Converting existing transmission corridors to HVDC is an overlooked option for increasing transmission capacity

Liza Reed[a,1], M. Granger Morgan[a], Parth Vaishnav[a], and Daniel Erian Armanios[a]

[a]Department of Engineering and Public Policy, Carnegie Mellon University, Pittsburgh, PA 15215

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A changing generation mix and growing demand for carbon-free electricity will almost certainly require dramatic changes in the infrastructure and topology of the electricity system. Rather than build new lines, one way to minimize social opposition and regulatory obstacles is to increase the capacity of existing transmission corridors. In addition to upgrading the capacity of high-voltage alternating current (HVAC) lines, we identify a number of situations in which conversion from HVAC to high-voltage direct current (HVDC) is the least-cost strategy to increase the capacity of the corridor. If restricted to the existing right-of-way (ROW), we find DC conversion to be the least-cost, and in some cases the only, option for distances of >200 km or for increases of >50% capacity. Across all configurations analyzed, we assess HVDC conversion to be the lower-cost option at >350 km and >50% capacity increases. While we recognize that capacity expansion through HVDC conversion may be the optimal solution in only some situations, with future improvements in the cost and performance of solid-state power electronics, conversion to HVDC could be attractive in a growing set of circumstances.

HVDC | transmission planning | electricity transition | decarbonization

While it is impossible to know with certainty the future of the electricity system, 3 developments are highly likely. First, changes in the mix of generation toward more renewable sources that have already occurred will accelerate. This will partly result from changing market conditions but, more fundamentally, from a growing commitment to creating a more sustainable energy system through a dramatic reduction in emissions of greenhouse gasses and conventional air pollutants. Second, after years of low, and in some regions even negative, demand growth, there will be much wider electrification. Growth in demand will occur because, with affordable carbon-free electricity available, electrification is an effective strategy for decarbonizing much of the energy system. Third, these 2 developments will result in a need for large changes in the nature and topology of the infrastructure of the bulk electric power system (1–4).

Recent studies have shown that the use of more high-voltage direct current (HVDC) transmission could provide many benefits as part of these topological changes. A national HVDC overlay or macrogrid could be a cost-competitive route to decarbonization, provide interregional stability between the western and eastern interconnection, and increase reliability and resilience in the grid in the face of changing weather patterns (5–7). Even if that vision is not realized, it is clear that the country will need to move more power through the high-voltage system, often over routes that are operating at close to capacity. However, siting and building new high-voltage power lines has become much more difficult, indeed, in some cases impossible, due to regulatory constraints, entrenched interests of utilities and generation owners, and aesthetic and environmental opposition from the public (8–10).

Many utilities already look for opportunities to increase the capacity of existing transmission rights of way, typically through "reconductoring" which can increase alternating current (AC) power transmission capacity by up to 50%. Venturing beyond this paradigm, in Germany, the Ultranet HVDC conversion project is currently converting an existing AC corridor to a hybrid AC/DC corridor to bring wind power from the north of the country to loads in the south (11). This project is a first. Up until now, because of the cost and the operational limitations of previous technologies, most utilities have only considered HVDC for new, high-power, long-distance transmission. However, if it were feasible and cost-effective, HVDC conversion could increase the active power transfer capacity up to 4 times depending on the allowable DC voltage and the existing AC operating conditions (12), and could theoretically transmit 3.5 times the total power in a corridor using existing lines and structures, based on the thermal limits of the lines (13).

The International Council on Large Electric Systems concluded, in a 2016 study, that expanding capacity through HVAC to HVDC conversion is typically only attractive when building new transmission is not possible (14). This situation now applies to much of the United States. Current planning tools do not incorporate HVDC conversion (6), so such conversion is typically not considered. Here we demonstrate why HVDC conversion warrants consideration when there is a need to increase the capacity of an existing transmission corridor.

Significance

A sustainable electricity grid will likely need to move large amounts of low-carbon bulk power as part of a strategy to reduce emissions. That will require expansion of transmission capacity, and changes in the topology of the system, even as the use of distributed generation increases. In many cases, maximizing the capacity of existing transmission corridors may best be done by conversion to high-voltage direct current (HVDC). While typically not included in planning tools, such conversion is surprisingly cost-effective, even over relatively short distances, and, in some cases, may be the only way to achieve dramatic increases in the capacity of existing corridors. Conversion may become even more attractive as new solid-state power electronics become available.

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[1]To whom correspondence may be addressed. Email: lbr@cmu.edu.

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We present a comparative assessment of the relative cost and performance of upgrading existing HVAC corridors versus converting those corridors to HVDC. We identify a number of situations in which conversion from HVAC to HVDC is likely to be the preferred strategy when taking long-term demand projections into account. With future improvements in the cost and performance of solid-state power electronics, the range of situations in which conversion to HVDC is attractive can be expected to grow.

Our analysis considers transmission capacity upgrades ranging from 20 to 250% [limited by the lines' thermal capacity (13)], and compares the expected costs for lengths between 50 and 800 km. The project cost analysis includes conductor costs and performance, right-of-way (ROW) costs, cost of any needed new or expanded supporting structures, and the cost of electrical line losses. The least-cost option is identified across parameters including availability of additional ROW, technical feasibility of various AC configurations, energy cost, and project timelines.

Within the power community, new overhead HVDC lines are generally assumed to be lower-cost than HVAC for point-to-point transmission over distances of at least 600 km to 800 km (15, 16). Our analysis suggests that HVDC conversion may be the least-cost option over distances as short as 350 km, particularly if an increase of between 50% and 150% in delivered power capacity is needed.

Fig. 1 displays the several cases we have examined. Our study compares upgrading options for the case of an existing double-circuit 345-kV HVAC line with conventional ROW and conventional substations at both ends. Costs are estimated and compared for different AC and DC configurations that could be adopted to increase the amount of power that can be moved through the existing corridor. There are over 110,000 km of 345-kV lines in the United States and Canada (17). Details on the assumptions that underlie each case are provided in *Methods*.

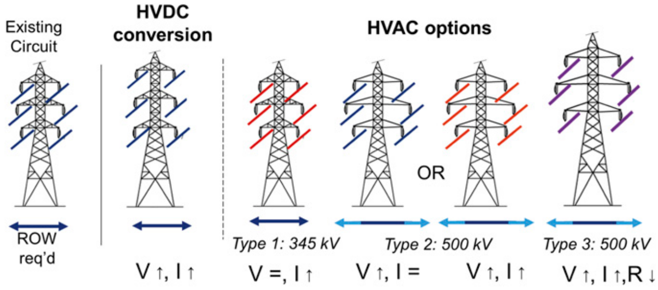

Fig. 1. Existing circuit (left) and 5 upgrade configurations analyzed to achieve increases in transmission capacity. Power capacity can be increased by increasing voltage (V), increasing current capacity (I), or decreasing resistance (R). Safety standards determine the required ROW clearances, which increase with voltage, and the tower configuration (modification or replacement may be required depending on the spacing needs). Four types of corridor changes to an existing 345-kV double-circuit line are considered. HVDC option (second from left) uses the same ROW, existing conductors, slightly modified structures, and replaces 2 3-phase AC circuits with 3 double-pole DC circuits. HVAC type 1 uses the same ROW with new conductors on the existing structures. Two configurations are analyzed within this type. HVAC type 2 requires an expanded ROW and could use existing or new conductors of similar size on the modified structures. Four conductor configurations are analyzed. HVAC type 3 requires new structures, conductors, and expanded ROW. Two conductor configurations are analyzed.

Results

Achievable Transmission Capacity. The upgrade configurations are compared in terms of maximum increase in deliverable power under normal operating conditions. Fig. 2 shows the increases in delivered power over different distances with each type of AC upgrade. The total deliverable power (in megawatts) decreases with distance for all cases due to Ohmic losses, but, in some configurations, the percentage increase in delivered power is higher at longer distances relative to the base configuration because the losses in the base configuration are higher than in the replacement configurations.* Within the existing corridor, higher-performance conductors at 345 kV provide less than a 100% increase, falling to ∼50% increase at 600 km. Type 2 configurations, with additional ROW but existing structures, can provide more than 150% increase. With new structures and additional ROW, type 3 AC configurations are comparable in power transfer capacity to HVDC. For lines not operated with a unitary power factor, reactive power losses would further limit the capabilities of the HVAC configurations.

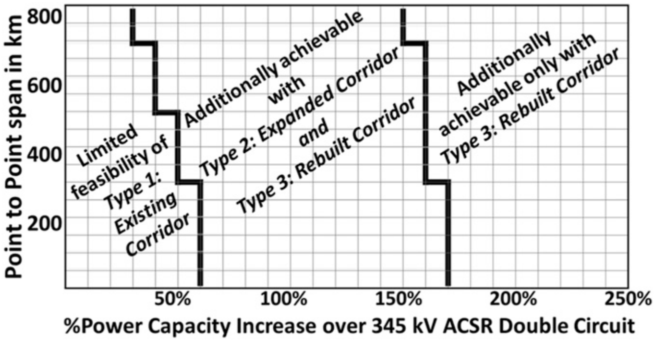

Fig. 2. Feasibility of achieving increases in delivered power over different distances with each type of AC configuration. Percentage increase in power carrying capacity over the existing 345-kV double-circuit line is calculated from increase in ideal power minus Ohmic losses. Ohmic losses increase with distance, giving rise to the jagged edges that divide the figure. Performance is based on example conductors (detailed in *SI Appendix*), and may vary with different stranding. HVDC can achieve all distance and power combinations compared.

Cost Comparison. We estimate the total project cost as the sum of construction capital costs and the 30-y net present value (NPV) of line losses, assuming a wholesale energy cost of $25 per megawatt hour, maximum designed load (i.e., demand factor of 1), and 5% discount rate.

HVDC vs. HVAC type 1: Existing corridor configurations. These are the only configurations that can be achieved within the existing ROW. If acquisition of additional land is a constraint, due to either regulatory, social, or physical reasons, the corridor upgrade options are limited to HVDC or HVAC reconductoring. Reconductoring is a common choice for modest power increases. Fig. 3 compares project costs for type 1 HVAC configurations against costs of HVDC conversion. As shown in Fig. 2, within the existing corridor, AC options can only deliver limited increases in capacity; any additional increase requires a wider ROW or HVDC conversion. This boundary is denoted in Fig. 3 and subsequent figures with a heavy black line that delineates those situations when HVDC is least-cost versus those where HVDC is the only option. For power increases of more than 70%, or distances greater than 350 km, HVDC conversion is the least-cost option when limited to the existing corridor, based on capital costs and the present value of the cost of Ohmic losses. Indeed, these results suggest that HVDC may be cost-competitive at distances as short as 200 km, even for an increase in capacity as low as 10%.

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*More than a 250% increase is possible with HVDC, since we are comparing delivered power, and the losses associated with HVAC are greater than those with HVDC. Clerici et al.'s conclusion of 3.5× (250% increase) is based on ideal power (13).

HVDC vs. HVAC type 2: Expanded corridor configurations with existing structures. If it is possible to acquire additional land for ROW along the entire corridor, increasing the AC voltage to 500 kV is a way to increase the power capacity with lower losses. Type 2 configurations would require modifications increasing structure height and span that may not be feasible. The feasibility of HVDC structure modifications is well documented, but the HVAC modifications would increase the cantilever weight on the structure by lengthening the arms to provide phase spacing (13, 18). Four configurations using 3 new conductor options are compared. Although the Ohmic losses of the HVAC configurations still exceed those of HVDC conversion, HVAC losses in AC type 2 configurations are only 3 or 4 times the DC losses. HVAC type 1 configurations have losses of 6 times or more those of HVDC conversion.

Fig. 4 shows the differences in project costs for each of the AC type 2 configurations compared with HVDC. The 4 configurations have very different cost and capacity characteristics, so the comparison shown in Fig. 4 appears discontinuous as the lowest cost solution jumps from one to another configuration. Operating the existing lines at 500 kV (i.e., no new conductors), is the least-cost configuration at the limited distance and power increases it can achieve. This is because the only capital cost is ROW acquisition, which is more than 2 orders of magnitude lower per kilometer than the cost of new conductors of any material, which must be considered in all other configurations. This solution contributes to the left-hand side of the figure where AC dominates at all distances, but is constrained by deliverable power, ending abruptly at a 50% power increase, which is only achievable for long distances. Note that this configuration with a 50% increase (1,800 MW to 2,000 MW) is not an option for distances of less than 450 km. Due to the lower losses compared with the base configuration, 500 kV on the existing lines can deliver proportionally more power only at long distances.

The least-cost HVAC options for increases in capacity of 50 to 120% and 130 to 170% are new conductors made from high-cost materials and are therefore less cost-competitive at long distances.

HVDC vs. HVAC type 3: Expanded and rebuilt corridor configurations. The largest AC power capacity configurations require that the ROW be increased and that existing structures be replaced to accommodate heavier conductors. Two HVAC configurations of new conductors are assessed. HVAC type 3 configurations can provide much higher power than previous configurations. Fig. 5 shows the breakeven analysis results. For high power increases, e.g., 150%, type 3 configurations are less expensive than HVDC up to 200 km and of comparable cost up to 400 km. As the power capacity increases, the cost-competitive distance for HVAC type 3 also increases. There is a tradeoff between power and distance in the AC versus DC costs in comparing these configurations. HVDC conversion costs primarily scale with megawatts, due to the conversion equipment, whereas the AC costs primarily scale with distance. The losses between the transmission types are comparable, since reactive power losses (which accumulate in AC configurations) are not considered in this assessment.

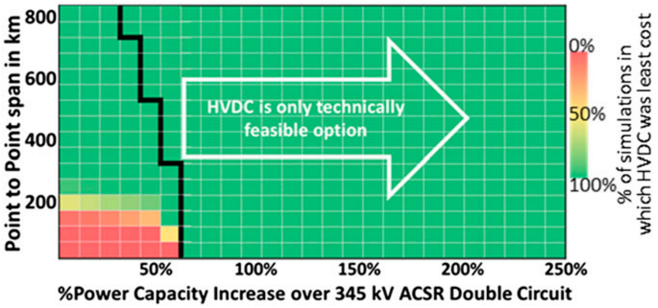

Fig. 3. Comparison of project costs for type 1 HVAC configurations and HVDC conversion. The color scale (right) indicates the percentage of Monte Carlo simulations in which HVDC was least-cost, ranging from 0% (red), to 50% (yellow), to 100% (green). The power capacity performance limitation of type 1 configurations is indicated with the bold black line. At distances longer than 200 km, the combined cost of higher losses and new conductors is higher than the cost of HVDC converter stations.

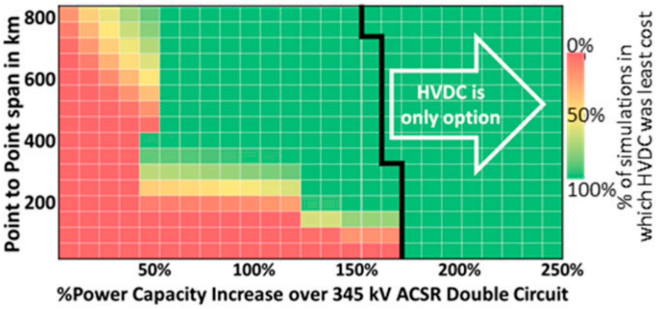

Fig. 4. Comparison of project costs for HVAC type 2 configurations with HVDC conversion. Four HVAC configurations are included in the analysis, resulting in discontinuities in distributions. The color scale (right) indicates the percentage of Monte Carlo simulations in which HVDC was least-cost, ranging from 0% (red), to 50% (yellow), to 100% (green). The least-cost configuration for 40% power increase or less is HVAC using the existing conductors at higher voltage. This configuration is capacity-limited. It can increase capacity by, at most, ~50% across any distance. The remaining HVAC configurations require new conductors. These costs increase with distance, and eventually exceed the cost of HVDC converter stations. The black line indicates the performance limitation of type 2 configurations, beyond which they cannot achieve the desired increase in power transmission capacity.

HVDC versus all HVAC configurations. Fig. 6 compares project costs for HVDC to all HVAC configurations, combining Figs. 3–5. As a conservative estimate of HVDC potential, the minimum cost AC configuration was compared against HVDC in the Monte Carlo results. The conventionally cited breakeven distance for new DC over AC overhead lines is ~600 km to 800 km, noted on Fig. 6 (15). The results of this study indicate that HVDC conversion breakeven distances may be much shorter, particularly if a 50 to 150% increase in delivered power capacity is desired.

Discussion

Our results suggest that, in increasing the capacity of existing transmission corridors, conversion to HVDC may be the least-cost option relative to HVAC upgrade alternatives at much shorter distances than is currently assumed, particularly if an increase in capacity of between 50% and 150% in delivered power capacity is desired. Depending on the configuration, at 350 km, converted lined could deliver an increase of between 1,900 MW (50% increase) and 3,200 MW (150% increase). Many of the HVAC scenarios have power capacity limitations, which may be reached via consecutive short-term planning cycles, creating a transmission bottleneck that will eventually require new corridors or HVDC conversion. To reach decarbonization goals and prepare for wider electrification of the economy, longer-term planning may be required (19).

This analysis is based on line-commutated conversion (LCC) technology for AC → DC and DC → AC conversion. LCC is an established technology currently used in most US HVDC stations. In the past decade, voltage source conversion (VSC) power and voltage performance have increased. There has been limited implementation, to date, of VSC at high voltage and power, but the dollar per megawatt cost of VSC systems is estimated to be similar to LCC, due to the smaller physical size and the fact that VSC does not require the extensive AC filtering

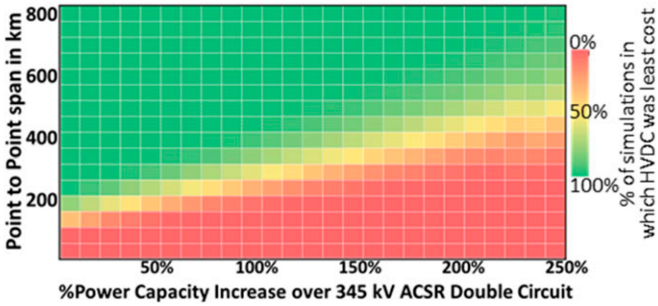

Fig. 5. Comparison of project costs for HVAC type 3 configurations and HVDC conversion. The color scale (right) indicates the percentage of Monte Carlo simulations in which HVDC was least-cost, ranging from 0% (red), to 50% (yellow), to 100% (green). Both HVAC type 3 configurations considered require new conductors but also have lower losses than the HVDC conversion.

required by LCC. This can result in HVDC converter stations that are only 20 to 33% of the size of those for LCC. In addition to the smaller footprint, a second, perhaps even more important, advantage of VSC over LCC is its black start capability and the ease and potentially lower cost of creating lowpower tap-offs at intermediate points along the line (20). These tap-offs could provide regional and local benefits for what would otherwise be pass-through communities, likely increasing the contribution to power system resilience as well as both the public and Public Utility Commission acceptance of such projects. In addition to the economic feasibility illustrated, HVDC is therefore also becoming more operationally flexible, for both new transmission and conversion scenarios.

Today, VSC has higher losses than LCC. Investment in VSC development and its deployment as part of a policy to support decarbonization could result in technical improvements that could reduce losses, costs, and uncertainty. The rise of offshore wind power as a generation source is leading to more discussion and consideration of HVDC technology, particularly VSC stations, which have not yet been deployed in the United States. The reluctance to introduce HVDC technology into the grid will likely fall as system planners and operators see more applications and become more familiar with its benefits. These offshore wind projects will provide additional benefits to our transmission challenges by providing a platform for deployments of HVDC, allowing the electricity community to gain more experience and learn about power systems integration.

The operational impacts of any of these existing corridor upgrades are unclear. This is especially true for the downtimes and service interruptions required to make the conversions and how that may factor into the decision and cost analysis. We are currently examining the downtime and disruption associated with HVAC reconductoring projects as a surrogate for the work that would be involved in HVAC to HVDC conversion.

Technical power flow analysis suggests that increased use of HVDC power in the grid can provide many operational benefits. Specific to conversion, a comparison of power and load characteristics when a 66-kV line is converted to HVDC concluded that conversion could be a feasible mechanism for addressing bottlenecks in networks (21, 22). Technical characteristics and system implications for converting an underground medium-voltage line to DC showed capacity and efficiency improvements (23). An assessment of the technical characteristics of a high-voltage conversion, including electrical field strength, load flow, transient stability, and a short-circuit study, simulated and analyzed the benefits of conversion for an existing circuit in India (24). Our work is intended to bring attention to the economic as well as the nonquantitative issues, such as ROW acquisition and regulatory process. Together with these ongoing technical analyses, the case for HVDC as a solution that should be included in simulation, planning, and investment is even stronger.

Using existing transmission corridors to increase the capacity of the grid has, to date, not been a policy priority for the Federal Energy Regulatory Commission (FERC), which has instead focused on defining new National Interest Electric Transmission Corridors under the 2005 Energy Policy Act (25). Transmission planning tools do not include HVDC conversion in their operations or cost models, and rarely do academic studies incorporate conversion as an option. We find that HVDC conversion of an existing HVAC corridor is technically feasible and may be the least-cost approach to increasing electricity transmission capacity even at fairly short distances. Accordingly, FERC should find ways of removing the barriers to such line conversions, which is likely easier to accomplish than siting and building new lines, and both the Electric Power Research Institute and the Department of Energy Office of Electricity should devote considerably more attention to HVAC to HVDC conversion. Transmission planning tools should be reconfigured to include HVDC conversion in the suite of available options and provide fair and rigorous comparisons with AC alternatives.

We recognize that capacity expansion through HVDC conversion may be the optimal solution in only some circumstances. However, our analysis shows that it is more widely relevant than currently thought. In light of this, system planners should give this strategy greater consideration, and their analysis toolkits should be expanded to support easy consideration of such conversion.

Methods

Our study compares upgrading options for the case of an existing double-circuit 345-kV line with conventional ROW and conventional substations at both ends. Costs are estimated and compared for different AC and DC configurations that could be adopted to increase the amount of power that can be moved through the existing corridor, based on standards established by the Western Electricity Coordinating Council (WECC) (26). There are over 110,000 km of 345-kV lines in the United States and Canada (17).

Transmission Capacity Configurations.

Baseline transmission configuration. In the existing 345-kV double-circuit line, each circuit is assumed to have 2-conductor bundles per phase. We make the following additional assumptions: conductors, 2 Southwire Drake ACSR conductors per phase; ROW, 150 ft (45.7 m); operating temperature, 50 °C; ideal transmission capacity (no electrical losses), 1,400 MW; deliverable power ranges from 1,380 MW at 50 km to 1,140 MW at 800 km when

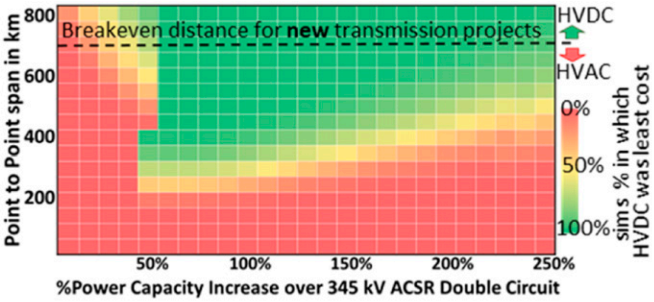

Fig. 6. Comparison of project costs for any HVAC configuration and HVDC conversion. The color scale (right) indicates the percentage of Monte Carlo simulations in which HVDC was least-cost, ranging from 0% (red), to 50% (yellow), to 100% (green). The conventionally accepted breakeven distance for HVDC vs. HVAC for new transmission (600 km to 800 km) is indicated with the dashed line.

demand factor (ratio of maximum load to maximum possible load) is 1, and factoring in electrical losses over range of distances.

Conductors. Because the amount of power moved is proportional to the product of voltage and current, increasing transmission capacity requires increasing voltage (V), current carrying capability (ampacity, I), or both. Ampacity changes based on the size of the conductor, the conducting material, and the operating temperature. Operating temperature is important because, with growing resistance losses (I^2R), lines sag and hot weather results in less line cooling (27).

The conductors we consider include Aluminum Conductor Steel Reinforced (ACSR; the most common), and 2 high-performance options: Aluminum Conductor Steel Supported (a lower-cost replacement with high temperature capabilities) and Aluminum Conductor Composite Reinforced (a higher-cost replacement with much higher temperature capabilities). HVDC conversion is compared with 3 types of HVAC configurations: 1) the use of existing structures and ROW, 2) the use of existing structures but with expanded ROW, and 3) new structures and expanded ROW. Importantly, 500-kV DC bipole lines require the same ROW as 345-kV double-circuit lines (26). *SI Appendix* includes additional assumptions for the base case and details the multiple cases within each configuration type.

HVDC basic configuration. This configuration uses the existing corridor ROW, structures, and conductors. The 500-kV HVDC bipole lines and 345-kV AC double-circuit lines require the same ROW, and existing structures can be modified for HVDC transmission (13, 18, 26). This case only requires additional land for converter stations.

Existing corridor: HVAC type 1 configurations. These configurations use the existing corridor ROW and structures and operate at the existing 345-kV level. Two different conductor replacements are considered here, with similar size (same cross-sectional area) and weight (8 to 15% heavier) to the existing conductors. We assume that these lines will remain within the strength limits of the tower structures given the frequency of reconductoring projects, although this is not always the case.

Expanded corridor: HVAC type 2 configurations. The 500-kV AC transmission requires an expanded corridor ROW. These configurations use existing or new conductors of similar weight on the existing structures, assuming the required safety modifications can be accommodated. Four conductor configurations are considered based on preferred conductor size and bundling, and weight limitations of the structures. The feasibility of these type 2 configurations is unclear due to the changes required to the structures to provide phase and line spacing. More details can be found in *SI Appendix*.

Rebuilt corridor: HVAC type 3 configurations. In addition to expanding the ROW, typical 500 kV AC configurations require 3 to 4 conductor bundles with much larger conductors (twice the cross-sectional area of the assumed 345-kV AC lines). According to the manufacturer specifications, the recommended sizes weigh twice or thrice as much as the existing lines (28). Existing structures would need to be replaced completely to accommodate this weight. Two conductor configurations are considered.

Power Transmission Capability. The maximum delivered power per phase (or per DC pole), not including any emergency overage operating conditions, is calculated based on the thermal capacity of the lines,

$$P_{delivered} = V_{L-N}I - I^2R. \qquad [1]$$

For a double-circuit 345-kV AC transmission line, the power delivered per phase is multiplied by the number of phases (3) and circuits (2) to determine the power that can be conveyed in the corridor. For DC transmission, the delivered power is multiplied by the number of poles (2, 1 + and 1 −) and circuits (3). Transformer losses are ignored for AC configurations as transformers are typically modeled as ideal (i.e., 0-MW losses), but the AC/DC conversion is less efficient, with ∼0.7% of power lost at each end, so an additional L_{conv} term is included in the HVDC delivered power calculation (29). We assume the lines operate at unitary power factor. All power is realized as active power, and there is no reactive current or reactive power loss. If these are taken into consideration, HVAC losses would be higher.

Capital Costs. The WECC Transmission Expansion Planning Policy Committee funded a study in 2012, updated in 2014, on the capital costs for transmission and substations (26). The cost and performance components identified in those studies were adapted in our analysis.

The capital costs for transmission expansion depend on the type and configuration and may include new equipment (e.g., change from a 345-kV to a 500-kV transformer or adding AC/DC converter stations), new conductors, additional land, or structure changes. The capital costs for each configuration vary with power (megawatts) and distance (kilometers), and are given by

$$\text{Cost}_{total} = \text{Cost}_{power}\left[\frac{\$}{\text{MW}}\right]P_{MW} + \text{Cost}_{distance}\left[\frac{\$}{\text{km}}\right]D_{km}. \qquad [2]$$

Costs that scale with required power. The power-related costs are based on the sizing requirements for new AC voltage transformer stations or AC → DC and DC → AC converter stations. The equipment is sized the same on each end of the line, based on the starting power transmission level (e.g., if 2,000 MW must be generated to deliver 1,800 MW due to Ohmic losses, a 2,000-MW transformer is sized on both ends of the line).

Costs that scale with distance. The possible distance-related costs are new conductors, additional land for when increased ROW is required, and changes in structures (because, to first order, distance determines the number of structures required in a corridor). The capital cost per distance calculation for corridor conversion configurations is adjusted from the calculation for new transmission construction (26),

$$\begin{aligned}\text{Cost}_{distance}(\$/\text{km}) = {} & \text{New Conductor Cost}(\$/\text{km})\\ & + \text{Additional ROW cost}(\$/\text{km})\\ & + \text{Restructuring Cost}(\$/\text{km}).\end{aligned} \qquad [3]$$

The 2014 WECC study identifies a base cost per mile for various new transmission configurations, which includes land clearing, structure construction, and conductors. Some cases require different conductor sizes than those available in the WECC data. For these configurations, higher-performance conductors are used with the same cross-sectional area as the existing ACSR with higher-performance materials. The prices for these are estimated using a conductor multiplier estimated for us by an industry expert; the price is included in *SI Appendix*, Figs. S1 and S2. Initially, Restructuring Cost is set to $0 due to the high uncertainty; *SI Appendix* includes additional results with parameterized structure costs.

Cost of losses. Ohmic and conversion losses vary across the cases because of the differences in the conductors and different terminal equipment. The power lost must be accounted for to appropriately compare the expected 30-y systems costs. Losses scale with required power (due to increase in current) and distance (due to linear increase of line resistance with distance). The method for calculating power losses was previously used to determine deliverable power (Eq. **1**). These formulae are converted to energy losses (megawatt hours) as given below, assuming the line load is equal to the planned capacity increase over the entire 30-y project timeline. A growing load scenario is included in *SI Appendix*, *Additional Results and Discussion*.

The cost of these losses is treated as a parameter. Annual losses for 30 y, starting in the present, are calculated using this method, and then the NPV of these costs is computed using a discount rate of 5%.

The total costs for the projects is thus

$$\text{Cost}_{total} = \text{Cost}_{power}P_{MW} + \text{Cost}_{distance}D_{miles} + \text{Cost}_{losses}. \qquad [4]$$

Uncertainty. The uncertainty in the equipment and conductor costs is modeled using triangular distributions around the point estimates from the WECC study, ranging from 90 to 200% of the estimated cost, with the mode set to 100% of the estimated cost. The cost of land and the cost of losses are treated parametrically. All cost data were converted to 2017 dollars assuming a 2% inflation rate each year. Although there are often multiple options for a given conductor size and material with varying performance, a single option was selected for analysis in each case, making the conductor resistance and ampacity defined constants (see *SI Appendix* for these values). Cost of losses is initially set at $25 per megawatt hour, and parametrized at $5 per megawatt hour and $75 per megawatt hour (the mean, low, and high in the Great Plains region in 2016) (30). Land costs are initially set at $1,000 per acre (a typical purchase cost), and further parameterized at $10,000 per acre and $100,000 per acre. Transmission distance is parameterized from 50 km to 800 km in 50-km increments. Deliverable power is parameterized at 10 to 250% increases over the existing baseline in 10% increments.

A Monte Carlo simulation (n = 1,000 realizations) is used to compare the project costs and assess the uncertainty. Reactive power losses are not considered for the HVAC configurations, since these can be minimized by the use of compensating devices.

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1. Intergovernmental Panel on Climate Change, Global warming of 1.5°C. https://www.ipcc.ch/report/sr15/. Accessed 23 October 2018.
2. Electric Power Research Institute, "U.S. National Electrification Assessment" (Rep. 3002013582, Electric Power Research Institute, 2018).
3. T. Mai *et al*., Renewable electricity futures for the United States. *IEEE Trans. Sustain. Energy* **5**, 372–378 (2014).
4. D. Steinberg *et al*., "Electrification decarbonization: Exploring U.S. energy use and greenhouse gas emissions in scenarios with widespread electrification and power sector decarbonization" (Tech. Rep. NREL/TP-6A20-68214, National Renewable Energy Laboratory, 2017).
5. A. E. MacDonald *et al*., Future cost-competitive electricity systems and their impact on US CO_2 emissions. *Nat. Clim. Chang.* **6**, 526–531 (2016).
6. P. Fairley, Building a weather-smart grid. Renewable energy will rule only when weather data drive the design of a new electric grid. *Sci. Am.* **319**, 61–65 (2018).
7. J. McCalley, North American HVDC Interconnection Seam Study (2019). https://pserc.wisc.edu/education/webinars.aspx. Accessed 4 June 2019.
8. N. L. Cain, H. T. Nelson, What drives opposition to high-voltage transmission lines? *Land Use Policy* **33**, 204–213 (2013).
9. A. B. Klass, E. J. Wilson, Interstate transmission challenges for renewable energy: A federalism mismatch. *Vanderbilt Law Rev.* **65**, 1801–1873 (2012).
10. S. P. Vajjhala, P. S. Fischbeck, Quantifying siting difficulty: A case study of US transmission line siting. *Energy Policy* **35**, 650–671 (2007).
11. Amprion, Project Description: Ultranet (2018). https://www.amprion.net/Grid-expansion/Our-Projects/Ultranet/. Accessed 22 August 2018.
12. "DC Capability of AC Transmission Lines" (Tech. Rep. 1016072, Electric Power Research Institute, Palo Alto, CA, 2008).
13. A. Clerici, L. Paris, P. Danfors, HVDC conversion of HVAC lines to provide substantial power upgrading. *IEEE Trans. Power Deliv.* **6**, 324–333 (1991).
14. R. Adapa, L. O. Barthold, D. Woodford, "Technical and economic incentives for AC to DC line conversion" (Reference B2-203_2010, International Council on Large Electric Systems, 2010).
15. Grid Tech Team, "Applications for high-voltage direct current transmission technologies" (Department of Energy, Arlington, VA, 2013).
16. ABB, Why HVDC Economic and environmental advantages–Why choose HVDC over HVAC (2017). https://new.abb.com/systems/hvdc/why-hvdc/economic-and-environmental-advantages. Accessed 21 August 2018.
17. E. Fisher, "Annual U.S. Transmission Data Review 2016" (Department of Energy, 2017).
18. M. Hausler, G. Schlayer, G. Fitterer, Converting AC power lines to DC for higher transmission ratings. *ABB Rev.* **3**, 4–11 (1997).
19. M. G. Morgan, Opinion: Climate policy needs more than muddling. *Proc. Natl. Acad. Sci. U.S.A.* **113**, 2322–2324 (2016).
20. D. Van Hertem, M. Ghandhari, Multi-terminal VSC HVDC for the European supergrid: Obstacles. *Renew. Sustain. Energy Rev.* **14**, 3156–3163 (2010).
21. D. M. Larruskain, I. Zamora, O. Abarrategui, Z. Aginako, Conversion of AC distribution lines into DC lines to upgrade transmission capacity. *Electr. Power Syst. Res.* **81**, 1341–1348 (2011).
22. D. M. Larruskain, I. Zamora, O. Abarrategui, A. Iturregi, VSC-HVDC configurations for converting AC distribution lines into DC lines. *Int. J. Electr. Power Energy Syst.* **54**, 589–597 (2014).
23. A. Shekhar, E. Kontos, L. Ramírez-Elizondo, A. Rodrigo-Mor, P. Bauer, Grid capacity and efficiency enhancement by operating medium voltage AC cables as DC links with modular multilevel converters. *Int. J. Electr. Power Energy Syst.* **93**, 479–493 (2017).
24. R. Manickam, S. N. Palaniappan, Upgrading transmission line capability by AC–DC conversion. *Comput. Electr. Eng.* **68**, 616–628 (2018).
25. 42 USC §149 (2005).
26. R. Pletka, J. Khangura, A. Rawlins, E. Waldren, D. Wilson, "Capital costs for transmission and substations" (Project No. 181374, Black and Veatch, 2014).
27. R. Thrash, A. Murrah, M. Lancaster, K. Nuckles, Eds., *Overhead Conductor Manual* (Southwire, Carrollton, GA, ed. 2, 2007).
28. Southwire, Product catalog. https://www.southwire.com/products/ProductCatalog.htm. Accessed 22 August 2018.
29. M. Claus, K. Uecker, D. Retzmann, Power electronics for enhancement of grid efficiency. *Das Energie Fachmagazin* **60**, 6–13; reprinted (2008) (Siemens).
30. US Energy Information Administration, Wholesale electricity and natural gas market data. https://www.eia.gov/electricity/wholesale/#history. Accessed 22 August 2018.