricity costs by 3-4% (Fig. S5), 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, simply due to low clean energy costs resulting from IRA incentives. 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. S6). In the restricted buildout 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 regional installed transmission capacity over time (Fig. 5A and 5B, Fig. S7). In regions such as ERCOT, PJM and CAISO, a larger share of reconductoring is the least-cost strategy to increasing transmission capacity compared to regions such as MISO or SPP, where reconductoring plays a smaller role (Fig. 5A). For these latter regions, the increase of 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. 5A) with the restricted build-out case (Fig. 5B) 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. 5C). 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. 5: Regional variation in transmission expansion.** (A) Cumulative installed capacity for the unrestricted build-out scenario. (B) Cumulative installed capacity for the restricted build-out scenario. (C) The capacity factor of installed wind farms as a function of the cumulative installed capacity for the restricted build-out case, with reconductoring in blue and without reconductoring in yellow.

#### 4. 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 widespread availability of composite-based advanced conductors as well as low-cost high-quality renewable resources in close proximity to the existing US transmission network have created an opportunity to meet most of the near-term transmission needs through leveraging existing ROW. Our results indicate that reconductoring can rapidly increase transmission capacity and unlock RE on a US-wide scale at significantly lower cost, meeting over 80% of the transmission required for a >90% clean power system by 2035. 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. From an operational perspective, the elimination of the steel core in advanced conductors has been demonstrated to significantly improve corrosion resistance in areas near seawater compared to standard 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. These 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 to nearly double transmission capacity, 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. However, because reconductoring unlocks RE capacity and accelerates build-out on a large scale, the benefits of reconductoring can't be fully captured by evaluating its merits on a line-by-line basis. To ensure that advanced conductors make their way into widespread use, the DOE or IEEE could consider a national conductor efficiency and/or resistance-based standard - similar to the energy conservation standards for distribution transformers (57). Meanwhile, FERC's proposed reform of transmission planning could mandate the consideration of advanced conductors and reconductoring practices as alternatives to new lines within long-term regional transmission planning. This would ensure reconductoring is not only an end-of-life option for infrastructure, but instead 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 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 in their networks. There is a range of available advanced conductors with increased thermal ratings, however their technical parameters may differ and must be carefully evaluated for the needs of each transmission project and its 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. A reconductoring project may also provide an opportunity to simultaneously reinforce existing towers, replace insulators or

perform other necessary maintenance work, depending on their age and state. Moreover, sectionalization with inverter-based resources 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 transmission capacity increase potential and system stability implications of both AC-to-DC conversion and sectionalization as well as investigate the potential for large-scale reconductoring in other global regions.

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## 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):

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

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 and no installed compensation. We benchmark the resulting estimated GW-mile total (~160,000) against the current GW-miles deployed in the US (~150,000), within an acceptable range (62).

### *Estimate the capacity of reconducted 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 i.e. compensation and sectionalization that is used - based on the line length. In line with previous 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 (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<sup>®</sup> conductors (38). For each voltage level, we establish a reference conductor size selection and bundle quantity (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).

### *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. If needed, depending on the line length, we do include the cost of compensation within the reconductoring 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). If needed, depending on the line length, we also include the cost of sectionalization within the reconductoring 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 reductor 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. We match every physical transmission line with a path in ReEDS and estimate its cost of reductoring by taking a GW-mile weighted average of the cost to reductor each individual line that makes up the path.

### ***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 reductoring 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 ReEDS model (66). We model a high rate of electrification, with correspondingly high load and high generation build-out. To the base model we also add additional constraints to retire coal capacity by 2035, implemented linearly with the oldest plants retiring first, and disallow new gas capacity post-2023, except plants that are already under construction - reflective of not only pending policy from the Environmental Protection Agency (EPA) but also the investment uncertainty regarding the construction of new fossil plants.

#### ***Implementing reconductoring in ReEDS***

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). We also apply intraregional and interregional constraints, similarly limiting annual expansion to the recent historical rate. For reconductoring, which may be hindered by interregional cost allocation issues, we similarly limit annual expansion of interregional capacity to the recent historical rate. No additional expansion is allowed between the three interconnects.

## 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 reconducted 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 reconducting 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: reductor 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

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

and calculate line load via

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

where  $I_{\phi}$  is the phase current,  $N_{\text{cond}}$  is the number of conductors per phase,  $R$  is the resistance per unit length,  $N_{\text{circ}}$  is the number of circuits per line,  $N_{\phi}$  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 reconducting 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 reconducting 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 reconducted, 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 1/3 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

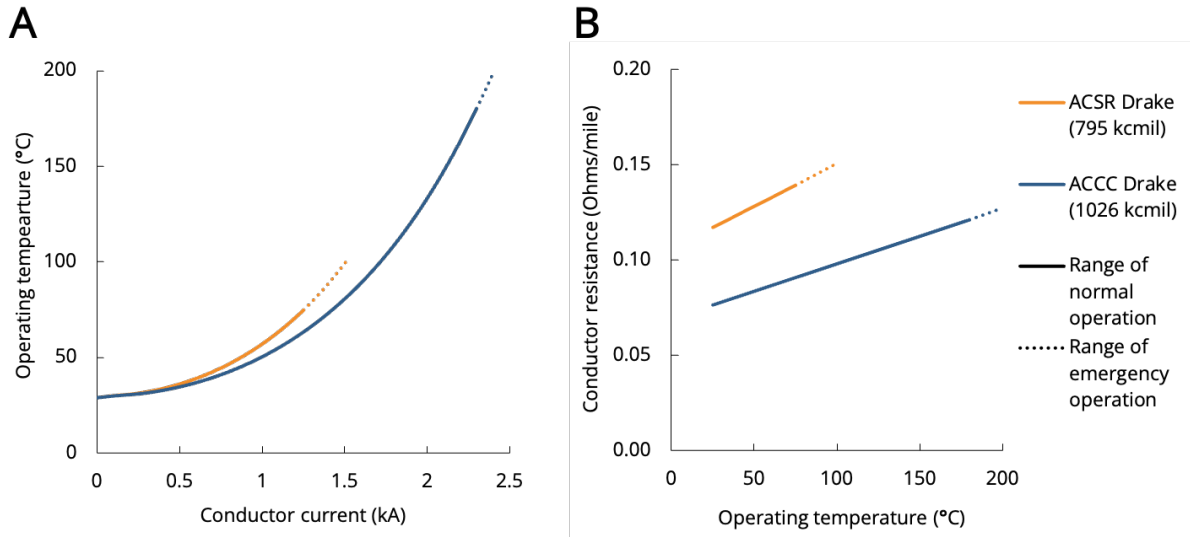
Recent work (59) and ongoing real-world projects like CAISO's new Manning substation (87) and NV Energy's new Greenlink transmission line (88) suggest that sectionalization - the addition of a new substation(s) with active and reactive power generation sources along the transmission line - can help enhance 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 ( $50 < l_{13} \leq 100$  results in 1 new bus and 2 sections,  $100 < l_{13} \leq 150$  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  $p_3^d = 100$  MW, increasing to a target case load of  $p_3^d = 1000$  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  $\lambda$ , which is proportional to the bus 3 active power demand.

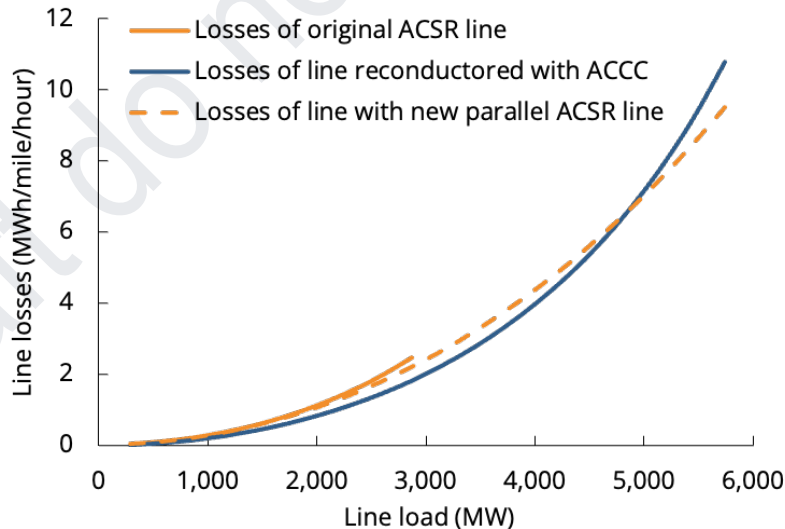
For short lines, reconductoring enables higher power transfers over branch 1-3 and thus higher active power consumption at bus 3. Due to the lower resistance of ACCC over conventional ACSR, the PV curve shifts to the right for an equivalent bus 3 voltage. For long lines, which are

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  $\lambda$ . 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.

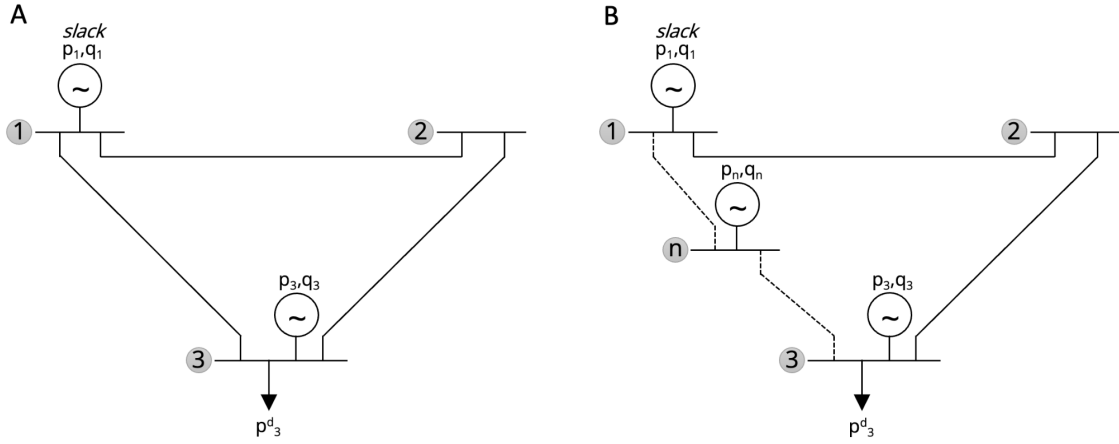
## Supplementary Figures



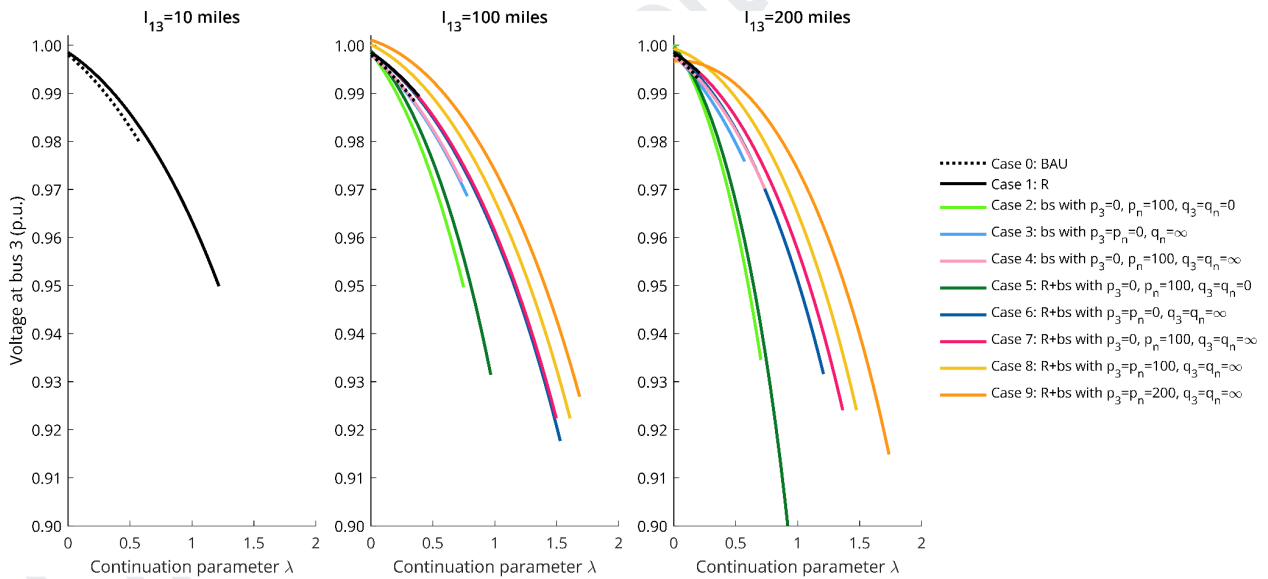
**Figure S1: The relationship between conductor properties and operating temperature.** (A) Conductor operating temperature as a function of current through the conductor. (B) Conductor resistance as a function of conductor operating temperature. Solid lines refer to the conductor's normal range of operation, while dotted lines indicate the conductor's range of emergency operation. Calculations performed at 25.0°C Ambient Temperature, 1028.7 (W/m<sup>2</sup>) 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).



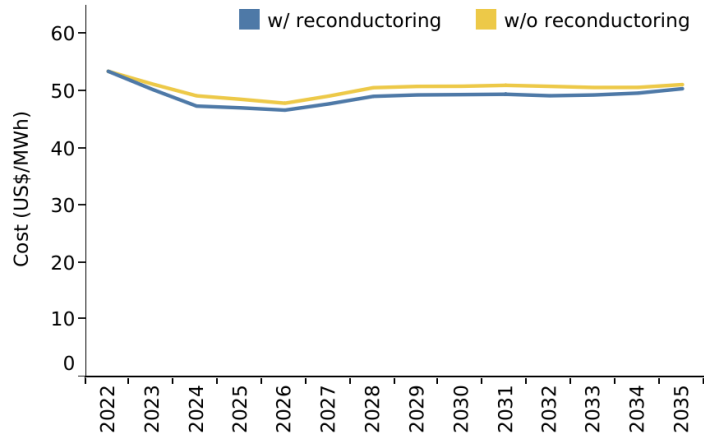
**Figure S2: Line losses as a function of line load.** The figure shows how the losses would change as a function of line loading for a double-circuit 345 kV line with 3 phases and 2 "Drake"-size conductors per phase, originally wired with ACSR, either through reconducting or the building of a new parallel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



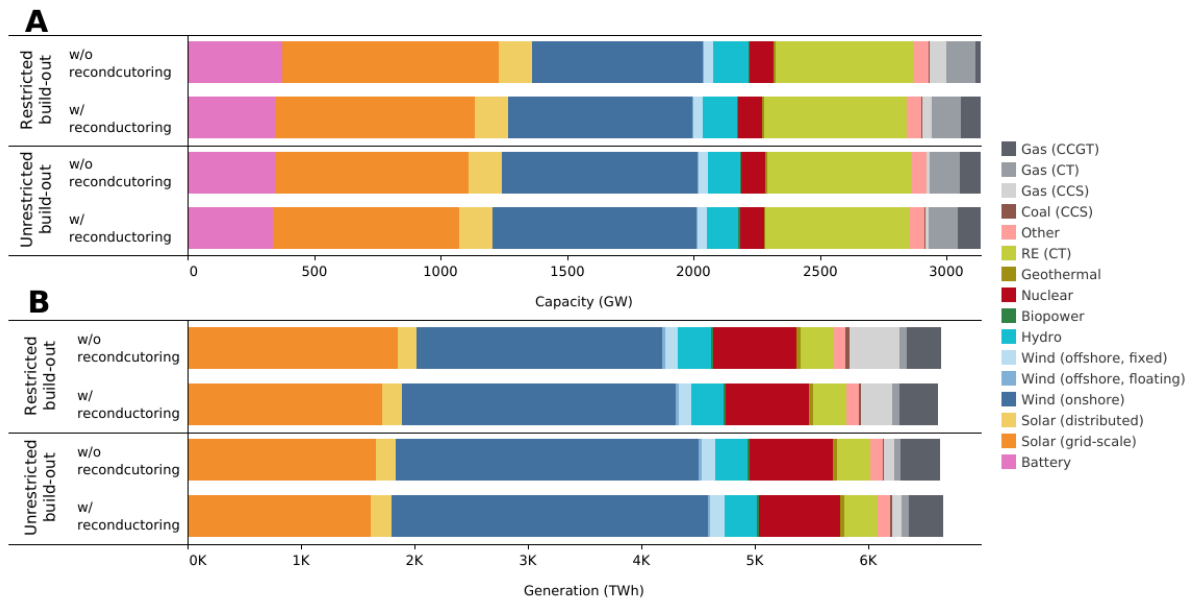
**Fig. S3: Single line diagram of the three-bus test system.** (A) The Business-As-Usual (BAU) case. (B) The sectionalized case, featuring a new substation between bus 1 and bus 3. In both cases, bus 1 serves as the slack bus while bus 3 serves as the load bus.



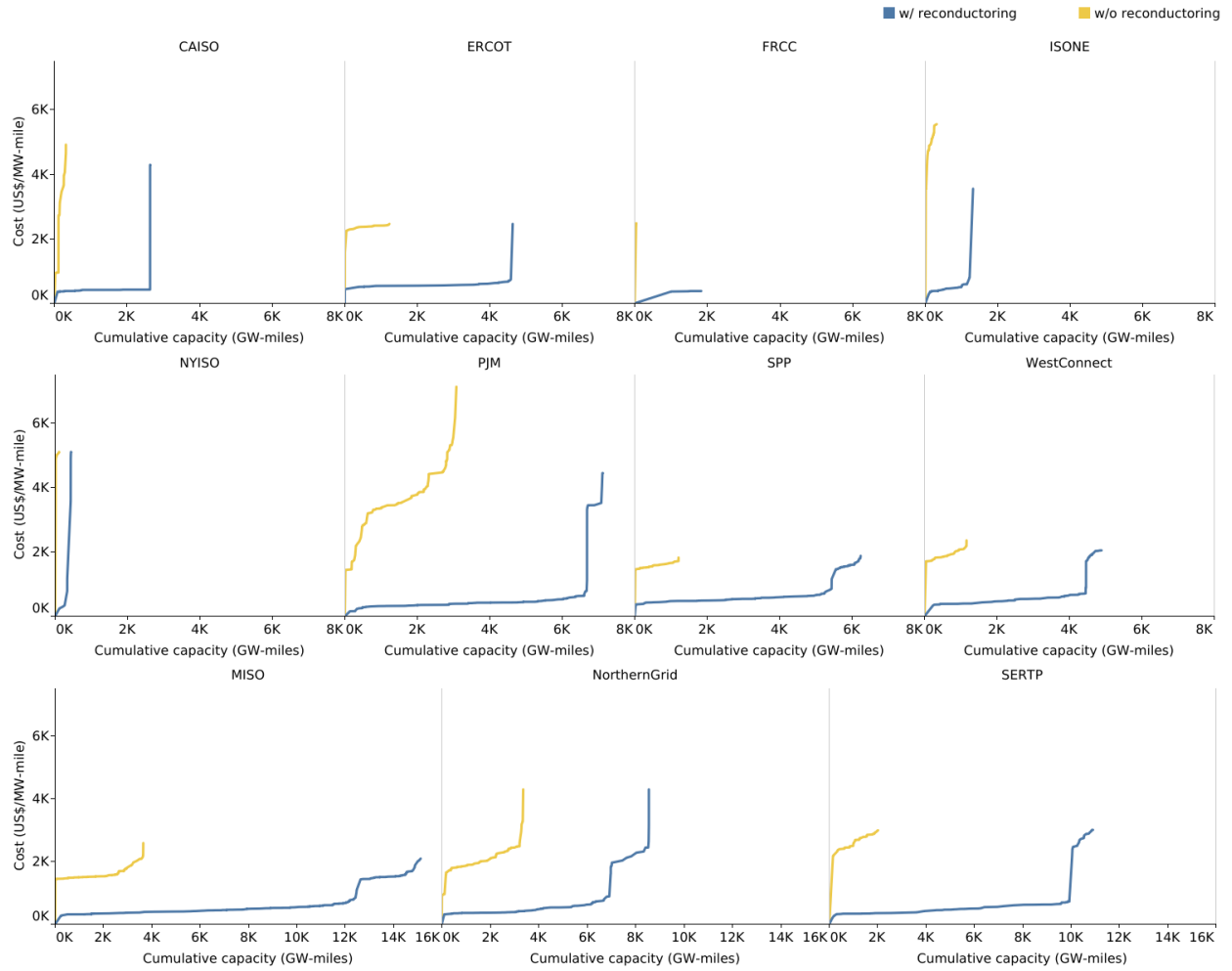
**Fig. S4: PV curves of bus 3 for different lengths of branch 1-3.** These PV curves show the results of the continuation power flow on various cases of the three-bus test system. In long lines, sectionalization and the injection of active and reactive power can boost power flow on branch 1-3 and thus enable higher demand at bus 3, which is directly proportional to the continuation parameter  $\lambda$ .



**Fig. S5: 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 recondcutoring is not offered as an option.



**Fig. S6: 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. S7: 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<sup>1</sup>.**

Abbr.	Full name	Year invented	Composition	Ampacity increase over ACSR	Operating temperature	“Drake”-size area <sup>2</sup>	“Drake”-size strength <sup>3</sup>	“Drake”-size weight <sup>3</sup>	“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 <sup>4</sup>	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 <sup>5</sup>		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 <sup>6</sup>	yes: Southwire	n/a	(91)
ACCC	Aluminum Conductor Composite Core <sup>7</sup>		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		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)

<sup>1</sup> 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.

<sup>2</sup> 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.

<sup>3</sup> 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.

<sup>4</sup> Standard strength, although high strength options are also available (67).

<sup>5</sup> Also known as the C<sup>7</sup> overhead conductor.

<sup>6</sup> AC resistance at 180°C since AC resistance at 75°C was not available.

<sup>7</sup> 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 <sup>1,2</sup> (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”) <sup>3</sup>		New-build	2028		62 miles	-	6 GW	584	9.4	1.6	(30)
Stevin-Avelgem (“Ventilus”) <sup>3</sup>			2028		56 miles	-	6 GW	467	8.4	1.4	(30)
Diemen-Lelystad-Ens	Netherlands	Reconductor	2022	380 kV	45 miles	3.3 GW <sup>4</sup>	5.3 GW <sup>4</sup>	123	2.8	1.4	(30)
Ens-Zwolle			2024		20 miles	3.3 GW <sup>4</sup>	5.3 GW <sup>4</sup>	48	2.4	1.2	(30)
Krimpen-Geertruidenberg			2023		21 miles	3.3 GW <sup>4</sup>	5.3 GW <sup>4</sup>	48	2.3	1.2	(30)
Eindhoven-Maasbracht			2025		30 miles	3.3 GW <sup>4</sup>	5.3 GW <sup>4</sup>	58	1.9	1.0	(30)
Zwolle-Hengelo-Doetinchem-Dodewaard			2040		102 miles	3.3 GW <sup>4</sup>	5.3 GW <sup>4</sup>	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 <sup>5</sup>	2.4 GW <sup>5</sup>	225	0.9	0.7	(37)
CREZ lines		New	2013		3600 miles	-	-	6900	1.9 <sup>3</sup>	2.5 <sup>3</sup>	(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)

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

<sup>2</sup> 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.

<sup>3</sup> In Belgium, the costs of new-build projects reflect new lines which will be wired with ACCC.

<sup>4</sup> Capacity estimated based on provided current rating, voltage, number of circuits and other known information.

<sup>5</sup> 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.