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Advanced Conductor Scan Report

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Advanced Conductor Scan Project

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Executive Summary

Large additions to the United States (U.S.) electric transmission capacity are needed to enable decarbonization policy goals as transmission capacity has become one of the largest barriers to increasing levels of carbon free power generation. Transmission capacity expansions must accelerate from historical rates if current decarbonization timeframes are to be met. Despite this need, this study found that capacity expansion rates have actually slowed in recent years. Many factors are responsible for this trend, ranging from permitting delays, to increasing land prices, to supply chain bottlenecks.

One option increasingly used by utilities to mitigate some of the challenges of building transmission lines is reconductoring. Reconductoring existing overhead transmission lines using advanced conductors can increase transmission capacity more quickly than most alternatives. In reconductoring, the existing transmission structures stay in place and only the electrical conductors are replaced. Some modifications to the structures or substations may be required, depending on the conductor used and initial condition of the line. However, generally these modifications are quicker and cheaper than a new construction or rebuild. Advanced conductor technologies make it possible to increase transmission capacity for roughly one-third of the cost of building new lines and in a much shorter timeframe.

The Aluminum Conductor Steel Reinforced (ACSR) conductor (and comparable conductors) are considered traditional conductors compared with conductors introduced to the market beginning in the early 2000s. The so-called improved overhead conductors are very similar in construction to a conventional Aluminum Conductor Steel Reinforced (ACSR), but the improved overhead conductors have design improvements and are sometimes conflated with "advanced conductors". These technologies have largely been supplanted by modern conductors which feature composite cores. As this report focuses on the state-of-the-art, these improved conductors are not discussed in detail and the term "advanced conductor" will be used to refer to these latest conductor technologies. The exception to this is when discussing ACSS with modern high-strength steel alloys, which this report considers "advanced". The subject of conductor technologies is discussed in much greater detail in Section 2.

The conductors used for the majority of the existing grid are of a type called ACSR. ACSR conductors are manufactured with strands of hardened aluminum wrapped around a galvanized steel core. This basic design has been in use for over a century. Because these conductors operate at high voltages, they must be kept a safe distance from the ground, structures, vehicles, and other conductors for safety and reliability. Conductors are suspended from insulators that are attached to tall structures, typically made of wood or steel, which must be strong enough to survive extreme weather over many decades of service.

When an electrical current passes through a conductor, its temperature increases due to electrical resistance. Modern ACSR conductors are designed to operate at continuous temperatures of up to 93°C (200°F) without being damaged and at even higher temperatures for brief periods during emergency conditions. At these high temperatures, the steel and aluminum expand, which causes the conductors to "sag" closer to the ground. Consequently, every transmission line is limited in the amount of current it can carry based on how much it will cause the conductor to sag. The limit on line loading is often a material limit - the annealing temperature for ACSR, the melt temperature for Misch Metal for Aluminum Conductor Steel Supported (ACSS), and the polymer degradation limit for composite cores. Designing lines with sufficient clearance to operate at the maximum possible sag is critical for safety and reliability, and is a major factor in the design of overhead power lines.

Since the advent of the electrical system, conductors have been evolving with new innovations to improve different performance attributes. An ACSS conductor was first introduced in the 1970s and occupied a niche spot in U.S. utility deployments in the 1980s and 1990s. Despite the advent of newer composite-core technologies beginning in the 2000s, ACSS remains a staple in many power systems in the US and abroad.

Advanced conductors introduced this century replace the traditional steel conductor core with stronger materials that sag less than ACSR would at high temperatures and may be treated with heat-dissipating coatings to further improve capacity and efficiency. Traditional steel cores have been replaced with composite matrix materials of carbon fibers, ceramic fibers, or with ultra-high strength or higher grades of steel. Composite core materials are lighter and stronger than traditional steel so the difference in weight bearing capacity can be replaced with more aluminum. Ultra-high strength steel is one-third stronger than traditional steel and even higher strength steels are being introduced that are over 50% stronger. Composite core advanced conductors can typically replace ACSR without increasing structure loading, while the stronger ACSS conductors can reduce sag by increasing tension on the lines, which may require tower modifications that are not necessary with composite core designs. Heat-dissipating coatings work on any conductor type to reduce conductor temperature, which can improve efficiency or capacity.

The first modern advanced conductors were introduced in the early 2000s and over 70% of the 44 utilities profiled for this scan have deployed advanced conductors developed since then on at least a limited basis. Of these utilities, 95% have used some type of ACSS, including both traditional and advanced designs. Our study finds that utilities are generally willing to try new conductor technologies and most have at least some awareness of the benefits and disadvantages of available products from their own deployments. Utility experiences with composite core designs have been mixed, with some utilities completing hundreds of miles of circuits, while other utilities are hesitant to deploy outside of niche applications. A few utilities have decided to no longer deploy certain classes of advanced conductors because of negative experiences. To address some of the perceived deficiencies, a new generation of advanced composite core conductors is now being introduced that reduces the risk of failure during installation and operation. All of these conductor designs with their pros and cons are profiled later in this report.

Advanced conductors have several well-established use cases in both transmission and distribution systems. The best fit is in reconductoring applications, where line capacity can be increased while existing structures are preserved. This study considers the entire U.S. electrical system and investigates the extent to which reconductoring can increase capacity on existing lines. The study concludes that 20% of the existing transmission and distribution lines in the U.S. are candidates for reconductoring. Many of these reconductoring projects would also require substation upgrades to accommodate increased power flows. The condition of existing structures must also be considered, as structures that are at end of life may need to be replaced, making reconductoring non-viable.

While reconductoring can increase transmission capacity, there are other alternatives, such as rebuilding with higher voltages or double circuits, which can increase capacity by 12 times or more. While rebuilding will be more expensive and time consuming, the opportunity cost of upgrading with reconductoring should be considered along with other alternatives that can deliver a larger and more-efficient capacity upgrade. Advanced conductors can also perform in a complementary manner with other grid-enhancing technologies to amplify the grid benefit. Another very common application for advanced conductors are projects that take advantage of the low-sag characteristics, such as long spans for river crossings or lines where sag needs to be reduced for reliability or safety reasons. Finally, advanced conductors are beginning to be used for line rebuilds or new line construction. The conductors are used either to increase capacity for future load growth or to reduce initial project costs by reducing conductor size and operating at elevated temperatures. However, this is typically only economically viable when considering extremely high voltages not seen in the U.S.

Advanced conductors are most often used in difficult applications, (e.g., reconductoring), where other options (e.g.,building a line) with a higher voltage are not feasible because of regulatory or permitting areas. While the highest value projects for the grid would be high-voltage interregional lines, reconductoring is more likely to address shorter lines on existing routes. In some ways, the inability of utilities and developers to build new lines actually increases demand for advanced conductors because reconductoring may be the only viable upgrade path. Regulators are increasingly considering advanced conductors. For example, the recently issued Federal Energy Regulatory Commission Order 2023 requires that advanced conductors be considered when utilities are evaluating interconnection requests.

International adoption of advanced conductors and reconductoring has similar drivers to U.S. deployments. Major projects with advanced conductors can be found in Asia, Europe, Africa, and Latin America. Difficultly in building new lines, rapid or unexpected load growth, and long spans between structures are all reasons that advanced conductors are adopted in international markets.

The future of advanced conductors is likely to see increased adoption, with many utilities already widely adopting ACSS. While a few utilities have deployed hundreds of circuit miles of composite core conductors, many are still hesitant due to perceptions that composite core conductors are fragile and easy to damage. Manufacturers have introduced innovations to address this concern and decrease the probability of conductor damage during installation. New technologies being developed also allow installers to verify successful performance of the conductor during and after installation. These innovations should result in increased deployment if they are successful and if the long-term performance of the conductors installed 20 years ago continues to be stable. For industry to adopt the potentially hundreds of thousands of miles of advanced conductors that could be needed, industry standards on design and testing of advanced conductors and hardware need to be developed and applied to ensure the robustness and interoperability of products from different manufacturers.

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Acronyms

AAAC .... All Aluminum Alloy Conductors
ACCC .... Aluminum Conductor Composite Core
ACCR .... Aluminum Conductor Composite Reinforced
ACIR .... Aluminum Conductor Invar Reinforced
ACSR .... Aluminum Conductor Steel Reinforced
ACSS .... Aluminum Conductor Steel Supported
ACT .... Advanced Conductor Technology
AW .... Alumoweld
BIL .... Bipartisan Infrastructure Law
CISA .... Cybersecurity and Infrastructure Security Agency
CITAP .... Coordinated Interagency Transmission Authorization and Permits
ComEd .... Commonwealth Edison
CPE .... CenterPoint Energy
CREZ .... Texas Competitive Renewable Energy Zone
CTE .... coefficient of thermal expansion
DLR .... Dynamic Line Rating
DOE .... Department of Energy
DRC .... Democratic Republic of the Congo
ETESA .... Empresa de Transmision Electrica
FERC .... Federal Energy Regulatory Commission
FPL .... Florida Power and Light
GDP .... gross domestic product
GIS .... geographic information system
GT .... Gap-Type
HCLS .... High-Capacity Low-Sag
HIFLD .... Homeland Infrastructure Foundation-Level Data
HS .... harmonized system
HTLS .... High Temperature Low Sag
HVDC .... high voltage direct current
IACS .... International Annealed Copper Standard
IEC .... Israel Electric Corp
IRA .... Inflation Reduction Act

MDU	Montana Dakota Utility
MOT	maximum operating temperature
NEFPL	NextEra Energy Florida Power and Light
NIETC	National Interest Electric Transmission Corridor
OTP	Otter Tail Power
PECO	Philadelphia Electric Company
PG&E	Pacific Gas and Electric Company
PGE	Portland General Electric
RBS	rated breaking strength
RoW	right of way
SCE	Southern California Edison
SDG&E	San Diego Gas and Electric
SSEN	Scottish and Southern Electricity Networks
SWPA	Southwestern Power Administration
T&D	Transmission and Distribution
TCN	Transmission Company of Nigeria
TEP	Tucson Electric Power
TSED	Transmission Siting and Development
TSO	Transmission System Owner
TVA	Tennessee Valley Authority
TW	trapazoidal wire
U.S.	United States
ULS	ultra-low sag
WAPA	Western Area Power Administration

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SECTION 1: Introduction

In order to meet emissions targets and to satisfy international commitments, the United States (U.S.) has been aggressively building sources of renewable energy and decommissioning hydrocarbon generators. This is occurring at the same time as the country is experiencing an industrial resurgence in the aftermath of the Covid-19 pandemic. Combined with the effect of significant demographic shifts in recent decades, these factors have led to a considerable shift in where electrical energy is produced and consumed within the U.S. power system. Consequently, much of the existing Transmission and Distribution (T&D) network is operating at or near capacity. If the policy objectives of the recent Bipartisan Infrastructure Law, CHIPS Act, and Inflation Reduction Act are to be realized, significant expansions of the nation's power system are required.

Despite this need for additional capacity, the rate of expansion of the bulk electric system has slowed. This trend can be attributed to a number of factors, including the rising cost of land, reduced availability of construction materials, a shortage of experienced labor, and long delays in the permitting and environmental review process. In some portions of the system, it can be decades between when the need for a new transmission line is identified and when construction actually begins. In total, the rate of capacity expansion has dropped by nearly half compared to historical build rates. The current rate of capacity expansion is insufficient to meet demand, and as a result there is a growing backlog of new generation and industrial customers waiting on interconnection agreements. If this problem is not addressed, it is unlikely that current policy objectives can be achieved.

One solution that electrical utilities and Transmission System Owners (TSOs) have increasingly begun to embrace is reconductoring. Reconductoring is the process wherein the wires of a transmission or distribution line are replaced while most or all of the other equipment remains unchanged. Utilities and TSOs have used reconductoring as part of basic maintenance for decades; however, it is increasingly being used to increase the capacity of T&D lines because it allows the utility to bypass many of the challenges that inhibit new constructions. This has only been possible due to the advent of modern Advanced Conductor Technologies (ACTs).

In this report, an attempt is made to explore and characterize modern ACTs being used in the North American power system. Due to the short timeframe of this report and the urgent need for policy decisions, an exhaustive academic study of all conductor technologies was not performed. Instead, it is the intent of this report to inform regulators, utilities, conductor manufacturers, and other industry stakeholders regarding the state of the industry and steps that can be taken in the immediate to near term to assist in the expansion of T&D capacity.

The remainder of this report is structured as follows; Section 2 provides an overview of the state of the modern power system industry, including explanations of the basic concepts and terminology used by power line engineers. This section also includes descriptions of the types of conductors most commonly found in the U.S. power system, including the most recent ACTs. Section 3 provides a discussion of some of the most important policies and regulations that affect the construction of T&D lines decisions around reconductoring. Some policies facilitate these projects, while others may inhibit them and this section attempts to address both. Section 4 addresses the availability ACTs and their relative vulnerability to supply chain disruptions. This is done by first describing the manufacturing process for conductors to identify their essential components, and then by presenting a qualitative vulnerability assessment based on these components. Section 5 identifies the opportunities for increasing the use of ACTs to increase transmission capacity. This is done by describing the criteria utilities use for determining when to replace or reconductor a line and then identifying the best candidates for reconductoring. The section also estimates the number of T&D lines in the U.S. that could be reconductored to improve capacity. Section 6 identifies additional opportunities for the use of ACTs based on their use in other power systems around the world. This section identifies several novel applications of these technologies not yet found in the U.S., as well as identifying the typical scenarios where these technologies are used. Section 7 offers a glimpse into the future of ACTs by describing some of the most recent advancements in overhead conductor technologies, as well as providing an assessment of the broader industry trends. Section 8 concludes this report by summarizing the main findings and suggestions. Attached to this report is also an appendix featuring profiles of the largest utilities in the U.S. and highlighting their experiences with ACTs. Appendix A is meant to emphasize the findings of this report by showcasing relevant examples from industry and to promote the sharing of institutional experience amongst utilities and other stakeholders.

SECTION 2: Industry Assessment

2.1 State of the Industry

A society's quality of life generally improves with increased energy consumption [1]. However, in the case of fossil fuel energy sources, this trend is limited based on environmental pollution that degrades the quality of life [2]. Energy efficiency advancements within the U.S. have failed to reduce energy consumption [3] and by proxy environmental impact. Renewable energy and electrification of energy consumption has been seen as one solution to this issue [4]. The U.S. electrical energy consumption will further increase as digital technologies are progressively integrated into daily life [5] . For example, or example, a study by Waite and Modi estimated a 70% increase in the U.S. electrical demand from phasing out fossil-based space heaters alone [6]. Achieving the goal of decarbonization will require a rapid grid capacity expansion to accommodate renewable generation in distributed locations. [7]. The United States Energy Information Administration projects electrical energy generation will increase by more than 1,000 billion Kilowatt-hours (kWh) from 2021 to 2050 [8]. According to the U.S. Department of Energy (DOE), "independent estimates project that transmission systems will need to expand by 60% by 2030 and may need to triple by 2050 to meet the country's growing clean electricity and resiliency demands." Over the next few decades, it is clear the power grid will need to expand to satisfy growing energy demand, construction of additional renewable energy generation and the desire for improved resilience.

Additionally, a large majority of the power grid is aged and suffers from severe weather outages. The DOE's 2015 Quadrennial Technology Review stated that 70% of transmission lines and power transformers have been in service for 25 years or more, which represents at least half of their life [9]. Sixty percent of circuit breakers are 30 years or older [9]. The aged infrastructure was not designed with today's vison of the power grid in mind and often lacks capacity to take on new renewable generation or facilitate transfer of renewable energy to needed locations. Tangentially, severe weather-related outages are also on the rise [13–15], which adds an additional cost and competing incentives when considering which parts of the system to upgrade.

System repairs and rebuilds due to severe weather-related events must be completed rapidly to restore power to affected populations. Conversely, plans to upgrade infrastructure under typical conditions are subject to a bevy of lengthy regulatory processes and can easily take over a decade to receive all approvals and permits that are needed to start construction. In an industry that is marked by its conservative approach tends to cautiously and slowly adopt new technologies to not disrupt the current low cost and highly reliable electric power status quo. The length of time that it takes to permit and build new lines is unsuitable for the immediate and growing needs for transmission.

Utility scale renewable energy projects connect directly into the transmission grid. Before interconnection, a study must be performed to evaluate grid capacity to accommodate the additional power flow. The study may determine that the grid has sufficient capacity and the generation project can connect, but often the study will reveal that the new generation source could overload some element of the grid. The potentially overloaded grid element or elements become the constraints that must be upgraded before interconnection can occur. While grid capacity additions need to accelerate, the rate of expansion has actually fallen from historical levels of 2% per year from 1978-2020 to approximately 1% per year. As the grid has reached its capacity, wait times and cost to interconnect new projects have soared. The queue of renewable generation projects waiting for interconnection to the grid grew by over 40% from 2021 to 2022 [16] and this is only expected to worsen without an acceleration of new capacity.

Generation resources that are already connected to the grid are also experiencing the consequences of a grid operating at its capacity, with consequences for the consumer. Ideally, the lowest cost generation resource would be allowed to inject power into the grid before other more expensive sources. Increasingly, the lowest cost resource is not able to operate because of transmission constraints that prevent the energy from flowing from the source to the load. In these cases, higher cost generation that does not suffer from the constraints will need to be dispatched by grid operators instead. The cost difference between the lowest cost generation resource and the generation that operates because of grid constraints is called congestion cost. U.S. consumers paid for $20.8 billion of congestion costs in 2022— a 56% increase from 2021 [17].

Both the large congestion costs and the lengthy interconnection time for renewable generation are symptoms of constraints on the transmission grid and the need for a rapid capacity expansion. Creative solutions to add transmission capacity are desperately needed. These range from new high voltage direct current (HVDC) lines that can transport many gigawatts of renewable energy across hundreds of miles to simple operational changes in how grids are operated, driven by software and sensor solutions. Grid Enhancing Technologies (GETs) are a rapidly developing group of technologies that enable better use of existing infrastructure. Software and hardware solutions, such as topology optimization and power flow control devices, can route power around from constraints. Dynamic line rating solutions monitor weather conditions along transmission line routes, allowing line ratings to be increased on cooler and/or windier days without fear of overheating conductors. Advanced conductor technologies can increase capacity on existing transmission towers with minimal or no modifications required. There are many transmission solutions to solve grid constraints. The urgent need for transmission capacity calls for aggressive deployment of creative tools to expand capacity as rapidly as possible, while considering costs and reliability standards. A suite of advanced conductor technologies gives utility planners and line designers many tools that did not exist in the last century.

2.2 Overview of Power Line Parameters

An admirable amount of complexity is accounted for in overhead conductors and structures which goes unrecognized in ordinary life. The suspended electrical conductors for overhead transmission lines must be strong enough to survive intense weather, light enough to not overload the towers, conductive enough to carry power without high losses, and durable enough to operate for many decades in the elements. System planners and line designers must consider the interdependent variables of reliability, electrical performance, mechanical performance, and cost. These key attributes of overhead conductors for transmission lines are discussed in more detail below.

2.2.1 Electrical Characteristics

2.2.1.1 Ampacity

The term "Ampacity" is a shortened version of the phrase "amp capacity" and indicates the ability of a conductor to carry electrical current. The main properties of a conductor influencing ampacity are the cross-sectional area of the conductor, material conductivity, maximum conductor operating temperature, and the rate at which heat can dissipate from the conductor's surface. For example, a 1-in diameter conductor might carry 500 amps at 50 C while a conductor with half the diameter could still carry 500 amps but would need to operate at 100°C to do so.

2.2.1.2 Electrical Resistance/Losses/Efficiency

As current flows through conductors, some of the energy is wasted as heat. The hotter the conductor operates; the more energy is lost. Higher conductivity metals, larger cross-sectional area, or lower operating temperature reduce these losses. Lower conductivity, smaller cross-sectional area, or higher conductor operating temperatures increase line losses. In the example above, the more-efficient conductor would be the 1-in.-diameter conductor. Losses increase with the square of the conductor current, so doubling the current in a conductor increases the line losses by 4 times, as shown in Equation 1.

$$P_{loss} = I^2 R_{conductor} \tag{1}$$

where P_{loss} is the power loss (measured in Watts), I^2 is the square of the current passing through the conductor (measured in Amps), and R is the resistance of the conductor over its entire length (measured in Ohms or Ω for short). Resistance is often provided in terms of a per unit length (e.g., Ω/ft.). The total resistance of the conductor can then be calculated by multiplying the resistance per unit of length by the total length of the conductor.

2.2.1.3 Voltage

Voltage is the difference of electrical potential between two points in the line (or system) that drives the electrical current. Electrical current will flow from points of high electrical potential to points of low electrical potential. For transmission systems, voltage is measured in thousands of volts or kilovolts (kV).

2.2.1.4 Power

For transmission applications, power is typically measured in Megawatts, abbreviated as MW, which represents 1 millions of watts. Power is what is consumed by customers and a megawatt of power can provide electricity for approximately 800 homes. Power in watts is the product of amperage times voltage as shown in Equation 2.

$$P = V \times I, \tag{2}$$

where P is power (measured in Watts), V is voltage (measured in Volts), and I is the amperage (measured in Amps).

Thus, doubling of power (P) on a line can be accomplished by either a doubling of the current or a doubling of the voltage of the line. A drawback of designing for increased current is that power losses increase with the square of the current (I^2) so by doubling the current, power loss will increase by a factor of four. A drawback of increased voltage for transmission lines is that the tower sizes must increase in both height and width in order to keep the bare conductors separated from each other and from their surroundings.

2.2.2 Mechanical/Sag Characteristics

Flexible conductors suspended between two fixed points deflect vertically due to the weight of the conductor. The vertical distance between the points of attachment and the lowest point of the conductor is defined as sag. During operation, the amount of vertical deflection varies based on conductor temperature and on mechanical loading. As conductor temperature increases, the conductor materials expand which causes conductor elongation and increased sag. Different conductor materials expand at different rates and the conductors with the lowest sag at high temperatures are those that expand the least. A lower expansion rate is a key feature of composite core conductors. In some locations, ice can accumulate and stretch the conductors, which will also increase sag. Conductors that stretch the least under these conditions have the highest modulus of elasticity. Increased strength will allow conductors to be installed at higher tensions, which also reduces sag. Sufficient clearance between energized conductors and objects below must be maintained in all conditions for safety and reliability [18].

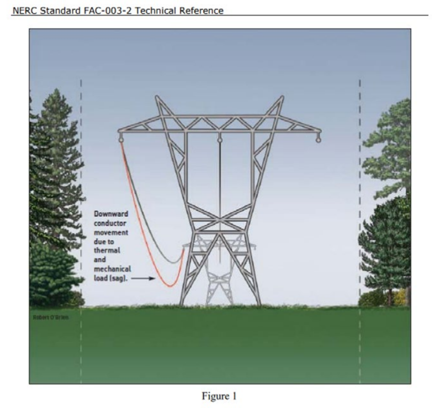

Figure 2-1 Visual representation of sag

2.3 Overhead Conductor Technologies

2.3.1 Advanced Transmission Conductors

Since the first transmission line was energized over 130 years ago, the basic concept of suspending energized metal conductors from sturdy structures while using the surrounding air to contain the electrical charges has remained the same. As the grid has evolved and grown, so has the number of available conductor technologies to meet the needs of electric utilities. Most of the electric grid and many of the transmission and distribution lines being built today use a conductor made of aluminum and steel, called Aluminum Conductor Steel Reinforced (ACSR) conductor, which has changed little from when it was introduced over 100 years ago. ACSR is reliable, inexpensive, and well understood by line workers. It can also be scaled up for the largest high-voltage interregional lines or scaled down for small distribution lines in neighborhoods. Advanced conductor technologies use improvements in material science to improve on aspects of the ACSR design.

This section contains an overview of contemporary conductor technologies followed by a comparison of the advanced technologies to the standard ACSR. Advanced conductors can be designed to improve on many different attributes of ACSR. However, with the pressing need to reduce grid congestion and increase grid capacity, the most valuable attribute of advanced conductors is their ability to increase capacity on new or existing lines. A particularly useful application for advanced conductors is reconductoring, where old conductor can be replaced with advanced conductors for a large capacity increase without the time and expense of replacing towers. For new lines, advanced conductors can be used to reduce initial project cost in some situations when substituted for larger traditional conductors or to "upsize" capacity for new lines while simultaneously improving efficiency.

While advanced conductors are typically more expensive than ACSR conductors, they are still a small percentage of the overall cost of a transmission line. According to the MISO MTEP 2022 Transmission Cost estimation guide, the average cost of a new 230-kV line is approximately $2 million per mile. If a standard ACSR 795 Drake conductor were used, the conductor expense would be less than $30,000 per mile for a three-phase line, which would be less than 1.3% of the project budget. Even if an advanced conductor were used that is four times more expensive, the conductor would still be only 5% of the line cost. With projections that transmission capacity will need to triple by 2050, the premium for advanced conductors would be a modest price to double the capacity of the transmission line conductors, when rebuilding the towers is undesirable or impossible.

There is no standard definition of what makes a conductor technology "advanced." References to advanced High Temperature Low Sag Conductors (HTLS) conductors began to appear in the early 2000s, coincident with the introduction of the first composite core conductors, but they also to refer to high-strength steel core conductors, such as ACSS. Where possible, this study will refer to conductor technologies by their specific acronym or trade name and will use the term "advanced conductor" to denote products produced since the introduction of the first composite core conductor. This includes all types of composite-core conductors, ultra-high strength steel-core conductors, conductors produced with heat-dissipating coatings, high-temperature super conductors, or other associated technologies that improve performance of the electric transmission grid. The following sections will discuss both legacy copper and aluminum conductor designs, high-capacity aluminum conductor designs, including steel and composite core options, and other technologies that can add capacity to existing lines.

2.3.1.1 Copper Conductors

Stranded Copper wire (Figure 2-2a) was popular for use in transmission from the advent of the electrical system in the 1880s through the 1970s. Copper was originally used due to its high strength, high conductivity, and weather resistance properties. The conductivity of copper is higher than other common materials used today; thus, it gave rise to the International Annealed Copper Standard (IACS) to which all other metals are compared. Fully annealed copper has an IACS conductivity of 100%. Copper suffers from softening at higher temperatures, which causes it to weaken. Alloying copper with small percentages of cadmium helps improve the mechanical strength to reduce sag while experiencing only a small reduction in electrical conductivity. Being significantly heavier than aluminum, copper requires larger and stronger structures for overhead transmission. Since it is more valuable, copper is also more prone to vandalism and theft. These disadvantages outweigh the benefit of better conductivity; therefore, it is no longer used for new construction in the U.S.

2.3.1.2 All Aluminum Alloy Conductors

Aluminum conductors (Figure 2-2b) have been used as early as the 1830s for power cables. Aluminum is not as conductive as copper but is a lighter metal. When ampacity is compared by weight, not by volume, aluminum has approximately twice the current carrying capacity as copper. Because the weight of long spans of transmission conductors is an important factor for line design, aluminum is an attractive choice for overhead lines. Pure electrical-grade aluminum is typically not strong enough for transmission conductors without a strengthening core. In 1968, all aluminum conductors started to improve their mechanical characteristics through alloying copper, iron, magnesium, and other materials with the aluminum [19]. This gave rise to All Aluminum Alloy Conductors (AAAC) that could be used for longer spans without a steel core. AAACs are still widely used , typically for new construction projects and for distribution lines. The disadvantages of AAAC are that it has lower strength compared to other designs, the alloy has lower conductivity, and AAAC conductors are not suitable for extended periods of high-temperature operation above 93°C.

2.3.1.3 Aluminum Conductor Steel Reinforced

Aluminum Conductor Steel Reinforced (ACSR) conductor is the most widely used and deployed overhead conductor in the world [1]. It was introduced in the early 1900s and is a mature technology. ACSR is fabricated with hardened aluminum wires, which are stranded around a coated steel core. In operation, the aluminum carries the majority of the electrical current. In a typical ACSR, the aluminum and the steel each contribute approximately half of the mechanical strength. ACSR is available from a wide-supply base, has a high level of familiarity with line workers, is relatively inexpensive, and is abuse resistant. Different ratios of steel to aluminum vary the mechanical characteristics of the conductor, and different sizes are available, with larger sizes having more strength and capacity. One disadvantage of ACSR is that it is not suitable for extended periods of high temperature operation. The maximum operating temperature (MOT) at which a conductor can operate is proportional to the conductor's capacity, with higher temperature conductors capable of higher capacity. While some advanced conductors can operate continuously at up to 250°C, the aluminum in ACSR, begins to weaken at temperatures above 93°C. Over time, operation at high temperatures will damage the conductor and cause excess sag, leading to potential reliability and safety violations. To prevent this damage from occurring, the capacity of transmission lines is rated at or below the thermal limits of the conductors and other equipment in the path of the power flow.

2.3.1.4 Vibration-Resistant Conductors

Special vibration-resistant conductors are used across the upper Midwest. Overhead conductors and systems are prone to damage from wind-induced vibrations. This is a concern in all parts of the U.S., but especially in areas with a high probability of concurrent ice accumulations and high winds. Ice can change the profile of the conductor and with wind, can cause a condition, known as galloping, in which the conductor is lifted by the wind and then dropped dramatically with high-amplitude vibrations. Repeated cycles of galloping, where thousands of pounds of conductors move through the air, can cause outages or even destroy towers. Several conductor concepts have been deployed to control these conditions and a common conductor design used in the midwestern U.S. is fabricated with a twisted pair of two ACSR conductors (Figure 2-2d). Trade names for these conductor types are T2 or VR2. This conductor type has low-torsional stiffness and a varying profile that prevents buildup of resonant vibrations in the line [20]. These designs allow the conductors to dissipate mechanical energy and reduce aerodynamic instabilities so the conductor can be installed at higher tensions and lower sag without concern damage from wind-induced vibrations. Existing lines that are built with twisted-pair ACSR may not be suitable candidates for reconductoring with advanced conductors that do not mitigate damaging vibrations as effectively.

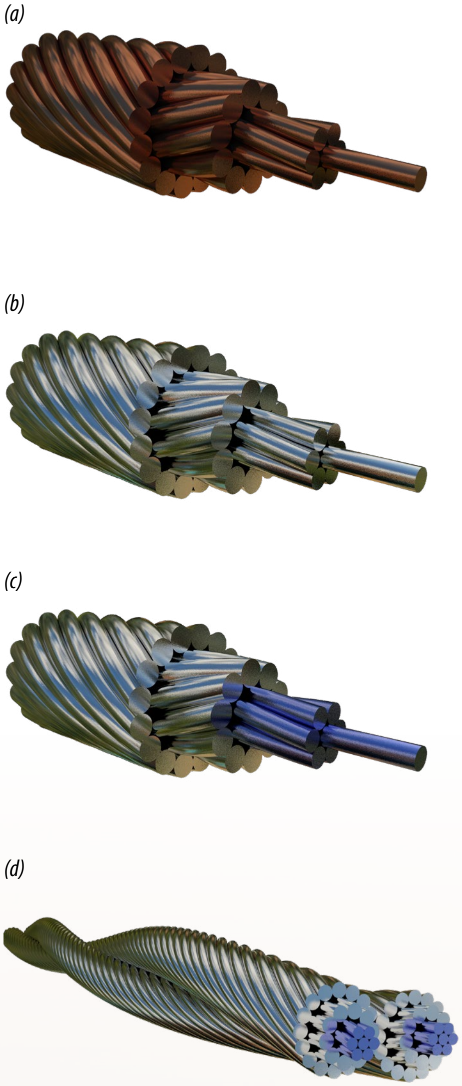

Figure 2-2. images of currently used overhead conductor technology (a) stranded copper (legacy technology), (b) all aluminum alloy conductors, (c) aluminum conductor steel reinforced (most used today), and (d) twisted pair (used in areas with high wind).

2.3.1.5 ACSS Overview and Comparison

2.3.1.5.1 DESIGN

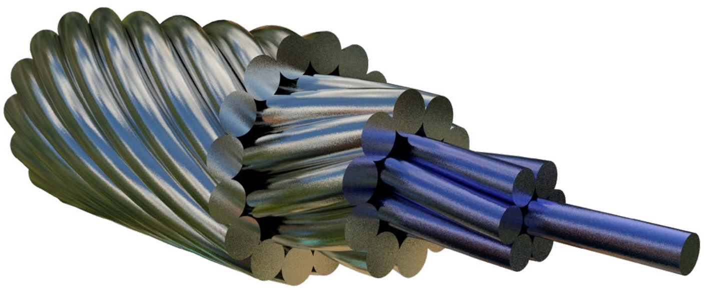

Figure 2-3. ACSS conductor.

The ACSS (Figure 2-3) conductor was developed in the 1970s by the Electrical Division of Reynolds Metals (now part of General Cable Corp.) [1]. The ACSS design is much like ACSR except it uses annealed aluminum versus hardened aluminum and a higher temperature zinc/aluminum mischmetal coating on the steel core versus zinc galvanized steel. In some cases, the aluminum strands are shaped into a trapezoid profile instead of a round cross section, providing more aluminum area for a given conductor diameter and greater current capacity [1].

Some of the benefits over traditional ASCR indicated by the manufacturer are provided below [1,2]:

- Two times the ampacity because of higher maximum operating temperature (MOT) of up to 250°C.
- Increased conductivity aluminum for more efficient conductor performance.
- Sags less than ACSR at equivalent temperatures.
- Similar installation methods, equipment, and fittings.

Some of the potential disadvantages of this conductor as compared to traditional ASCR include [3,4]:

- ACSS costs slightly more.
- More prone to damage during installation because of the softer aluminum temper.
- Can have higher sag or require greater tensions than ACSR to achieve the same sag profile.
- When operating at high temperatures with high-power flows, line losses increase and efficiency decreases.

- Traditional ACSS had reduced rated breaking strength (RBS) compared to ACSR, which did not always allow for the needed conductor tension to maintain sag requirements. New steel grades have increased the RBS of ACSS to where it is stronger than an equivalent diameter ACSR, so this is no longer a problem.

2.3.1.5.2 OTHER ACSS TYPES

Optional high-strength ACSS and ultra-high-strength (MA5/HS285) steel is available that allows for greater tension and less sag [5]. ACSS is also available with aluminum clad (AW) steel for very corrosive environments. ACSS is also available with E3X high-emissivity coating.

2.3.1.5.3 COMPARISONS WITH OTHER TECHNOLOGIES

The following provides a comparison of the ACSS conductor over traditional ASCR of the same diameter. Table 2-1 shows that ACSS costs slightly more, but it offers a large capacity gain. Sag at the higher maximum operating temperatures can be more than ACSR, but alternatives to achieve reduced sag do exist. From a reconductoring standpoint, ACSS provides an opportunity to increase capacity and RBS but may require more tower modifications to achieve necessary tensions to reduce sag. Many utilities commonly use ACSS in new and reconductoring applications as there are decades of positive experience with its use and advancements in the past 20 years have further improved the performance. Also, ACSS uses that same installation procedures, equipment, and fittings as ACSR.

Conductor Type	More Sag than ACSR	Continuous Capacity vs ACSR	Cost vs ACSR	Resistance vs ACSR @ MOT Continuous	Weight vs ASCR	RBS vs ASCR
795 Drake ACSR GA2						
795 Drake ACSS MA5	Yes, @ MOT	174%	108%	146%	100%	103%
795 Drake ACSS MA5/E3X	Yes, @ MOT	199%	135%	146%	100%	103%
959 Suwanee ACSS MA5	Yes, @ MOT	191%	139%	121%	121%	123%
959 Suwanee ACSS MA5/E3X	Yes, @ MOT	218%	152%	121%	121%	123%

Table 2-1. ACSS to ASCR Comparisons.

2.3.1.5.4 SUMMARY

ACSS has provided a solution for increasing the capacity of lines where needed for several decades. It has become an accepted option for many utilities based upon years of experience. ACSS has a higher maximum operating temperature than ACSR, which allows it to carry more current, however the efficiency is less at higher temperatures as is the case with all advanced conductors that operate at higher temperatures. ACSS does not work for every project because the tensions required to achieve low sag may not be possible, especially when existing structures are being used for reconductoring.

ACSS had a lower rated breaking strength than ACSR before the introduction of ultra-high-strength steel, which remedied that deficiency. ACSS is also generally not as costly as the other advanced conductors.

Finally, the experience of the community with conductors becomes an important factor in making a decision. This experience includes differences in the installation equipment or procedures where ACSS also had some advantage. As ACSS has been available and in use for several decades with a successful record, it has the expected greater acceptance.

2.3.1.6 ACCR Overview and Comparison

2.3.1.6.1 DESIGN

Figure 2-4. ACCR Conductor

Aluminum Conductor Composite Reinforced (ACCR) was the first composite core conductor when it was introduced in the early 2000s. The core is composed of aluminum oxide ceramic fibers embedded in an aluminum matrix. The aluminum oxide in the core has no galvanic corrosion issues and is inert to the environment. Ceramic fibers have half the density (i.e., are lighter weight) and thermal expansion coefficient compared to steel cores. Thus the sag at high temperatures, compared to steel used in ACSS or ACSR, is much less. The improved modulus of elasticity compared to steel. ACCR uses an aluminum- zirconium alloy for the outer strands. Unlike the aluminum used in ACSR, which weakens at temperatures above 93°C, aluminum zirconium alloy maintains its strength at temperatures of up to 210°C although addition of the zirconium does reduce the conductivity of the metal. ACCR can carry around double the current compared to ACSR technologies.

A drawback of ACCR is its cost as ACCR was reported to be among the most expensive advanced conductor (based on industry interviews conducted). Another drawback is the fragility of the core and special handling precautions. Because of the core's brittleness, special tools and hardware are needed to install splicing, jumpers, end terminals, or other electrical connections and the manufacturer is typically onsite during installation to oversee construction. Lastly, operating ACCR lines at high temperatures with high currents will result in increased resistive losses and reduced line efficiency.

2.3.1.6.2 OTHER ACCR TYPES

The core and conductor materials of ACCR cable do not change other than strand shapes and diameters and the number of strands included.

2.3.1.6.3 COMPARISON WITH ACSR CONDUCTOR

Table 2-2 shows a detailed comparison between ACSR and ACCR. Both outer aluminum conductors have fairly similar properties, but the 1350-H19 aluminum shows slightly higher tensile strength and conductivity (based on the IACS). The main difference lies in the ACCR's ceramic core's lower coefficient of thermal expansion (CTE) of 6 compared to ACSR's 11.5. This results in ACCR able to tolerate higher temperatures without sagging so much as to violate conductor to ground distance tolerances [6]. A sag test in Kinectric's Laboratory showed ACCR had 33.3% less sag compared to ACSR (25 in. versus 72 in at 240°C). The ceramics' higher modulus of elasticity means it resists deformation more than steel.

	Cable Conductor			Cable Core			
Conductor Type	Aluminum Type	Tensile Strength (ksi)	Conductivity (%IACS)	Material Type	Tensile Strength (ksi)	Modulus of Elasticity (msi)	CTE ($x10^{-6}$ C^{-1})
ACSR	1350-H19	24-28	61.2	Coated Steel	210-230	29	11.5
ACCR	Al-Zr Alloy	23-26	60	Aluminum oxide fibers in aluminum matrix	200	32	6

Table 2-2. Comparison between ACSR and ACCR.

2.3.1.6.4 SUMMARY

ACCR was the first composite core conductor introduced to the market in 2002, has higher capacity and can tolerate higher operating temperatures than ACSR while simultaneously maintaining ground clearances due to its low sag properties. ACCR is more expensive than other advanced conductors and requires special installation techniques to prevent damage.

2.3.1.7 ACCC Overview and Comparison

2.3.1.7.1 DESIGN

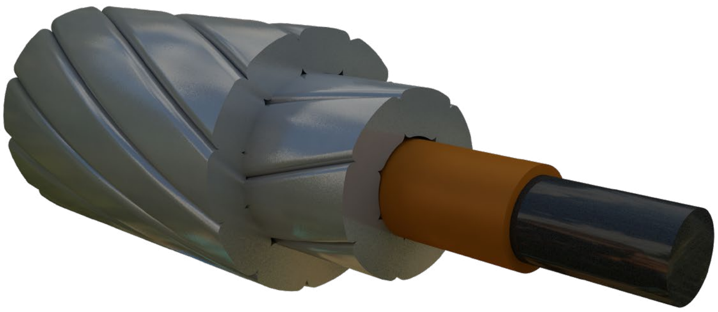

Figure 2-5. ACCC conductor.

An Aluminum Conductor Composite Core (ACCC, Figure 2-5) conductor was first commercialized in 2005 by CTC Global [6]. Since then, it has been installed in 1100 projects worldwide [2]. The ACCC composite core composed of carbon and glass fiber embedded in a thermoset epoxy matrix.

Some of the benefits over traditional ASCR indicated by the manufacturer are provided below [2]:

- Two times the capacity.
- Reduced line losses.
- Low thermal expansion and resulting reduced sag.
- High strength to weight ratio.
- Core technology that resists corrosion.
- Technology that allows verification of core integrity after installation.

Some of the potential disadvantages of this conductor, as compared to traditional ASCR, include [3]:

- ACCC generally costs 2.5–3 times the cost.
- Standard ACCC is has a lower modulus of elasticity, sagging more with ice loads. However, ultra-low sag (ULS) versions are available.
- If mishandled, the conductor can be damaged during installation leading to line failures.
- The conductor requires special fittings and installation equipment that are more expensive.

2.3.1.7.2 OTHER ACCC TYPES

2.3.1.7.3 ACCC ULS CONDUCTOR [2]

The ACCC ULS Conductor uses a higher strength, higher modulus core (375 ksi) compared to the standard ACCC Conductor (310 ksi). The ULS in the name means "Ultra-Low Sag." As such, it provides greater core strength for very long spans and for improved resistance to deflection from high wind and ice loads.

Figure 2-6. ACCC AZR (left) and ULS-AZR Conductor (right).

For added strength, the ACCC AZR Conductor (Figure 2-6) uses an aluminum-zirconium alloy to add another layer of strength to ACCC or ACCC ULS Conductor designs. This design provides a higher strength and stiffness over annealed aluminum and further resistance to high wind and ice loads, although for a small reduction in capacity and efficiency, and increased high temperature sag.

2.3.1.7.4 ACCC INFOCORE [2]

In 2020, CTC Global introduced a new technology advancement for the ACCC conductor where optical fibers are embedded longitudinally into the carbon-fiber core. The fibers can be used as a continuity check to verify that the core has not been broken during handling and installation.

2.3.1.7.5 COMPARISONS WITH OTHER TECHNOLOGIES

The following provides a comparison of the ACCC conductor over traditional ASCR. Table 2-3 shows that while more costly, capacity, sag, and weight are generally improved over ASCR. As such, from a reconductoring standpoint, ACCC provides an opportunity to increase capacity and rated breaking strength (RBS) at a reduced weight. ACCC with ULS and AZR would provide additional strength to the standard ACCC for hurricane, ice storm, and similar climate threats. Depending upon the condition of the towers, less rebuilding to accommodate reconductoring is generally a benefit. Several utilities have used the ACCC in new and reconductoring applications over the last two decades [4].

Conductor Type	More Sag than ACSR	Continuous Capacity vs ACSR	Cost vs ACSR	Resistance vs ACSR @ MOT Continuous	Weight vs ASCR	RBS vs ASCR
795 Drake ACSR GA2						
1026 Drake ACCC	No	165%	237%	99%	96%	129%
1026 Drake ACCC/E3X	***No***	***186%***	***237%***	***99%***	***97%***	***129%***

Table 2-3. ACCC to ASCR Comparisons.

2.3.1.7.6 SUMMARY

ACCC is the most widely deployed composite core technology and offers a wide variety of conductor configurations using different alloys and core types to meet project requirements for capacity and sag. Like other composite core conductors, ACCC can be damaged during installation if mishandled; however, the new Infocore technology reduces that risk by checking core integrity after installation.

2.3.1.8 TS Conductor Overview and Comparison

2.3.1.8.1 DESIGN

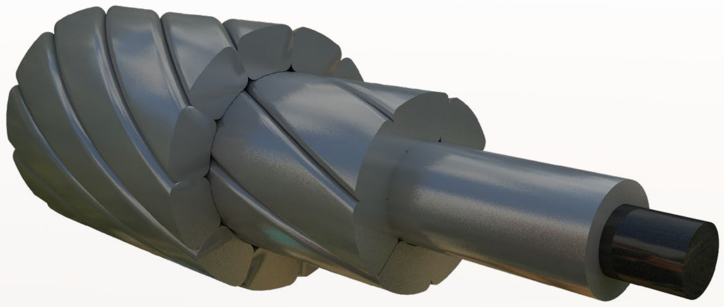

Figure 2-7. TS conductor.

TS Conductor (Figure 2-7) was founded in 2018. The TS core is composed of carbon fiber embedded in a thermoset epoxy matrix and encapsulated with an aluminum tube.

Some of the benefits over traditional ASCR indicated by the manufacturer are provided below [2]:

- Three times the ampacity with existing structures.
- 50% better efficiency.
- Same installation equipment and fittings as ACSR.

Some of the potential disadvantages of this conductor, as compared to traditional ASCR, are provided below [3]:

- It is expected that TS generally costs more than ASCR, as with other conductors released since 2000, but the vendor did not provide a cost.
- As one of the newest designs, there are fewer implemented miles and utility experience with operation as compared with other conductors.

2.3.1.8.2 COMPARISONS WITH OTHER TECHNOLOGIES

The following provides a comparison of the TS conductor versus ASCR. Table 2-4 shows that capacity, sag, and weight are generally improved. As such, from a reconductoring standpoint, TS provides an opportunity to increase capacity and RBS at a reduced weight. From an efficiency standpoint, it has a notably low resistance. TS conductor is one of the newest designs, which limits broad operational experience, but several utilities have used the TS in new and reconductoring applications [4]. TS uses that same installation procedures, equipment, and fittings as ACSR.

Conductor Type	More Sag than ACSR	Continuous Capacity vs ACSR	Cost vs ACSR	Resistance vs ACSR @ MOT Continuous	Weight vs ASCR	RBS vs ASCR
795 Drake ACSR GA2						
1039 M3 9 Fishers	No	168%	Unk.[5]	75.59%	95.80%	147%
1051 TS Sun M3 8.5	No	159%	Unk.[5]	74.65%	96.20%	134%

Table 2-4. TS to ASCR Comparisons.

2.3.1.8.3 SUMMARY

TS, as one of the most recent advanced conductors, indicates some level of evolution from prior designs but also has the least amount of operational experience. Discussions within the community indicated a level of interest in evaluating TS noting the potential beneficial design features. If convinced of the performance and cost for the benefit received, adoption rate may increase.

2.3.1.9 C7 Conductor Overview and Comparison

2.3.1.9.1 DESIGN

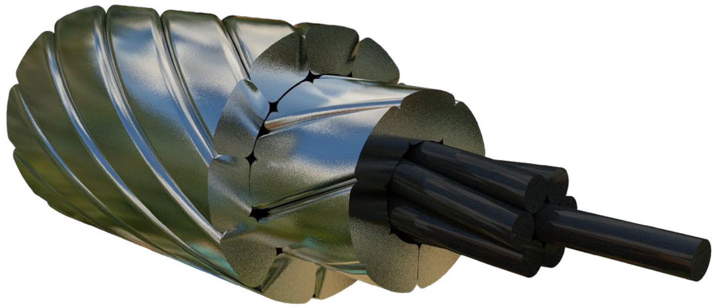

Figure 2-8. C7 conductor.

C7 conductor (Figure 2-8) was first commercialized in 2014 by Southwire after 7 years of development [1]. The C7 conductor has a stranded continuous carbon-fiber thermoset composite core.

Some of the benefits over traditional ACSR indicated by the manufacturer include [2]:

- Two times the capacity.
- Minimal thermal expansion and resulting sag.
- Uses traditional installation methods and hardware.
- Designs for light and heavy mechanical loads.

Some of the potential disadvantages of this conductor as compared to traditional ACSR include [3,4]:

- Cost is expected to be higher than traditional ACSR.
- Reduced bend tolerance when compared to ACSR

2.3.1.9.2 OTHER C7 TYPES

Optional aluminum-zirconium or annealed-aluminum options are available for low-line loss, high capacity, and heavy mechanical loading [2].

2.3.1.9.3 COMPARISONS WITH OTHER TECHNOLOGIES

The following provides a comparison of the C7 conductor over traditional ASCR. Table 2-5 shows that while more costly, capacity, sag, and weight are generally improved over ASCR. As such, from a reconductoring standpoint, C7 provides an opportunity to increase capacity and rated breaking strength

(RBS) at a reduced weight. A smaller number of utilities have used the C7 in new and reconductoring applications than other advanced conductors. C7 uses the same installation procedures, equipment, and fittings as ACSS with the addition of a protective aluminum tube [3,4].

Conductor Type	More Sag than ACSR	Continuous Capacity vs ACSR	Cost vs ACSR	Resistance vs ACSR @ MOT Continuous	Weight vs ASCR	RBS vs ASCR
795 Drake ACSR GA2						
Southwire C7 Everglades/TW	No	159%	Unk.[5]	108%	90%	149%
Southwire C7 Samoa/TW	No	165%	Unk.[5]	102%	95%	154%

Table 2-5. C7 to ASCR Comparisons.

2.3.1.9.4 SUMMARY

C7 conductors have the fewest users among the utilities interviewed and profiled.

2.3.1.10 E3X and Other Heat Dissipating Coatings

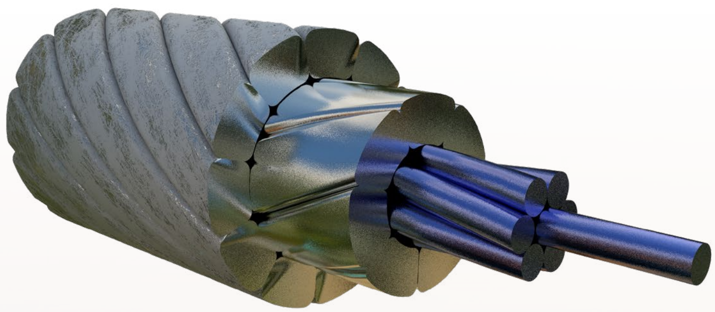

Figure 2-9. E3X coating on ACSS cable.

E3X is a heat-dissipating ceramic coating that can be applied to any aluminum conductor type. Advanced conductor coatings are unlike other conductor technology improvements because they enhance the capacity and efficiency of the underlying conductor. ACCC, ACSS, and TS Conductor, are advertised to be available with a heat dissipating coating and there have been multiple ACCC and ACSS deployments with E3X coating from Prysmian. The ceramic coating works by radiating out more heat while simultaneously reducing heat absorption form the sun. The thermal capacity of a conductor is calculated based on a maximum conductor operating temperature and the balance of the rate at which heat builds up and the rate at which heat can dissipate. By increasing heat dissipation, these coatings allow cooler operating conductors for efficiency while increasing capacity by up to 25%. Testing shows that E3X is durable and is expected to have a similar life expectancy to ACSR. Conductor coatings are a relatively new idea, commercially introduced in the U.S. in 2015; however, engineering high-temperature materials with heat dissipating coatings are a long-established practice in other areas, such as aerospace. Both the NASA space shuttle program and the Lockheed SR71 Blackbird (so nicknamed because of use of a high-emissivity black surface) used high-emissivity coatings to better dissipate heat. E3X is also advertised to have icephobic properties. A high-emissivity coating is also now being promoted by TS Conductor. Because E3X enhances the performance of the underlying conductor but does not change the mechanical properties, utility objections to a new technology have been easier to overcome. E3X was first deployed in a U.S. pilot project in 2013 with Oklahoma Gas and Electric; and in less than 10 years, E3X has achieved widescale deployment with multiple utilities.

According to the manufacturer, E3X coating can also be retrofit to existing lines with robots, including on energized lines. This can increase thermal line ratings, reduce line losses, or reduce sag instead of reconductoring. Applying E3X coating onto existing conductors can increase static line ratings of existing lines by as much as 25%. E3X can also be used to reduce conductor operating temperature, which can reduce line sag at high temperatures and increase operating efficiency. The robotic system involves both a cleaning and a coating robot that traverse in tandem across existing lines to first prepare the conductor's surface and then to apply the coating. The cost of deploying the robot is unknown but is expected to be less expensive and faster than reconductoring. Exelon is the only utility currently using robots to retrofit E3X coating on existing lines.

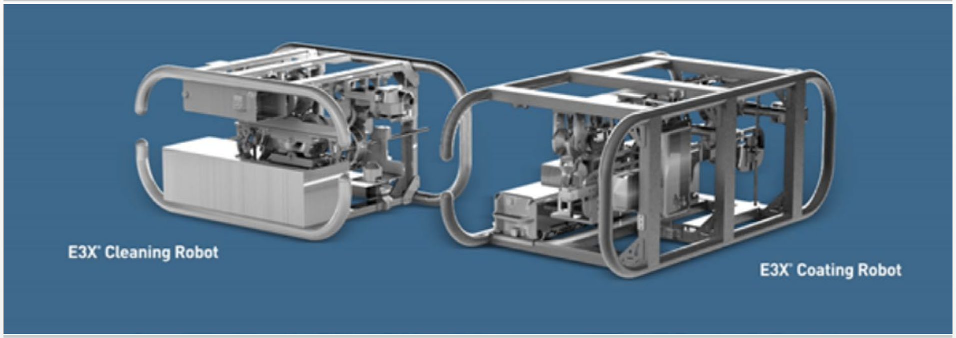

Figure 2-10. Robots for cleaning powerlines (left) and coating (right) with E3X ceramic material.

2.3.1.11 Tower Raising

There are existing transmission lines where the installed conductors are capable of higher temperature operation without damage, but the transmission towers do not have sufficient height to operate the conductor at this maximum temperature because of sag limits. In these cases, if the towers can be raised, the conductors can operate at higher temperatures and be rated for higher capacity. Some systems can increase tower height while a transmission line remains in service. Where this work is done, typically only a portion of the structures on a line will need to be raised since clearance on some spans will already be sufficient. Project cost will vary based on the type of towers and how many towers need to be modified, but the method is advertised as a lower cost way to upgrade transmission capacity.

Tower raising is accomplished either with large cranes lifting the upper portion of a tower or with a mechanism that holds the existing structure in place while it is partially disassembled, then a new section is added and the tower is fully reassembled into the taller structure (Figure 2-11). Tower raising can also be used in other situations where more clearance is required, such as to remediate safety violations from excess sag or where existing conductors are being replaced with higher temperature conductors that have more sag.

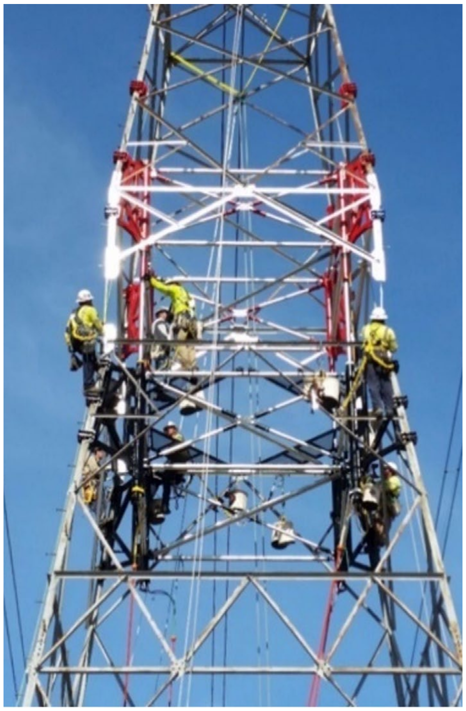

Figure 2-11. Linemen raising the height of a tower.

2.3.1.12 Dynamic Line Rating

Traditionally, utilities have used static line ratings to establish maximum capacity for transmission lines. Static line ratings are typically calculated using conservative weather assumptions that stay the same over time. Multiple solutions now exist that can measure or calculate actual conductor conditions with sensors and software so that line ratings can be matched to real-time conditions. This solution can be quickly deployed at a lower cost than reconductoring or tower raising, but gives a variable capacity increase, not a constant capacity increase. For example, on a day when the wind is blowing strongly, the sun is not shining, and the air temperature is cooler, the conductor will operate cooler and can carry significantly more power without overheating. Dynamic line rating is the process of matching line ratings to actual weather conditions to increase line ratings when weather is favorable and decrease ratings on the very hot days when the wind is not blowing. Various dynamic line rating systems use different methods to measure real-time conditions, including sensors to monitor conductor position and sag, as well as software to calculate conditions based on current and forecast weather conditions. Dynamic line rating systems should work well with advanced conductors; however, systems that rely only on the change in conductor sag to calculate conductor temperature may have difficulty operating on advanced conductors with sag that does not change with temperature. New composite core conductors with embedded fiber optics, such as Infocore from CTC Global and as advertised by TS Conductor, hold promise of using optical temperature sensing to determine conductor temperature throughout the span. Experiments on embedding fiber optic cables with conventional steel-core conductors have also shown promise.

2.3.2 Conductor Comparison

A detailed comparison of conductors was performed as part of this study including mechanical, electrical, and budgetary cost . Domestic conductor manufacturers were asked to propose solutions for a common reconductoring scenario in which an existing ACSR conductor was to be replaced with a higher capacity advanced conductor of equivalent diameter. The conductors proposed had a variety of performance characteristics and costs. The ideal mix of attributes would be a conductor that is stronger in tension, lighter in weight, sags less, has higher capacity and efficiency and all for the lowest cost. Unfortunately, no single technology dominates in all categories and line designers must consider the tradeoffs when selecting advanced conductors.

Compared to traditional ACSR, all the advanced conductors considered have higher capacity, higher strength, and lower losses when operating at day-to-day temperatures. Where capacity and cost are the most important considerations, advanced ACSS conductors offer the best fit, making ACSS the best solution for maximizing capacity on new lines or for reconductoring applications where additional sag can be accommodated. When efficiency is the most important consideration, TS Conductor has the best performance and ACCC is also excellent while the remaining conductors having higher losses than ACSR when operating at full capacity/maximum temperature. In a reconductoring situation where high-temperature sag is critical, ACCC conductor with E3X coating is the top solution to maximize both capacity and efficiency. Other solutions may perform better where heavy ice loading, extremely long spans, or hurricane force winds must be planned. Reliability and technology risk cannot be directly measured, but the longer that a specific technology has been deployed, the more understood its behavior is and the lower the reliability risk is of unexpected behavior. No single ideal conductor, but rather a variety of advanced conductors meet the constraints of every application.

		History	Mechanical			Capacity	Efficiency/Line Losses		Unit Cost
Conductor Type	Conductor	Year Introduced	More Sag than ACSR	Rated Breaking Strength vs ACSR	Weight vs ACSR	Ampacity @ MOT Continuous vs ACSR	Resistance @ 20 C vs ACSR	Resistance @ MOT Continuous vs ACSR	Cost vs ACSR
ACSR	795 Drake	1900's	No	100%	100%	100%	100%	100%	100%
3M ACCR	795 T16	2002	No	102%	85%	158%	94%	129%	unknown
ACCC	1029 Drake	2003	No	129%	96%	165%	77%	99%	237%
ACSS/MA5	795 Drake	2007	Yes, @ MOT	103%	100%	174%	97%	146%	108%
ACCS/TW/C7	973 Everglades	2014	No	124%	92%	153%	82%	106%	unknown
ACCC/E3X	1029 Drake	2015	No	129%	97%	186%	77%	99%	237%
ACSS/TW/MA5	959 Suwanee	2015	Yes, @ MOT	123%	121%	191%	80%	121%	139%
ACSS/MA5/E3X	795 Drake	2015	Yes, @ MOT	103%	100%	199%	97%	146%	135%
ACSS/TW/MA5/E3X	959 Suwanee	2015	Yes, @ MOT	123%	121%	218%	80%	121%	152%
TS Conductor	1051 Sun M3	2021	No	134%	96%	168%	75%	96%	unknown

Table 2-6. Conductors listed by year introduced, high temperature sag profile, and other factors.

2.3.2.1 Conductor Capacity Comparison

With a need to rapidly expand the grid, having a higher conductor capacity is a positive attribute. While all high-temperature conductors increase capacity compared to ACSR, some have larger increases than others. Conductor capacity depends on conductor cross-sectional area, conductivity of material, rate of heat dissipation, and maximum operating temperature. ACSS conductors can withstand the highest operating temperatures without being damaged; therefore, these conductors can have the highest conductor capacity. For scenarios where structures can accommodate more sag or can be modified to allow for more sag, the highest capacity conductor option may be ACSS [22]. Capacity for both steel core and composite core conductors can be further increased with a high-emissivity coating, making ACCC with E3X the highest capacity low-sag conductor.

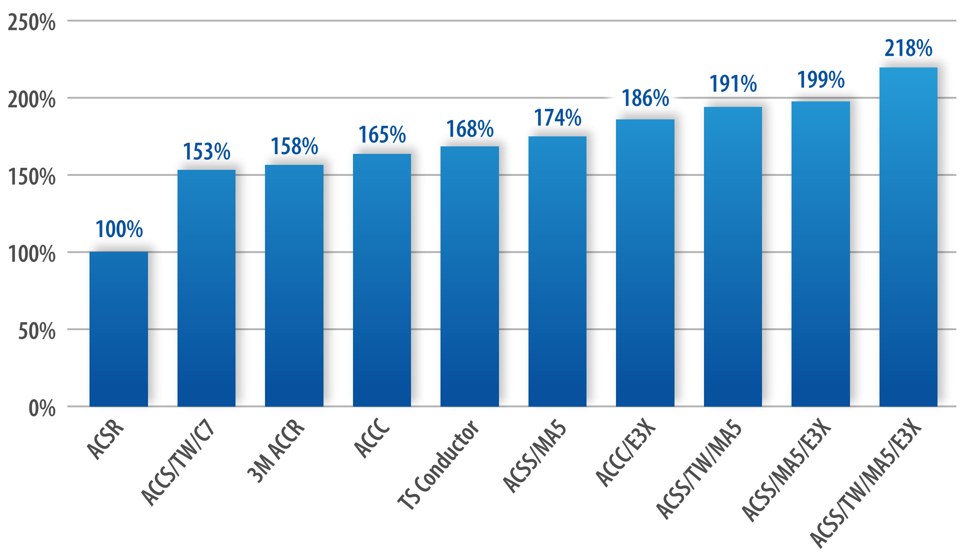

Figure 2-12. Maximum continuous ampacity of various conductors vs. ACSR.

2.3.2.2 Conductor Efficiency

Conductor Type	Conductor	DC Resistance @ 20 C Ω/kft	Maximum Operating Temp (MOT) C Continuous	AC Resistance @ MOT Ω/kft	Efficiency	
					Resistance @ 20 C vs ACSR	Resistance @MOT continuous vs ACSR
ACSR	795 Drake	0.0213	93	0.0277	1.00	1.00
ACSS/MA5	795 Drake	0.0207	250	0.0405	0.97	1.46
ACSS/MA5/E3X	795 Drake	0.0207	250	0.0405	0.97	1.46
ACSS/TW/MA5	959 Suwanee	0.0171	250	0.0336	0.80	1.21
ACSS/TW/MA5/E3X	959 Suwanee	0.0171	250	0.0336	0.80	1.21
ACCC	1029 Drake	0.0164	180	0.0275	0.77	0.99
ACCC/E3X	1029 Drake	0.0164	180	0.0275	0.77	0.99
TS Conductor	1051 Sun M3	0.0159	180	0.0266	0.75	0.96
ACCS/TW/C7	973 Everglades	0.0175	180	0.0294	0.82	1.06
3M ACCR	795 T16	0.0201	210	0.0357	0.94	1.29

Table 2-7. Conductor efficiency.

Not all of the electrical power that enters a transmission line is delivered as some of the energy is converted to heat as the current passes through. This wasted energy is a major component of line losses. The lower the resistance of a conductor, the lower the line losses and the more efficient the conductor. Resistance is influenced by the conductivity of the materials, the cross-sectional area of the conductive elements, and the operating temperature of the materials. Because operating temperature depends on conductor electrical loads and weather conditions the State of Montana has established a conductor efficiency standard based on the comparison conductor resistance at 20°C, which can represent day-to-day operating conditions [24]. The advanced conductors proposed all have efficiency improvements by this measure with the largest improvements being for TS Conductor and ACCC.

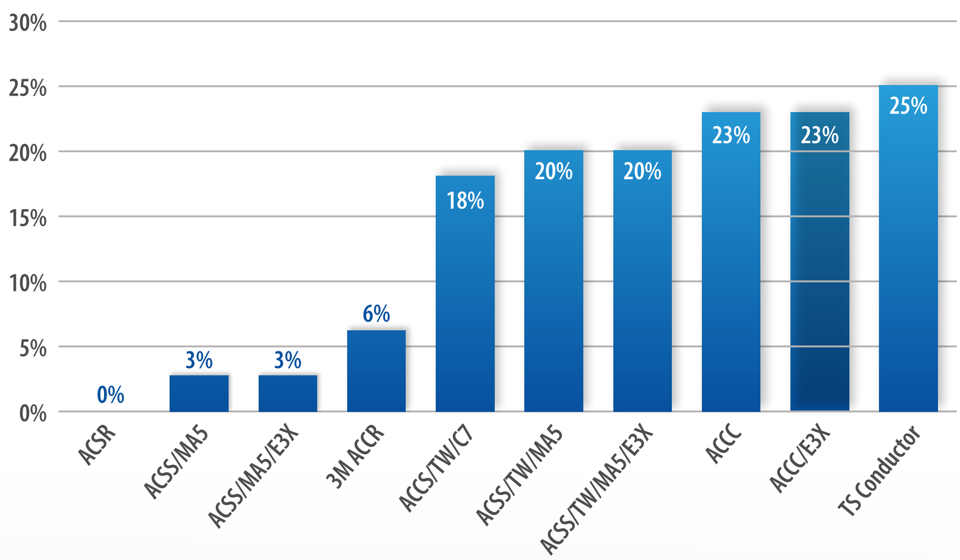

Figure 2-13. Efficiency of conductors at 20°C vs. ACSR.

CTC Global, Southwire, 3M, TS Conductor, and Prysmian were each asked to provide conductor data including DC Resistance at 20°C, which is the basis of comparison in Montana HB0729 [24], as well as the AC Resistance at the conductor's maximum continuous operating temperature which would be achieved when the conductor is at maximum capacity. Electrical losses are directly proportional to the electrical resistance of a conductor, thus the lower the resistance, the more efficient a conductor is. Two efficiency measures of each conductor were calculated by comparing electrical resistance for the advanced conductor with the electrical resistance of ACSR at 20 degrees C and at maximum conductor operating temperature. For example, ACSS/MA5 has a 3% lower electrical resistance than ACSR when both are operating at 20 °C and has a 46% higher resistance at maximum operating temperatures where the ACSS operates at 250 °C compared to the ACSR at 93°C. The table below summarizes the electrical resistance of each conductor at 20C and at MOT from which electrical resistance was calculated.

Resistance/efficiency should also be considered for conditions where conductors are fully electrically loaded, such as when the grid is under stress or operating in a contingency situation. Conductor resistance increases with temperature and so efficiency decreases the hotter a conductor operates. When conductor resistance/efficiency is compared at the maximum conductor operating temperature, there is still a marginal efficiency gain for ACCC and TS compared to ACSR while ACSS, ACCR, and C7 exhibit efficiency decreases. Because efficiency decreases with conductor temperature, the most efficient conductor of any type is a cool-operating conductor. This is one reason that many utilities chose to operate their advanced conductors below the highest possible operating temperature of a conductor. It is also the reason that heat dissipating coatings increase line efficiency.

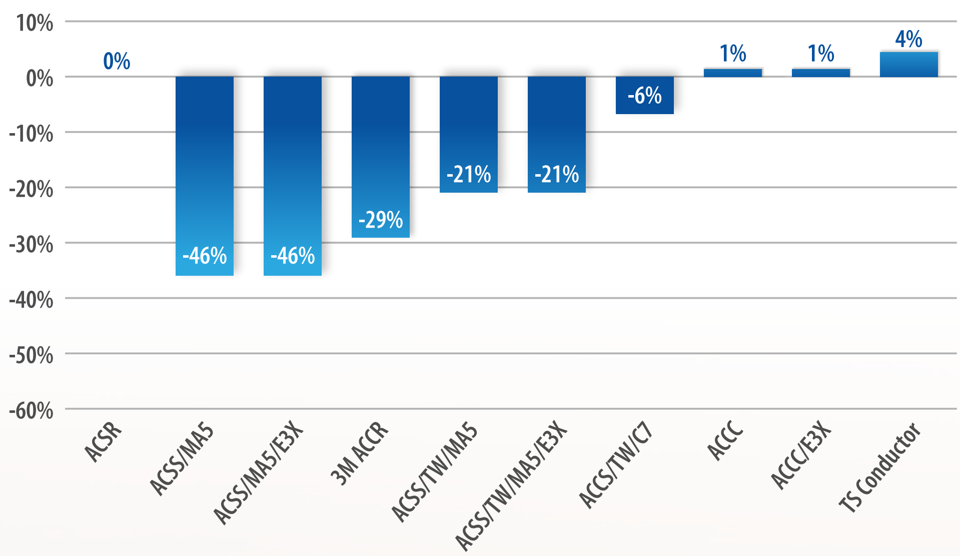

Figure 2-14. Efficiency change at the maximum continuous temperature of various conductors with respect to percentage deviation from ACSR's efficiency at max continuous operating temperature.

2.3.2.3 Conductor Cost

Budgetary conductor costs were provided by some but not all of the manufacturers. ACSR is the least expensive on a unit cost basis. ACSS conductor is a small increase while composite core conductors cost more. Structures make up a larger percentage of transmission line cost than conductor, so where existing structures can be preserved, the added cost of advanced conductors should be easily justified. Composite core conductors cost more than advanced ACSS conductors but can save money on projects because their lower sag, which can allow reconductoring of existing structures with fewer tower modifications.

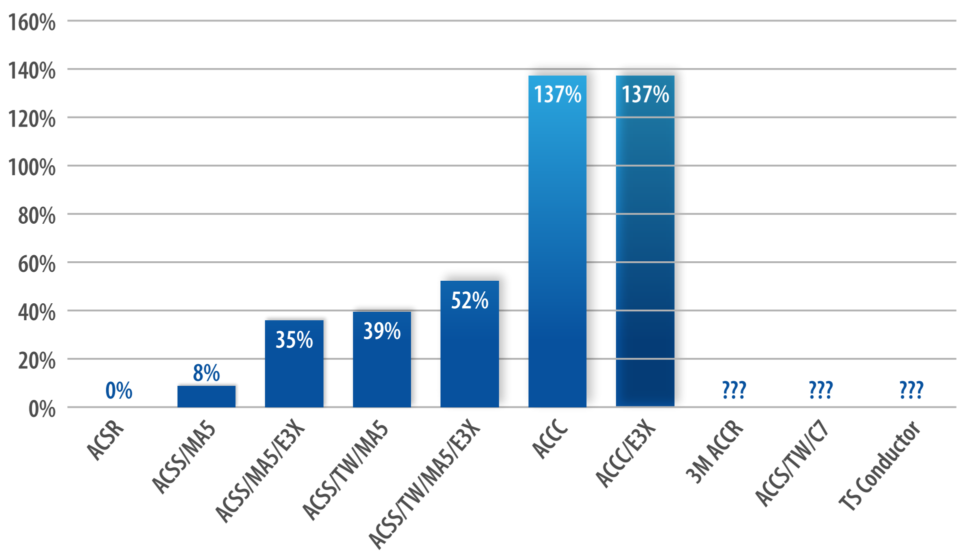

Figure 2-15. Conductor cost increase compared to 795 kcmil Drake ACSR, which is $13,866/mile.

2.3.3 Industry Concerns

Mainly, the utility industry is very conservative and desires to see proven results for new technologies before mass deployments. This is especially true for new transmission materials that are critical to the power grid, are difficult to replace, and must last for decades. To add to the skepticism, many utilities have experience with new cable and conductor technologies that did not meet their expectations for performance or life expectancy. For example, utilities, including Nebraska Public Power District and the Southern Company experienced a high rate of failure on over 2000 miles of a new type of overhead conductor that was developed and widely deployed in the 1970s called self-damping conductor [8]. Several common themes of concern for advanced conductors were observed across almost all the utility interviews: higher per unit cost, insufficient field deployment data, installation challenges, and conductor failures.

2.3.3.1 Cost

Advanced conductors with composite cores, such as ACCC, C7, TS, and ACCR, can be two to four times the unit cost of ACSR while ACSS conductors can be 10–50% higher. While higher cost was mentioned, it was also commonly acknowledged that the additional expense may be easily justifiable when existing structures can be preserved through reconductoring or on very long spans, such as river crossings. Appendix A has many examples of reconductoring and long-span river crossings where advanced conductors were used by utilities in spite of the higher cost. The cost of conductor material is less than 5% of the cost of a new transmission line.

2.3.3.2 Insufficient Field Deployment Data Regarding Advanced Conductors

ACSR has a 100-year performance history along with a set of established engineering practices that has evolved along the way based on operational experience. ACSS conductors now have over 50 years of deployment history and performance is also well understood. Most line design engineers and line workers have experience with these two types of conductors, which have proven themselves over many thousands of miles and decades. Appendix A shows that many of the deployments of composite core conductors are relatively small and do not fully reflect the varied operating conditions for a given utility. Even American Electric Power, the largest transmission utility in the U.S. who has built 447 circuit miles of transmission using ACCC conductor, has only used the product regionally in Texas. AEP has no reported deployments of ACCC in transmission systems in Ohio, Virginia, West Virginia, Kentucky, Indiana, Louisiana, or Tennessee where they also operate. Utilities may desire to build operational experience with a technology in each region in which they operate, as operating conditions, weather conditions and geography can all require different line designs.

Composite core conductors were introduced roughly 20 years ago. During that time, there have been several reported failures that are widely known in the industry. While technologies have evolved to address some of the early deficiencies in procedures and products, it was pointed out by multiple utilities that every new conductor technology and even every new size of conductor must be tested and installed to ensure that no unintended consequences occur from a product change. For example, CTC Global's original ACCC product was introduced in 2003, ACCC with ULS core in 2015, ACCC with aluminum zirconium alloy in 2018, and ACCC with the Infocore system in 2020 [6]. Conservative utilities ideally would like field deployment data from each new design iteration operating in their own system. For an industry tasked with reliability, utilities want to observe how new iterations on products perform to make sure new problems have not been introduced. As the technologies mature, industry standards will be agreed to for performance of both conductors and the accessories that connect lengths of conductor together. Of the advanced conductors, only ACCR and ACSS conductors are produced according to a published ASTM industry standard specific to that conductor technology. Standards for core manufacturing exist for ACCR, ACSS, and ACCC. There is no industry standard for testing of the splices and accessories for any of the advanced conductors, although the ANSI C119.7 standard for connectors for aluminum conductors operating at temperatures above 93°C is expected to be published in 2024.

2.3.3.3 Conductor Failures

The majority of utilities have utilized advanced conductors at least for limited projects. Many of the utilities seem to have done so for one-time applications, and at least two utilities have stated they will no longer install composite core conductors due to installation issues. Utilities have experienced failures of composite core conductors, which have been a setback for the industry. Manufacturers attribute the failures to improper installation techniques and offer onsite training for the installation teams; however, failures have continued to occur. Carbon and ceramic composites, while possessing a high-tensile strength and low-thermal expansion (i.e., low sag), are more brittle than the steel competition and cannot withstand a small bend radius compared to stranded steel, which can occur during installation without special precautions. Composite core cables require more delicate handling during installation compared to ACSR or ACSS to avoid any excessive bending and require special splicing hardware to mechanically and electrically join the connectors together, which can also be an area of failure. These splices involve connecting both the core and the surrounding aluminum of two conductors by using a hydraulic press that generates forces of up to 100 tons, often while workers are over 100 feet above ground. If not done properly, the hardware and press can crush the conductor components. Steel core conductors are not susceptible to failure from crushing although the connectors have been the source of failure on lines for both ACSR and ACSS lines where proper installation procedures are not followed. Any material can fail if installed improperly, but there is a perception that composite core materials are less forgiving if procedures are not followed.

Advanced composite core conductor technologies, hardware, and installation methods are evolving to address these problems with new technologies introduced in the last few years to. The technologies fall into two camps. One technology approach is to modify existing products and procedures to add a step to verify that conductors have been installed without damage. For example, the manufacturer of ACCR requires that field splices be tested with a portable x-ray machine to verify that connections have been done correctly. ACCC conductor introduced a technology called Infocore in 2020 that can check conductors for damage after installation by using embedded fiber optics in the carbon-fiber core to perform a continuity check. Both approaches require additional time and specialized equipment, which adds costs; however, these approaches help prevent the scenario where a conductor is damaged during installation or a splice is incorrectly performed, and then the line fails after the line is energized. The other approach is to develop more-robust conductor technology. TS Conductor advertises that a thick layer of aluminum encapsulation on the carbon-fiber core will make the conductor more rugged and less likely to fail during construction or from the environment. TS also advertises that the aluminum encapsulation allows

ACSR style connections to be used with no special precautions. C7 conductor also advertises that it is more robust because it uses seven individual carbon composite elements, which are stranded together to provide greater flexibility, reliability, and single-failure tolerance. These advertisements focus on the deficiencies and risk of other products, which further fuels industry concerns. Since there are not yet industry standards for most of these products, utilities are left to evaluate competing manufacturer claims. Idaho National Laboratory has launched a program to evaluate these new technologies and manufacturer claims on reliability and durability. Since most of the newest technology improvements have only been deployed in the U.S. on a limited basis, successful large-scale testing will help inform the industry on these product enhancements.

2.4 Transmission Line Applications and Conductors Used

A wide variety of transmission line types place different demands on the electrical conductors used. Line length, line voltage, and capacity required all must be considered along with conductor type. The following subsections detail several different types of transmission lines and the conductors commonly used today.

2.4.1 High Voltage Lines (500+ kV)

The largest benefit from added transmission capacity would come from new high-voltage long-distance or interregional transmission lines to connect the different geographies around the country. Interregional lines reduce consumer costs by allowing power to flow from low cost to high-cost regions and allow greater integration of renewables across diverse geographies. Interregional lines are also important for reliability and resiliency in extreme weather events, allowing power to flow from other areas, which might have available generation capacity. After years of delay, there are some major long-distance projects finally in construction. PacifiCorp's Energy Gateway is being built using an ACSR standard and the SunZia project and Transwest Express have broken ground.

2.4.1.1 Conductor Needs for Interregional Transmission

Lines that are longer than 30–50 miles are typically not limited by conductor temperature. Instead, the capacity is limited by the physics of transmitting power over long distances like voltage drop and line stability. Interregional transmission lines that stretch for hundreds of miles eliminate the need or even the possibility of operating conductors at the high temperature offered by advanced conductors. Additionally, at higher voltages, larger conductors than are strictly needed for capacity reasons are typically used to prevent corona discharge. Overhead lines use surrounding air and the distance between the conductor and the ground as the insulation system to safely keep electricity in the conductors. At high voltages, electrical fields around the conductor can cause ionization of the air in a process called corona discharge. This phenomenon causes both higher line losses and audible crackling noises from the ground. To prevent this from happening, high-voltage lines must use multiple conductors per phase in a bundle to reduce electrical stresses and to better distribute the electrical fields in the air (see Figure 2-16). These bundled configurations are often sized with more aluminum than would be needed were thermal capacity alone the main consideration. Since a high-temperature operation is not required and larger conductors than are needed for capacity are already in use, new lines with voltages at 500 kV, have little benefit from high-temperature operation. ACSR is commonly used for new construction of lines over 345 kV, including interregional lines (Table 2-8).

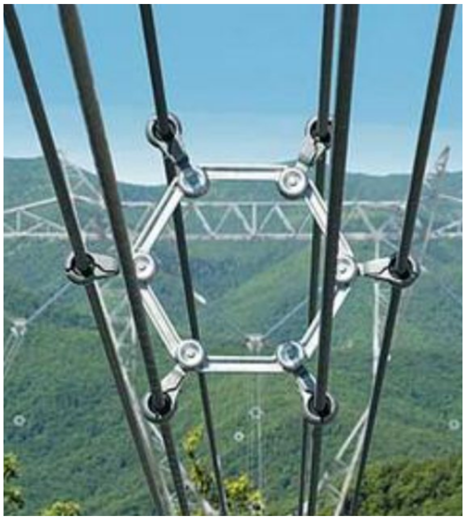

Figure 2-16. Example of bundled conductor to reduce corona effect on transmission power lines.

Project	Voltage Level	Line Length	Capacity	Budget	Conductor
Energy Gateway	500 kV AC	2,300 miles	2,000 MW	$8 billion	ACSR
Transwest Express	+/-600 KV HVDC	720 miles	3,000 MW	$3 billion	ACSR
Sunzia	+/-525 KV HVDC	550 miles	3,500 MW	$10 billion	ACSR
Grain Belt Express	+/-600 kV HVDC	800 miles	5,000 MW	$7 Billion	ACSR/E3X

Table 2-8. Examples of long-distance high-voltage transmission .

There are applications where advanced conductors are used for interregional lines. For example, an 800 mile ± 600 kV HVDC Grain Belt Express project which will interconnect with multiple balancing authorities (SPP, MISO, AECI, and PJM) has specified ACSR/E3X as advanced conductor to economically accommodate the losses and power flows of the 5000 MW line. The use of the ACSR/E3X reduces peak losses and maximum operating temperature by approximately 5% and 15%, respectively, compared with standard ACSR. Grain Belt Express has also specified composite core conductor for low sag properties on the spans which exceed 3500 feet across the Missouri and Mississippi rivers.

2.4.2 New-Construction Regional Lines

The largest regional transmission expansion in the U.S. in recent decades were the Texas Competitive Renewable Energy Zone (CREZ) projects that were nearly 3600 miles of new 345-kV lines, proactively constructed to enable 18,500 MW of renewable generation to be integrated onto the grid (Table 2-9). These lines were mostly greenfield builds, and transmission line developers had to compete with each other for the best solutions and the most value. Seven different project developers were awarded the right-to-construct lines based on performance and cost. The preferred design for the CREZ lines was to use a bundle of two ACSS conductors per phase. Composite-core conductors were used for specific sections, such as long spans and river crossings. For regional lines, ACSS is widely deployed because of its high capacity and relatively low costs. While ACSS does sag more than composite-core conductors at high temperatures, new towers can be built taller to accommodate the additional sag. While the vast majority of the line miles were constructed with ACSS, at least one short section crossing the Red River used ACCR conductor, as profiled in Section 2.5.2.

Project	Voltage Level	Line Length	Capacity	Budget	Conductor
CREZ	345 kV	3,600 miles	18,500 MW	$7 billion	ACSS/TW

Table 2-9. Texas competitive renewable energy zone (CREZ) project details

Figure 2-17. A double circuit rebuild for the New Your Energy Solution project with the 115 kV circuit on the left side of the tower and the 345 kV circuit on the right side of the tower.

2.4.3 Building Regional Lines on Existing Rights of Way

Acquiring new rights of way for construction of regional lines is very difficult, especially in more densely populated areas. In lieu of acquiring new routes, utilities and project developers are increasingly rebuilding higher capacity lines on existing routes. In some cases, new transmission line cables are even buried underground or under water to eliminate objections of stakeholders, although at a much higher cost than overhead lines. New York State is a good example of creative solutions to increase transmission capacity in a densely populated area. A series of projects are being undertaken to bring power from upstate New York into New York City. A notable project is the "New York Energy Solution," which was built by a consortium of utilities who were able to piece together a route, primarily using land that was previously used for lower capacity 115-kV lines. The project removed the existing 1930's era structures and rebuilt double circuit structures with both a 115-kV and a 345-kV line on the same route, using high-capacity ACSS conductors. A short portion of the line used existing 345-kV structures, which were reconductored with higher capacity ACSS with E3X. Voltage increases are attractive because of much larger increases in capacity than simply reconductoring, although a detriment of higher voltage lines is a wider right of way (RoW) requirement. For example, rebuilding a 115-kV line to 345 kV with high-temperature conductors can achieve a 12-fold increase in capacity or higher, but could increase the required right-of-way width from 100 to 150 feet. Lines can also be rebuilt with double circuits on the same land, which allows the existing voltage line to continue to operate while a new circuit is added. The width of right-of-way that is owned or can be acquired for is another design constraint that must be considered when evaluating line design alternatives for every project.

Project	Voltage Level	Line Length	Capacity	Budget	Conductor
NY	345 kV	54.5	1,000 MW	$530 million	ACSS

Table 2-10. The New Your Energy Solution project details.

2.4.4 Reconductoring

Often when new capacity is needed quickly, existing structures can remain intact while new, higher capacity conductors replace existing conductors using reconductoring. By reusing a large amount of the infrastructure, project costs are reduced and project timelines are accelerated. Reconductoring is the largest use case for composite core advanced conductors. Existing ACSR conductors can be removed from service and replaced with a composite core conductor of equivalent diameter, weight, tension, and sag but with roughly double the capacity. When projects are being considered for reconductoring, the most important factor is often the state of the existing structures. If structures have reached their end of life with rusted metal or rotten wood, they may need to be replaced as part of any project upgrade. Structures may also need to be replaced for resilience purposes, for example to withstand higher wind loading from a hurricane, ice loading from a winter storm, or damage from wildfire. Where structures are being rebuilt, line designers may choose to build back with stronger or taller towers that can accommodate a wider range of conductors. Often a reconductoring project is a hybrid approach, where some portions of existing structures are modified to improve their condition and where some portions remain intact.

2.5 Success Stories with Advanced Conductors

In addition to the ACSS examples above, the following subsections are project profiles where different advanced conductors were used. Advanced conductor technologies have been successfully deployed by many utilities, and with these success stories are important data points to show the applications where they have been successfully used and the value that advanced conductors can bring to the transmission grid.

Additionally, Appendix A of this report profiles over 40 utilities and their adoption of advanced conductors.

2.5.1 ACCC

Back in 2009, Nevada Energy needed to reconductor 13 miles of transmission lines that ran from Reno to Carson City, Nevada. The original transmission line was built in 1952 and was composed of wood H-frame towers strung with 00 copper wire, which was only good up to 350 Amps. Nevada Energy needed to increase that ampacity to 1000 Amps, but the existing structures would need to be replaced to support the weight of larger ACSR cables. To complicate matters, the cities, originally outside of the transmission lines, had grown to surround the transmission lines, which complicated permitting and would likely require the lines to be buried underground, further driving up costs.

Looking at alternatives, NV Energy found that an ACCC linnet-type conductor would allow for the existing structures to be used, achieve the 1000 ampacity, and classify the project as maintenance project, which does not require new permitting. Additional line men training was needed on proper handling of the conductor and the cable manufactures sent out inspectors to oversee the work. They were able to complete the project for $4M, which was half their estimated cost of a complete rebuild. The only remaining question was how well the conductor would perform compared to the legacy ACSR and the copper wire in which NV Energy was familiar.

In 2010, a 100-mph windstorm blew through the area and completely uprooted many of the wood structures. Guy wires placed on the structures prevented them from completely toppling over, but still presented extra strain on the ACCC cables. Nevada Energy was able to repair all of the towers and continued using the existing ACCC cables with no issues. Then, in January 2012, a fire storm swept through the area burning down 27 wood structures in their system, four of which belonged to the ACCC span from Reno to Carson City. After inspecting the damage, the cables seemed to be unharmed despite the fires completely burning up the wood structures. The utility rebuilt the wood structures and continued to use the original ACCC to this day (confirmed though utility interviews). Since these early wins, NV Energy continued to install additional ACCC all throughout their system.

2.5.2 ACCR Enables 2,400 ft River Crossing for Public Utility Commission of Texas

In 2008, the Public Utility Commission of Texas (PUCT) sought to enable more wind energy development into their grid by upgrading existing transmission lines through the CREZ projects profiled above. They developed a $7 billion program aimed to adding 3600 miles of new transmission and a variety of 345-kV assets. On one 235-mile project, a large challenge was a line crossing over the Red River. The distance between towers placed on either side of the river amounted to 2,400 ft. Historically, for crossings such as this, wooden structures were placed in the river to reduce span lengths; however, environmental regulations would present a much greater challenge to receive approvals to build in the river. The main ACSS conductor used for the project would result in tower heights (over 200 ft.) that required permits from the Federal Aviation Administration (FAA), as well as visible lighting.

Engineering design teams turned to advanced conductors as a solution to keep line-sag tolerances high enough off the ground while keeping tower heights to less than 200 ft. The study considered ACSS with an HS285 high-strength steel core (ACSS/HS285), ACCC, and ACCR as options. Studies showed the ACSS/HS285 conductor resulted to a tower height of 205 ft, just above the requirement. Because the size of ACCC conductor (Falcon) needed was not available, one size smaller of the conductor (Lapwing) was used and resulted in tower heights of 210 ft. The ACCR conductor was able to achieve the height within tolerance of 185 ft. Custom tower and conductor fittings were used to tolerate higher cable tensions needed to make the cable crossing a success.

2.5.3 TS

In 2022, Montana-Dakota Utilities needed to upgrade 60 miles of transmission line that ran from Bismark to Napoleon to accommodate additional power generation from a nearby wind farm developments. Normally this type of project would require a costly and time consuming rebuild of the transmission line. The new aluminum-encapsulated carbon-core TS conductor allowed for triple the ampacity of cables with similar diameter to the existing conductor and a 40% cost savings compared to rebuilding the structures with a larger ACSR line. The project was able to be completed 1 year ahead of schedule and save $1.8 million of the original proposed budget.

2.5.4 C7

In 2014, CenterPoint Energy (CPE) completed the first installment of different types of C7 conductor. Normally, CPE used ACSR on lines that did not require high loading and ACSS on lines that required higher loading. However, C7 has a much lower sag than ACSS and its demonstration of their system would enable more options to meet customer needs in the future. Additionally, CPE's territory runs though many rural, industrial, and big cities, which can make permitting for new structures a challenge. HTLS conductors are one solution to overcoming permitting barriers.

While carbon composite cores are stronger than steel, steel core cables can tolerate deformation and continue to perform unlike carbon composite cables. Carbon fibers do not show many signs of deformation before they break. C7's design attempts to incorporate multiple carbon-fiber strands in a cable to prevent a single point of failure. CPE decided to test Southwire's new C7 conductor on a short 2.6 mile and 3.3-mile 138-kV lines marked to be upgraded in a rural industrial area. ACCR/TW/C7 and ACCS/TW/C7 conductors were both selected to replace the existing twin-bundle aluminum conductor aluminum reinforced conductors.

During linemen training, cable splices, dead ends, and other hardware were put to the test against IEEE 1138 requirements. All tests passed. Additionally, no new equipment was needed beyond what was typically used for ACSS installation. Installations went smoothly. Compared to the ACAR, the ACCS/TW/C7 cable possessed the same sag under normal conditions and 10% less sag at the rated temperature (180°C). The ACCR/TW/C7 had a slightly lower sag under normal conditions compared to the ACAR, but only 30% of the ACAR's sag at rated temperatures. CPE allows ACSS conductors to run at 200°C under emergency conditions and plans to increase that rating to 225°C for the C7 cables. This will give their system more flexibility under demanding conductions. The C7 conductor will also provide options to not replace existing structures, which can account for two-thirds of the cost for line rebuilds.

2.5.5 E3X

In 2006, the 138-kV transmission line from Apollo-East to Richardson substations was identified to be upgraded from the original ACSR conductor to a larger ACSS conductor due to growing system constraints within Oncor's system. The project was originally set to be completed in 2009, but construction for the project was delayed by over a decade until all the designs were completed and permitting approvals were received in 2017. The new transmission tower was ordered immediately due to their long lead times. Meanwhile, a new planning study found the load growth in the area was occurring much faster than originally predicted. This was due to recent requests to build new data centers that would rely on that transmission line. A request was made to increase the line ampacity by 16.7% to 3000 amps per conductor used (i.e., per phase on the transmission line). However, many of the new poles already ordered could not support the additional weight from a larger size cable and ordering new cables would greatly increase the cost and further delay the project. The system was designed to operate the ACSS cables at a maximum of 180°C to minimize resistive losses (ACSS can operate at temperatures up to 250°C). Engineering analysis of the system showed that maximum cable operating temperature could be increased to 200°C while still maintaining acceptable sag tolerances. However, this alone would not be enough to increase the ampacity to meet the additional 431 amps needed.

Oncor was actively evaluating E3X as an option for their system lines. Due to the criticality of transmission systems, utilities are hesitant to adopt new technology lest unforeseen issue compromise the systems reliability.

The tests that Oncor witnessed at Oakridge National Laboratory (ORNL) made them comfortable enough to test it out on their own system. In considering it for the Apollo-East Richardson line, they found the E3X coating allowed them to operate at 200°C while achieving ampacities typically observed at 250°C operating temperatures. The extra ampacity enhancement from the E3X coating enabled them to meet the new specifications asked for by planning, while minimally raising project costs with new line hardware rated to tolerate the extra 20°C on the line. During construction the ACSS cable was pulled through a 90-degree bend with the coating on it. After inspection, the coating had survived the bend and remained intact. To further verify the performance of the line and ensure the coating's integrity, Oncor installed DLR technology to actively monitor the line's performance. One year's worth of monitoring the live line showed results consistent with tests done at ORNL and by the manufacturer. Oncor will continue to monitor the lines and evaluate the performance of the E3X coating to gain further confidence in its performance, which could lead to further applications elsewhere in the system.

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SECTION 3: U.S. Regulatory Environment Assessment

3.1 Background

An ideal scenario for grid planners and transmission operators would allow needed transmission lines to be built rapidly, and the biggest challenges would be related to the construction of physical infrastructure. Instead, the permitting process typically takes longer than actual construction and many project never even break ground. Because it is so difficult to build new transmission, creative solutions are needed to add capacity to existing routes and existing lines. Advanced conductors can help project developers thread the needle through the permitting process by reducing the physical footprint of new projects and by enabling reconductoring of existing structures.

Transmission owning utilities in the U.S. are heavily regulated. There are several different types of transmission owning utilities that each operate within a different framework of federal, state, and local laws and regulations. Policies, laws, and regulations influence every aspect of investment and operation of electric utilities including safety, reliability, cost, and the mix of resources used to generate electricity. Insufficient transmission capacity is a threat to the reliability of the U.S. electrical system, impedes integration of renewable energy, and limits access to the lowest cost sources of energy [1]. A major reason for lack of transmission investment is the difficulty in permitting and building new lines due to federal, state, and local regulations. Reconductoring existing transmission structures with advanced conductors can help fill part of the gap as a lower cost, easier to permit, and a faster way to add capacity to the grid. Generally speaking, any law, regulation, or policy that makes it more difficult to build new transmission lines will favor reconductoring with advanced conductors, since reconductoring may be the only viable option in a reasonable timeframe. Building new lines can take well over 10 years to permit before construction even starts. Reconductoring can receive approvals and permits much faster since in many cases the towers are not modified and the line's appearance and footprint do not change. Reconductoring may even be possible with routine maintenance permits in some jurisdictions. Constuction is also faster for reconductoring since existing towers remain in place and can reduce project timelines by years.

Only a few regulations directly address conductor selection, as this level of granularity has historically been left up to system planners and line design engineers and is only one of many factors that impact performance and cost of transmission grid infrastructure. Policies, laws, and regulations that influence conductor selection should be considered in the context of policy objectives, reliability, and infrastructure costs for transmission infrastructure in general.

The United States electrical grid is made up of generation, transmission and distribution systems that are owned and operated by almost 3000 interconnected utilities [2] including 500 distinct transmission owners [3] that build and maintain the electrical infrastructure to deliver power from where it is generated to where it is consumed. Electric utility ownership structures vary and transmission providers can be investor owned, publicly owned, or member owned cooperatives [2]. Publicly owned utilities can be governed by municipal, state, or federal agencies. The regulatory environment for utilities differs based on utility type and location. Financial motivations of utilities also differ based on ownership structure. This varied environment and diverse set of utilities make it difficult to establish consensus on ownership, cost allocation, and location of new transmission lines, especially where they pass through a variety of public and private lands, different jurisdictions, and different planning regions. These challenging conditions can both contribute to and detract from adoption and deployment of advanced conductors.

3.2 Transmission Needed vs. Transmission Built

The U.S. Department of Energy has cited independent studies suggesting that transmission capacity needs to expand by 60% by 2030 and triple by 2050 [4].

In spite of the clear need, proposed transmission projects can languish for years before construction begins and permitting new lines is becoming ever more difficult. Local, state, and federal motivations are often at odds, land owner opposition can be fierce and is well organized, and immediate environmental impacts for major infrastructure projects must be considered [5].

The lack of new transmission capacity has caused long wait times for renewable projects trying to interconnect to the grid, which is impeding deployment of carbon-free generation. According to the REPEAT project at Princeton University, "Over 80% of the potential emissions reductions delivered by IRA in 2030 are lost if transmission expansion is constrained to 1%/year," which is the current rate of expansion [6].

Regional and local transmission capacity must be expanded as well. Fortunately, over 600,000 miles of transmission lines already exist in the U.S. and much of this can be potentially be upgraded for higher capacity. Upgrading existing routes is an excellent application for advanced conductors and can be the fastest and lowest cost way to offer sizable capacity increase.

3.3 Factors Influencing the Use of Advanced Conductors

3.3.1 Siting and Permitting Difficulty

The U.S. power grid is constantly evolving to accommodate different types of power generation and to serve the changing needs of electricity consuming customers. The transition of the power supply from fossil fuel-based generation to renewables is placing new demands on transmission infrastructure. New lines are needed, but are difficult to permit and construct. Transmission projects have been impeded by reasons as varied as environmental regulations, private property rights, defense department considerations, and cultural and archeological heritage and by general opposition to new infrastructure [7-11].

While the difficulty in building new transmission lines complicates efforts to modernize the electric grid, it actually supports the use of advanced conductors, which can be used as a way to work around the constraints on building new lines that society has imposed. Advanced conductors are ideally suited for increasing capacity on existing rights of way, which is an important way to streamline construction of new capacity. Policies, laws, and regulations that makes it more difficult to permit and build new transmission lines will encourage transmission owners to seek alternatives that can be permitted and constructed in a shorter time frame. Advanced conductors can carry more energy in a smaller footprint and so are ideally suited to increase capacity on existing rights-of-way and even on existing transmissions structures.

3.3.2 Load Growth

Load growth is a major driver for use of advanced conductors, as more transmission is needed to deliver power from where it is generated to where it is consumed. This will further tax the existing grid and require ever more transmission capacity. The traditional approach for transmission expansion was to build more lines or larger lines as load growth demanded more power. Today, when transmission expansion is limited by the ability to permit new lines, existing corridors become an attractive alternative to delivering capacity for the additional power flow. The combination of difficulty in constructing new lines and increased customer demand result in increased demand for high-capacity advanced conductors for both rebuilding of existing lines and for reconductoring of existing structures. When load growth is particularly fast, capacity on even relatively new lines can be exhausted. Newer transmission structures are likely to be in good condition and meet more modern standards for strength and resiliency in extreme weather. These newer lines are ideal candidates for reconductoring with advanced conductors as a way to reduce project cost, speed capacity expansion, and preserve existing investments. Rapid load growth from electrification of transportation, heating, and cooking and from large industrial users, such as data centers and resource extraction industries, has created demand for increased load on relatively new lines. Policies that encourage further electrification of the economy, as well as U.S. manufacturing load growth, will help stimulate demand for advanced conductors.

3.3.3 Sag/Clearance Safety Buffers

Overhead lines must be separated from the ground, vegetation, and any objects below by a sufficient distance to avoid dangerous conditions, line failure, and wildfires. The 2003 Northeast Blackout caused loss of power across much of the northeast U.S. and Canada, resulted in 11 deaths and cost the economy an estimated $6 billion [12]. The initial trigger for the cascading blackout was insufficient clearance between a transmission line and the vegetation growing below. In the aftermath, the North American Electric Reliability Corporation (NERC) issued a requirement that lines be surveyed, line clearance maintained, and that any encroachments or low sagging lines be remedied. In 2017, a tragedy involving low hanging power lines resulted in the Texas William Thomas Heath Power Line Safety Act (P0762), which dictated more stringent inspection of transmission lines and remediation of safety problems [13-14]. Line sag and minimum clearance to ground is treated as a reliability concern and is regulated by NERC. Because of the advanced conductor's ability to sag less than traditional conductors, reconductoring with advanced conductors has been widely used to reduce sag to remediate safety issues on existing lines. NERC now mandates annual inspections of transmission lines for sag/clearance violations and utilities can be fined up to $1 million per day for violating these reliability requirements. Utilities spend between $6 billion and $8 billion annually on compliance [15].

These regulations to enforce sag and safety clearances appear to be working to improve reliability. After years of steady declines, the years 2020 and 2021 had zero transmission line outages from NERC FAC-003 sag/clearance violations. If sag clearance level requirements were to be increased even further by NERC, it would require remediation of much of the existing 600,000 miles of transmission lines to increase these safety buffers, with advanced composite core conductors likely to play a large role. Any regulations that enforce more stringent sag/clearance requirements will increase demand for advanced conductors.

3.3.4 Transmission Line Costs

Costs, cost recovery, and cost allocation are major topics of utility regulations. Initial costs, operating cost, and asset life expectancy, and costs to the economy from outages all must be considered along with the difficult question of how costs are allocated among customers. Clearly there is a tradeoff between lowest initial costs and operating costs over the life of the line from line losses and maintenance. The lowest cost initial design may have lower efficiency, reduced reliability, and less capacity for future expansion. It is notable how small of a portion of the cost of a new transmission line is actually attributed to conductor material. The draft MISO 2022 Transmission Cost Estimation Guide details the different components of the costs of new transmission line construction [16]. The cost estimate for a new single-circuit 230-kV transmission line in Iowa is $2 million per mile. It can be assumed that costs are much higher in more densely populated areas. The cost impacts of using different conductor types can be calculated using the data in this guide. If one "Drake" sized conductor is used per phase of the 230-kV line, the ACSR conductor material would be 1.3% of the total cost, ACSS conductor would be 1.4%, and ACCC conductor would be 4.8%. Given the difficulty of permitting and building new transmission lines, the large growth in capacity needed, and the small percentage of the total cost of new construction attributed to conductor material, not installing the highest capacity, most efficient conductor can be a wasted opportunity. By spending between 0.1% to 3.5% more for initial project cost, line capacity can be dramatically increased while gains in efficiency could easily pay for the added costs in a short period of time. The same guide includes costs for reconductoring and rebuilding. Rebuilding is the process of removing an existing line from service and constructing a new line in its place without the need for a new RoW. To rebuild a 230 kV line, the cost is estimated to be $1.7 million per mile while reconductoring is only 20% of that cost at $340,000 per mile. When advanced conductors allow a line to be reconductored versus rebuilt, the premium for a more expensive conductor is easily justified. Regulators and policy makers should encourage utilities to reconductor where possible to save cost versus rebuilding, while also considering that when building new lines, a low single-digit price increase for advanced conductors that can double the transmission line capacity for future growth may be a prudent decision [16]. It is however worth noting that the choice of conductor can have significant impacts on the tower construction, so this analysis should not be construed as definitive.

3.3.5 Laws, Regulations or Mandates that Could Impact Use of Advanced Conductors

3.3.5.1 Permitting Reform

The most outstanding use case for advanced conductors is to upgrade existing RoWs and reconductor existing lines. While capacity could be increased more by rebuilding with higher voltage lines or higher capacity, lower-loss conductors, reconductoring is often the only viable option and it is an important tool for grid upgrades given the difficultly of permitting and building new lines. Permitting reform for transmission lines could accelerate the deployment of high-voltage interregional and regional lines, which could reduce the need for reconductoring shorter lines. The DOE is undertaking steps to help facilitate interregional and interstate transmission with the following programs [17].

3.3.5.1.1 FEDERAL PERMITTING COORDINATION

The U.S. Department of Energy is working to increase the coordination and communication among federal agencies with authority to site electric transmission facilities, including the Coordinated Interagency Transmission Authorizations and Permits (CITAP) Program to accelerate federal reviews.

3.3.5.1.2 PERMITTING AND SITING ASSISTANCE

The Transmission Siting and Development (TSED) grant program has announced a funding opportunity with up to $300 million in grants to strengthen the siting and permitting processes to help overcome state and local opposition to projects that expand transmission capacity.

3.3.5.1.3 PUBLIC PRIVATE PARTNERSHIPS

The Bipartisan Infrastructure Law includes authority for the Secretary of Energy to enter into public-private partnerships for the development of transmission facilities. The administrators of two of DOE's Power Marketing Authorities, Southwestern Power Administration (SWPA) and Western Area Power Administration (WAPA), similarly have authority to enter into public private-partnerships for the development of transmission facilities specifically in their jurisdictions. In this way, DOE can help facilitate transmission development in areas where state or local permitting requirements would otherwise make a project difficult or impossible to complete [18].

3.3.5.1.4 DESIGNATION OF NATIONAL INTEREST ELECTRIC TRANSMISSION CORRIDORS (NIETCS)

To expedite and streamline the permitting and siting of electric transmission infrastructure, the Federal Power Act authorizes the Secretary of Energy to designate any geographic area as a National Interest Electric Transmission Corridor (NIETC) if the Secretary finds that current or anticipated future electric energy transmission capacity constraints or congestion are adversely affecting consumers.

Designation of NIETCs can assist in focusing commercial facilitation, signal opportunities for beneficial development to transmission planning entities, and unlock siting and permitting tools for transmission projects in identified areas. A NIETC designation can unlock federal financing tools, specifically public-private partnerships through the Transmission Facilitation Program under the Bipartisan Infrastructure Law (BIL) and the Transmission Facility Financing Loan Program under the Inflation Reduction Act (IRA). A NIETC designation also allows the Federal Energy Regulatory Commission (FERC) to grant permits for the siting of transmission lines within the NIETC under circumstances where state siting authorities do not have authority to site the line, have not acted on an application to site the line for over 1 year, or have denied an application.

Each of these programs can facilitate expansion of interregional and interstate transmission lines, which would benefit from the use of advanced conductors.

3.3.5.1.5 FERC ORDER NO. 2023 IMPROVEMENTS TO GENERATOR INTERCONNECTION PROCEDURES AND AGREEMENTS

Addendum: *Following first publication of this report, FERC has issued an update to this order which defines "advanced conductors" as follows:*

"…we further clarify that advanced conductors are advanced relative to conventional aluminum conductor steel reinforced conductors and include, but are not limited to, superconducting cables, advanced composite conductors, high temperature low-sag conductors, fiber optic temperature sensing conductors, and advanced overhead conductors."

This report uses the definition as presented in the Executive Summary, however all future works should take care to use the FERC definition going forward.

FERC Order 2023 took effect on November 6, 2023, as a way to streamline the interconnection process for new generation sources. The order requires consideration of alternative transmission technologies when interconnection studies for new generation sources are performed, including advanced conductors. Other alternative transmission technologies listed in the order are static synchronous compensators, static VAR compensators, advanced power flow control devices, transmission switching, synchronous condensers, voltage source converters, and tower lifting. The order requires "transmission providers to include…an explanation of the results of the evaluation of the enumerated alternative transmission technologies for feasibility, cost, and time savings as an alternative to traditional network upgrade" [19].

This explicit acknowledgement of advanced conductors by FERC along with the requirement that they be considered will ensure that the benefits of advanced conductors are not overlooked by utilities under the FERC jurisdiction.

3.3.5.1.6 MONTANA HOUSE BILL 0729

Montana is unique in the nation as having passed a law encouraging the use of efficient advanced conductors. The Montana law considers efficiency as the key parameter for advanced conductors, and is written in a way to acknowledge the efficiency benefits for conductors, such as ACCC or ACSS, with high aluminum density from trapezoidal-shaped aluminum strands [20].

3.3.6 Summary

Reconductoring is estimated to be only 20% of the cost of decommissioning and rebuilding an existing line and can save years of construction and permitting time while adding capacity and increasing efficiency. Regulators and policy makers should encourage use of advanced conductors for reconductoring of existing lines as well as for new lines, where the incremental cost to improve line performance using advanced conductors should be considered. Building a new line with advanced conductors versus ACSR can double the line capacity for less than 5% added project cost, which would be a prudent approach given expected increases in load growth from electrification of the economy and the interconnection of new renewable energy to the grid. There are efforts by the DOE to streamline permitting of transmission lines, which will enable more interstate and interregional transmission lines to be built. Montana has passed a law encouraging the use of more-efficient advanced conductors, and the FERC is now requiring utilities to consider the use of advanced conductors as part of their evaluation of every generation interconnection request. Advanced conductors are a key tool in the toolbox for all transmission utilities.

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SECTION 4: State of Manufacturing

4.1 Introduction

Up to this point, this report has described the advanced conductor technologies being deployed to increase the capacity of the power system, as well as their various applications. The laws and regulations that affect the adoption of these technologies within the U.S. has also been discussed. However, whether or not a given technology is suitable for a particular application is not the only factor that determines if it can be used. One of the primary considerations for utilities when planning T&D projects is the availability of materials. The importance of the power system to national security motivates utilities to seek domestic suppliers for their conductors and conductor accessories. Furthermore, the effects of the Covid-19 pandemic have made the power industry wary of the vulnerabilities of international supply chains. However, as this section will show, relying exclusively on domestic manufacturing is not always an option.

This report presents the case that deploying advanced conductors may serve to alleviate some of the congestion problems in the modern power system and enable greater integration of renewable energy sources to meet emissions goals. However, these efforts may be stymied if the described technologies are not available in sufficient quantities to meet the demands of planned projects. To address this concern, this section assesses the production capabilities of ACT manufacturers. First, the various components of the conductor supply chain are described including the raw materials used in conductor manufacturing. Second, the manufacturing process for each technology (excluding proprietary information) is presented. Next, the current procedures for disposing of old conductors is discussed. Based on this information, an assessment is given regarding the overall manufacturing capabilities of domestic conductor suppliers. Finally, this section concludes by presenting a summary of the opportunities and challenges in the domestic conductor manufacturing industry.

4.2 Supply Chain Segments

The industry surrounding the manufacturing of electrical transmission lines, shown in Figure 4-1, includes raw material suppliers, engineered material suppliers, component suppliers, conductor manufacturers, end-users, and recyclers. The diagram focuses on direct materials that become part of the end products. Less emphasis has been placed on indirect materials used in the manufacturing process but are not part of the final conductor. Data for this section was obtained through stakeholder engagement and literature. Key direct raw materials sorted by use quantity include aluminum, iron, coke, crude oil, silicon, zinc, nickel, boron, manganese, molybdenum, phosphorous, chromium, zirconium, vanadium, copper, tungsten, titanium, niobium, bentonite clay, dolomite, kaolin, limestone, sodium, wood, and graphite. Most of these raw materials go into the production of the core. Some indirect materials, such as hydrogen chloride (HCl), beeswax, and grease, are used in the manufacturing process. The most used engineered material for stranding is aluminum 1350 (mostly used in the U.S., Canada, and European countries) or 1370 (used in other countries) [13], which is hard drawn or annealed depending on conductor type and requirements. Besides aluminum 1350/1370, aluminum-zirconium strands are also used. Conductor cores are diverse, including steel core (aluminum-clad steel, galvanized steel with zinc coating or zinc-aluminum coating, or high-strength steel with zinc coating), composite core (made mostly from carbon fiber that are encapsulated in S2-glass fiber, encapsulated in aluminum, or capped with a polymer), and aluminum metal matrix core, also known as ceramic core. Ceramic (E3X) or polymer coating is also an engineered material that can be used for coating any conductor type to enhance its surface emissivity [14].

Global manufacturers of conductors, by alphabetical order, include Apar Industries, Cabcon India Limited, CTC Global, Galaxy Transmissions Pvt. Ltd, General Cable, Gupta Power, Hanhe Cable, Hengtong, Hindustan Urban Infrastructure Limited, K M Cables & Conductors, LS Cable, 3M, Nexans, Prysmian Group, Saudi Cable, Southwire, Sterlite Power, Sumitomo Electric Industries, Tongda Cable, Tropical Cable & Conductor Ltd. (TCCL), and ZMS Cable [15, 16]. The leading manufactures in the United States are CTC Global, 3M, Prysmian, Southwire, and TS Conductors. While most of these manufacturers only focus on one supply chain segment, a few are vertically integrated and build their core in-house, such as TS Conductor. U.S. manufacturers of steel core include Conex, Bekaert, and Heico. 3M is a manufacturer of ceramic core. And Tokyo Rope, CTC Global, and TS Conductor manufacture carbon-fiber cores.

Utility companies are the end-users of conductors. Once conductors reach their end-of-life, materials will be scrapped and recycled by metal recyclers. Because the lifetime of conductors is 50 years or longer [17], most conductors installed since 2000 have not reached their end-of-life and gone through recycling. While metal core conductors can be recycled easily, less is known about the actual recycling practice of carbon-based cores. Although recyclability of carbon-based cores has little impact on utilities' adoption, recyclability is important for reducing supply chain risks in the future.

4.3 Manufacturing Process

Before discussing the manufacturing process of conductors, it is important to define some of the terminology used by industry. A rod is a cast metal having a diameter between 5 mm and 50 mm, depending on metal types, wound into rolls, coils, or reels. At the next step of the value chain, this rod is drawn into smaller wires. When multiple wires are stranded together, they are called a strand or cable.

Conductors have at least two parts, and potentially up to three: a core, conductor material, and an optional emissivity coating. The core provides strength to decrease the amount of conductor sag. The conducting material transfers the electrons. Emissivity is related to the ability of a material to dissipate heat to the environment. Therefore, emissivity coatings are designed to help decrease the temperature of the line which increases the current capacity.

The main distinction among various conductors is the core and stranding materials. Various types of core and stranding materials are shown in Table 4-1. ACSS and ACSR steel cores can vary depending on the steel composition (coated steel or high-strength steel). These steel strands can be clad or coated with aluminum. Composite core conductor types are Aluminum Conductor Composite Reinforced (ACCR), Aluminum Conductor Composite Core (ACCC), TS, and C7. ACCR is a 3M product that has a ceramic aluminum matrix core. ACCC is a CTC Global product that has a carbon-fiber core encapsulated in glass fibers. TS is a TS Conductor product that has a carbon-fiber core encapsulated in aluminum. The C7 conductor has a carbon-fiber thermoset core.

Conductor Type	Core	Strand
Aluminum Conductor Steel Reinforced (ACSR)	Aluminum-clad steel or galvanized steel, or high-strength steel with zinc or zinc-aluminum coating	Hard-drawn aluminum
Aluminum Conductor Steel Supported (ACSS)	Aluminum-clad steel or galvanized steel, or high-strength steel with zinc or zinc-aluminum coating	Annealed aluminum
Aluminum Conductor Composite Core (ACCC)	Carbon composite core encapsulated in fiber glass	Annealed aluminum or aluminum – zirconium
Aluminum Conductor Composite Reinforced (ACCR)	Ceramic (aluminum oxide in aluminum matrix)	Aluminum – zirconium
TS Conductor	Carbon composite core encapsulated in aluminum	Annealed aluminum
C7 Conductor	Carbon fiber composite core capped with a polymer	Annealed aluminum or aluminum – zirconium

Table 4-1 Core and stranding materials for major conductor types.

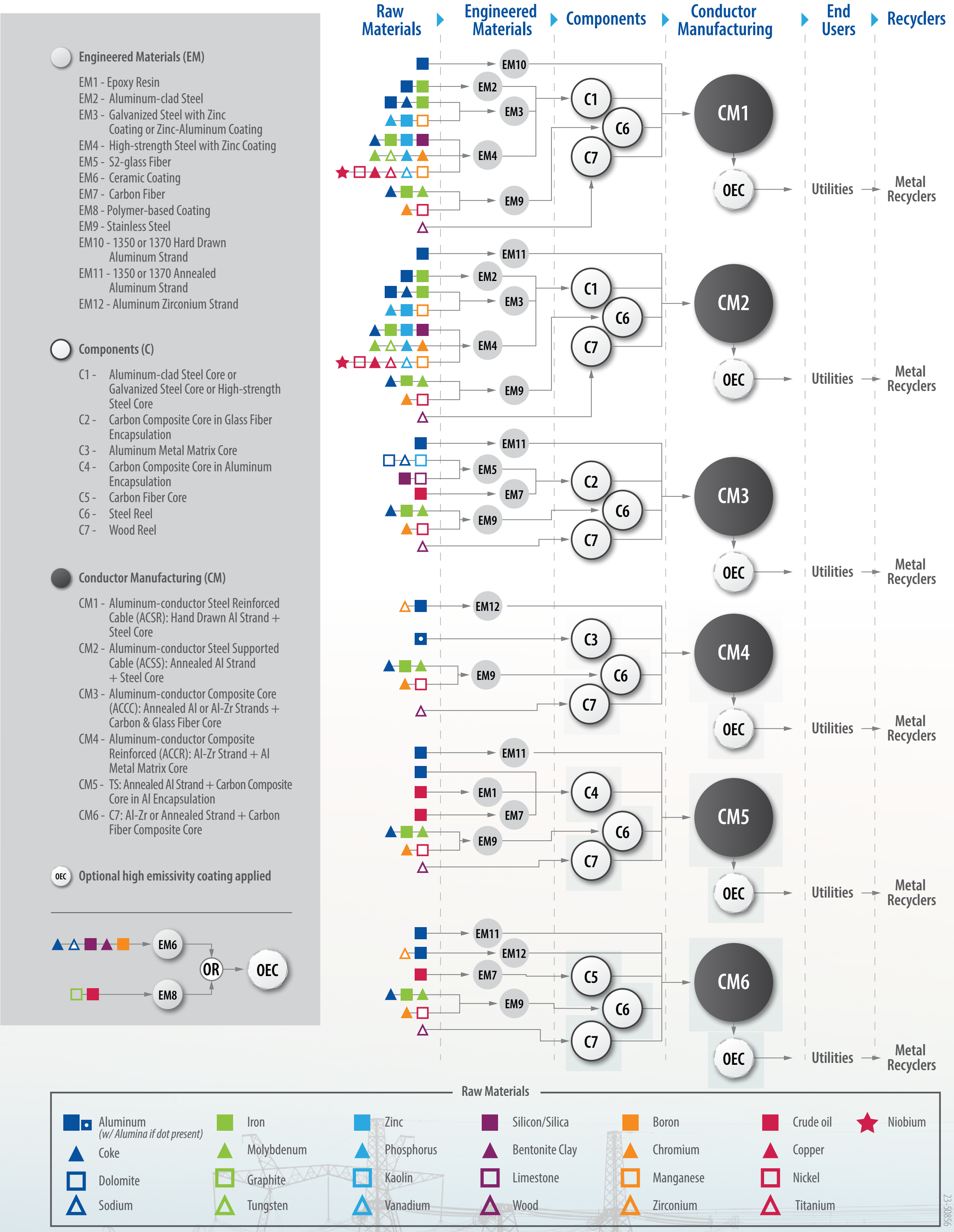


Figure 4-1 Supply chain segments of the conductor industry.

In the U.S., several different types of aluminum are used, including aluminum 1350 and aluminum-zirconium alloy. 6000-series high-strength aluminum alloy alloys have lower conductivity, but a higher annealing temperature than pure aluminum. The choice of one material or the other depends on the specific technology and application, and represents a trade-off between capacity and efficiency. Aluminum 1350 is 99.5% pure aluminum. Aluminum-zirconium contains 99% aluminum, 0.2–0.4% zirconium, 0.3–0.5% iron, and 0.01–0.2% tin [18]. The aluminum 1350 can either be hard drawn (or cold working, denoted as 1350-O-temper) or annealed (denoted as aluminum 1350-H19). Aluminum-zirconium conductors have hard-draw strands that can withstand temperatures of 210°C before they are annealed. There is a tradeoff between the two processing methods. The hard-drawn method increases the strength of the aluminum but decreases its conductivity. Annealing decreases the strength but increases its conductivity. These strands come in round or trapezoid cross-sectional shapes.

4.3.1 Conductor Manufacturing

Input materials for conductor manufacturing include aluminum rods, cores, steel/wooden reels, and other indirect materials, such as a corrugated plastic protective export guard, lubricant, and greases. An aluminum rod that comes in a large coil (weighing ~6,000 pounds) is drawn into wire using wire drawing dies. This wire drawing process includes various stages, under tension and using grease, to shape the aluminum into the right size and form. The wire might be further heat treated or annealed at 343°C (MatWeb, n.d.) to increase ductility and conductivity depending on the conductor type. The wire is then stranded around a core to make a cable or conductor. Depending on conductor type, if there is an additional layer, the stranded conductor goes through another stranding step [19]. Depending on the wire, it might get heat treated again (e.g., at 300°C) [20] to relieve all the stresses put onto the conductor during this stranding process.

Optional high-emissivity coating, such as ceramic coating E3X or polymer coating, can be applied in-house or in the field. Both types of high-emissivity coating can be applied to any conductor type. For in-house polymer coating, the conductor is guided continuously through gas burners in an oxidizing atmosphere at 100–150°C [21]. It then goes through a heated pipe to keep the outer layer between 60°C and 100°C, preferably 80°C. The coating is applied by paint spray guns and heated by a dryer. The coating thickness ranges from 5 to 15 microns, preferably 10 microns. For E3X coating, the surface of the conductor needs to be cleaned with chemicals, pressurized air, hot water, brush cleaning, heat treatment, sand blasting, ultrasound, deglaring, or plasma treatment [22]. The preferred cleaning method is sand blasting. Coating is applied using two or more spray guns, while the conductor's overhead temperature is maintained between 10°C and 90°C, depending on conductor material. The coating thickness is less than 200 microns, preferably 100 microns and ideally less than 30 microns. The coated conductor is dried by evaporation at room temperature or at elevated temperatures up to 325°C. After the coating is dry, the conductor is wound on steel or wooden reels. These reels are ready to be shipped to utilities for onsite installation.

4.3.2 Core Manufacturing

There are five different core types, as shown in Table 4-1: (1) steel core, including aluminum-clad steel, zinc/aluminum-coated carbon steel, or zinc/aluminum-coated high-strength steel; (2) ceramic-fiber aluminum matrix core; (3) carbon-fiber encapsulated in glass fibers with a thermoset epoxy; (4) carbon fiber with a thermoset epoxy encapsulated in aluminum; and (5) carbon-fiber thermoplastic composite. TS builds their core in-house. ACSS and ACSR cores are manufactured by several companies, including Conex, Bekaert, or Heico. ACCC core is manufactured by CTC Global, ACCR core is manufactured by 3M, and C7 is manufactured by Tokyo Rope.

4.3.2.1 Aluminum-clad Steel Core (ACSR/AW and ACSS/AW)

Aluminum-clad steel wire is produced mainly through two methods: a continuous extrusion process and a powder-metallurgical process. In the extrusion process, a carbon-steel rod is drawn through a series of dies that are drawn down until it reaches the desired diameter, such as 0.125 in. In one such process, the steel-metal wire is plated with nickel or copper through electroplating, having a thickness of ~0.0004 in. [23]. The plated wire is then cleaned thoroughly either by chemical or abrasive methods. An aluminum slug heated to approximately 1000°F is extruded onto the wire under a pressure of at least 50,000 psi at uniform speed. The wire is then drawn to the desired thickness, often with annealing between draws to allow recrystallization of the aluminum. The preferred lubricant used for drawing is 95% Society of Automotive Engineers (SAE) 10 motor oil and 5% tallow derived from animal fat [23]. The second method for aluminum cladding is applying high-purity aluminum powder around a high-strength steel rod [24]. The wire is heated to a temperature of approximately 1100°F in an induction furnace and rolled through. After cladding, the wire will go through one more set of dies and will be stranded together. The stranding machine places one piece of the aluminum-clad steel wire in the center and wraps multiple wires around the middle wire in the same direction. This serves as a core for ACSR/Alumoweld (AW) or ACSS/AW.

4.3.2.2 Galvanized Steel Core (ACSR and ACSS)

A carbon steel that comes in a 5.5 to 12 mm rod is first cleaned by either placing it in an acid bath or sending it through a cutter to remove the outer most layer that was applied to protect the rod during shipment. A lubricant is then applied to the rod before sending it to drawing dies. During this drawing process, the rod cross-section is decreased and its tensile strength is increased. The wire is cleaned with hydrochloric acid and rinsed. As soon as the wire is dried, it is fully immersed in flux, run through another furnace for drying, and then through the hot-dip galvanizing process to prevent corrosion. The steel wire is stranded together using a stranding machine, like the stranding process for the ACSR/AW and ACSS/AW. This will serve as the core for ACSR and ACSS.

The steel used in steel core was originally based on carbon and manganese blends with other residual elements being kept low. High-strength steel has a higher content of silicon and chromium to improve high-temperature strength [25]. Over time, other alloying elements, such as vanadium and boron, have been introduced. An example of high-strength steel contains, by weight, 0.4–1.2% carbon, ≤2% silicon, ≤2% manganese, ≤0.1% aluminum, ≤5% chromium, ≤1% of copper, ≤1% of nickel, ≤0.5% of vanadium, ≤0.2% of niobium, ≤0.2% of titanium and ≤0.2% of zirconium [25]. The higher the strength requirement, the more alloying elements are needed to increase the strength. As strength increases, processability decreases, resulting in more waste and lower yields. Developments in strength over time have relied on technological improvements in the blending and processing of steel to decrease waste and increase yields at higher strengths. Ultra-high strength steels, such as Southwire's trade name HS285, are also now being used for ACSS.

4.3.2.3 Carbon Fiber Encapsulated in Glass Fiber Core (ACCC)

This core is made from carbon fibers encapsulated in glass fibers. Aerospace-grade carbon fibers are pulled through a resin wet-out system. The resin acts as an adhesive that increases the strength and keeps the core together. The excess resin is removed before the core goes through a heated die between 200°F and 240°F [26]. This first die helps catalyze the resin and maintain the resin matrix. After leaving the first die at room temperature, S2-glass fiber coating (or wrapping) is applied to the outer surface of carbon fibers in the gap between the first and the second die. This gap is between 4 in. and 20 in. S2-glass fiber is different from conventional E-glass fiber because it does not contain boron, which can react with moisture to form acid. The acid could cause an early failure of the conductor. The wrapped fibers are pulled into a pultrusion equipment operating between 220°F and 400°F, corresponding to the first and second end of the second die, respectively. After leaving the pultrusion equipment, the core goes through multiple carding plates to cure and compact the composite core together [26].

4.3.2.4 Alumina Fiber Core (ACCR)

Alumina fibers, under the trade name of NEXTEL 610, are collimated into a circular bundle. The bundle is heat-cleaned by a furnace at 1000°C, then passed through an aluminum entrance tube into a vacuum chamber [27]. After leaving the vacuum chamber, the fibers are exposed to a molten aluminum bath at 726°C. To enhance the infiltration of molten aluminum into the fiber bundle, ultrasonic vibration was used. The infiltrated fibers leave the crucible through a silicon nitride die, and nitrogen gas is used to cool them [27]. The wire, having a diameter between 2.5 mm and 3.5 mm, is wound onto a spool and ready to be used as a core for ACCR conductor.

4.3.2.5 Carbon-Fiber Encapsulated in Aluminum (TS)

The TS core is made from carbon fibers encapsulated in aluminum. Carbon fibers undergo a pultrusion process to become fiber-reinforced composite material. The resin can be applied to carbon fibers by either a hot resin bath or pouring it over the fibers. The resin is heated between 225°C and 490°C to ensure its liquid form. The resin acts like an adhesive to increase fiber strength and keeps the core material together. To have the right pressure on the die, the pull force of the carbon core must be between 150 to 800 kg. The fibers run through a set of dies above the melting temperature of the resin to remove excess resin and ensure consistent fiber size. The twisted fibers or wire are slowly cooled to cure. Next, the wire is fed to a conforming equipment to electrically encapsulate a layer of aluminum around the composite. The conforming step softens (or melts) and extrudes aluminum, resulting in a layer at least 0.15 mm thick [28]. The aluminum is chilled to a temperature of ~100°C under 60 seconds to minimize strength degradation [28]. Because TS produces the core in-house, this core is ready to be stranded by additional layers of aluminum wire and wound onto a reel to become a conductor.

4.3.2.6 Carbon Fiber Thermoplastic Composite Core (C7)

The core is made from carbon fiber (accounting for 25–80 wt% of the core) and thermoplastic composite (accounting for 20–75 wt% of the core) [29]. Two or more continuous carbon ribbons are formed using an extrusion device. Each ribbon contains four to 20 rovings. Each roving contains 1,000 to 100,000 individual fibers. A thermoplastic polymer such as polyphenylene sulfide (PPS) melted at 200°C to 500°C is used to impregnate the fibers. The ribbons are then fed into a pultrusion line, heated in an infrared oven, and passed to a consolidation die. The die compresses the ribbons together and form an initial shape of a rod (preform) at 177°C. The preform is then cooled with ambient air at 1 psi. The next step is to pass the preform to nip rollers and to a calibration die at 140°C or up to 275°C for final shaping [29]. When leaving the die, the rod is capped with a melted thermoplastic polymer and cooled with an air stream. Examples of thermoplastic polymers are polyetherether ketone (under the trade name of PEEK), PPS 320, and Nylon 66. Seven of these rods will be stranded together to create the core for C7.

4.3.3 Engineered Material Manufacturing

This section discusses the manufacturing of engineered materials used in core manufacturing, cable manufacturing, and high-emissivity coating applications.

4.3.3.1 Aluminum for Conductor Material

As mentioned in Section 4.2, the two most-used types of aluminum are aluminum and aluminum-zirconium. Aluminum 1350 contains 99.5% aluminum while aluminum-zirconium contains 99% aluminum and other alloying elements such as zirconium, iron, and tin [18]. There are two processing methods for aluminum 1350, including hard drawn or annealed. Aluminum-zirconium wire is hard drawn to withstand temperatures of 210°C before the strands are annealed. There is a tradeoff between the two processing methods. The hard-drawn method increases the strength of the aluminum but decreases its conductivity, while annealing decreases the strength but increases its conductivity. There are many sources for both types of aluminum; however, the majority of aluminum used in the U.S. is sourced from North America [30].

4.3.3.1.1 HARD-DRAWN ALUMINUM

Ingots or cast bars of aluminum 1350 or similar aluminum alloy undergo a continuous casting process to form a rod. This rod is hot coiled at 300– 400°C [20]. The rod is drawn into wire using conventional techniques. The cross-section of this wire can be trapezoid or circle. This wire is ready to be stranded around a core to produce a cable.

4.3.3.1.2 ANNEALED ALUMINUM

Similar to hard-drawn aluminum, the process starts from ingots to wire drawing. The hard-drawn wire can withstand temperatures of 210°C. To increase higher temperature tolerance, the wire is annealed by heating to 343°C [31] in the case of aluminum wire or 280°C in the case of aluminum-zirconium wire for 1 hour [18]. This annealing process helps reset the crystalline grain structure, which reduces the stress on the wire for further processing.

4.3.3.2 Steel Rod

Steel rods are used for ACSR and ACSS type conductors. Most of the steel within the U.S, comes from recycled materials. Other alloying elements like carbon and manganese are added to steel to produce the required strength and ductility. Once the desired composition is reached, the liquid alloy is formed into billets or bars. After the billets are cooled and become solid, they can be hot rolled similar to aluminum to form rods. The rods are quenched until the core temperature reaches 850°C. The rod is air cooled, rolled onto a coil, and sent to the steel core manufacturers [32].

4.3.3.3 Carbon Fiber

Three companies manufacture different carbon-fiber cores: CTC Global (ACCC conductor), Southwire (C7 conductor), and TS Conductor (TS conductor). These companies all use the same aerospace grade carbon-fiber wire produced by the polyacrylonitrile (PAN) process. To begin the process, an acrylic or modacrylic polymer, polyols, and stabilizer mixture is created under heat of 140–170°C and agitation for 20 minutes. Then the mixture is cooled for 1 hour before going through an extruder between 200°C and 300°C to obtain the desired polymer shape [33]. The polymer is stretched to a wire at 175°C until the desired dimension is achieved (e.g., 30-micron filament). The fiber is pre-oxidized at 350°C and carbonized in an argon atmosphere at 1500°C [33].

4.3.3.4 Conductor Coating

There are two different types of conductor coating that are meant to increase amp capability: ceramic (E3X from Prysmian) and polymer (by Lumpi-Berdorf). These coatings have a very high-emission coefficient, between 0.6 and 0.9, that makes it hold more current at a lower temperature. The E3X is mostly utilized within the U.S. and Lumpi-Berdorf is mostly used in Europe. E3X coating has been used on ACSR, ACSS, ACCC, ACCR, and AAAC and it can add 0.3% more weight on each line it is applied to. E3X coating of overhead conductors is made from about 5–30% of an inorganic adhesive, 45–92% of a filler, 2–20% of one or more emissivity agents, and 1–5% of a stabilizer. It contains 13–15% sodium silicate, 69% SiO_2, 14–16% of boron carbide, and 1–2% boron nitride, and 1–1.5% bentonite all dry weight, then adding 36–38% of deionized water to complete the mixture [22]. The Lumpi-Berdorf product is made of polyurethane embedded in pigments, such as graphite [21]. These conductor coatings can be applied in-house, as described in Section 4.2.1.

4.4 End-of-Life Management

End-of-life management of conductors refers to the processing of conductors after being decommissioned. Utilities typically contract with local scrap yards or recyclers to have conductors recycled. Recycling of conductors comes down to recycling of engineered materials or raw materials contained in conductors. Metals like aluminum and steel can easily be melted to become input materials for rod manufacturing. On the other hand, actual recycling of composite material is less known because composite core is a newer technology and few to none have reached their end-of-life. Some core manufacturers are investigating ways to recycle them.

In addition to end-of-life recycling, materials are being recycled at different value chain steps. Core and conductor manufacturers contract metal recyclers to take care of their scrap materials. Remanufacturing is also done for defective conductors, but this activity is dependent on the nature of the defect. Returnable steel reels are returned to manufacturers after installation for inspection, refurbished, and reuse.

4.5 U.S. Manufacturing Capability and Supply Chain Risk Assessment

4.5.1 U.S. Manufacturing Capability

The U.S. has an annual production capability of and access to over 73,000 miles of conductor for the six conductor types considered in this section. The distinction of purely domestic production is challenging because most companies have international manufacturing facilities. The distinction of production capability by conductor type is also difficult because most companies manufacture multiple products using the same production line to diversify risks. Highly adopted conductors such as ACSR, ACSS, and ACCC have higher capability to meet demand than newer conductors like TS, ACCR, or C7. These companies can expand their output to meet growing demand; however, there are uncertainties related to demand projections as well as market adoption for new conductor types. In addition, a conductor is a grid component with a long lifetime of 50 years or more. Fast expansion of facilities could lead to large unused production potential once all the upgrades and new installations are complete. As a result, manufacturers are expanding capabilities very slowly or are satisfied with their current output levels. Even so, they are facing some supply chain issues related to several input materials and workforce.

4.5.2 Supply Chain Risk Assessment

4.5.2.1 Methodology

Risks are typically evaluated as a multiplication of disruption event probability and their impacts on the supply chain, such as supply shortages or prolonged lead time. However, for this report only qualitative methods were used for data gathering. Questionnaires were sent to major core and conductor manufacturers to gain insights into seven areas, including: (1) input materials; (2) manufacturing process; (3) equipment capital; (4) workforce;

(5) logistics; (6) after-sales services; and (7) recycling and remanufacturing. Regarding input materials, the focus is major input materials, their supply chain concerns, and major suppliers. For manufacturing, manufacturing bottlenecks, equipment capital, production capacity, and product testing are of interest. The workforce questions focus on specialized skills, labor availability, general demographics, a company's training program, and workforce concerns. Logistic questions aim at transportation challenges, use of specialized equipment for handling and transporting, and logistic providers for both forward and reverse logistics. After-sales services are related to warranty service, facility used, and onsite installation. Recycling and remanufacturing questions try to understand their recycling or remanufacturing practices. Results are aggregated by manufacturing segments (e.g., core and conductor). A color-coding assessment for supply chain impacts was applied for each area of manufacturing with a general guideline as follows:

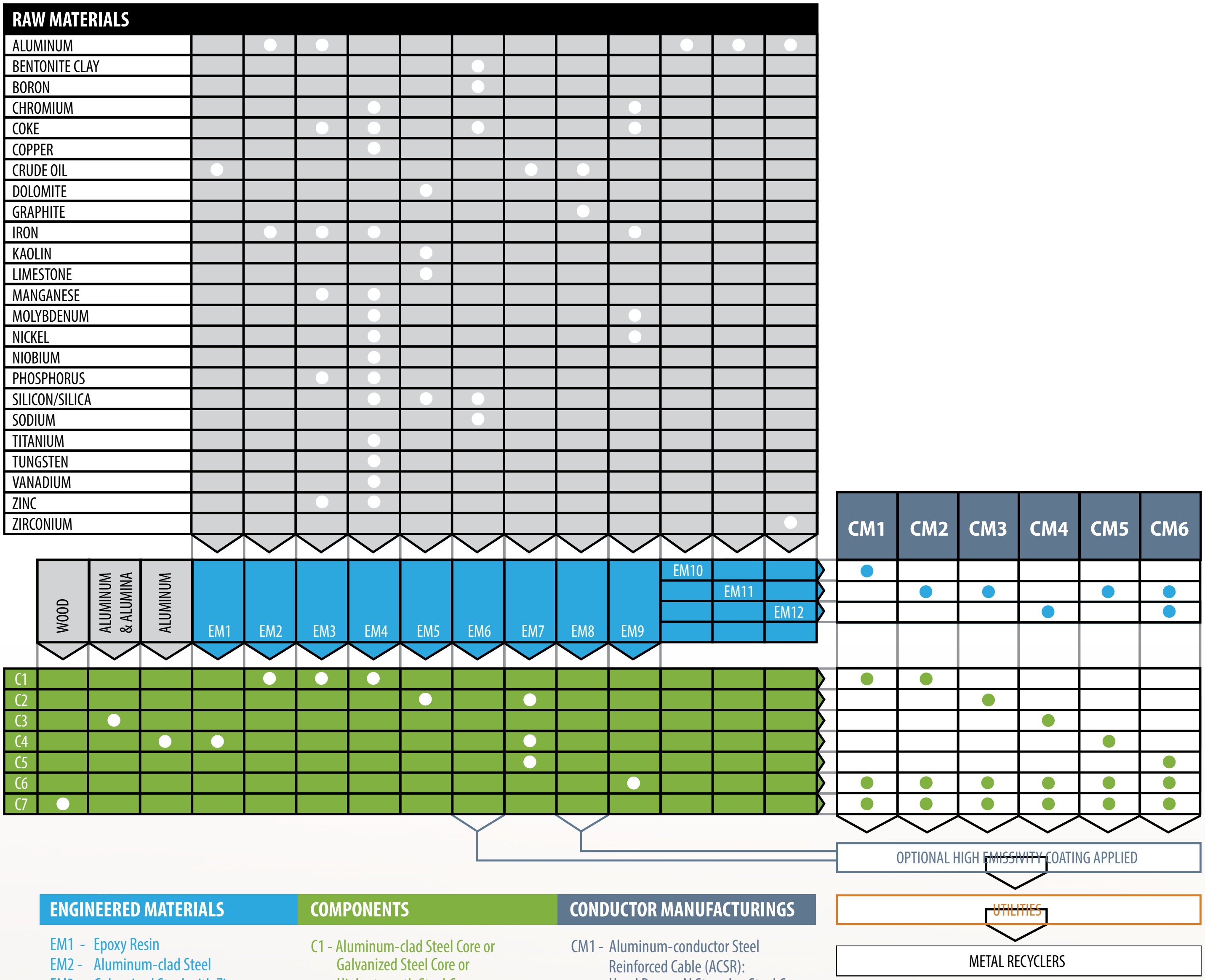
- Green: no supply chain impacts
- Yellow: minor supply chain impacts
- Orange: major supply chain impacts
- Red: significant supply chain impacts

For the probability of disruptions, the color coding is applied as follows:

- Green: very low likelihood
- Yellow: low likelihood
- Orange: medium likelihood
- Red: high likelihood

After the color code is assigned, a numerical value is also assigned to the color code for both the impact and probability: green – 1, yellow – 2, orange – 3, red – 4. The risk score for each category is the multiplication of these two scores, ranging from 1 to 16. The aggregated risk score is the sum of risk scores of all seven categories, ranging from 7 to 112. This risk score is converted back to color code for qualitative representation:

- Green: 7 – 33 points
- Yellow: 34 – 60 points
- Orange: 61 – 87 points
- Red: 88 – 112 points



ENGINEERED MATERIALS

EM1 - Epoxy Resin
EM2 - Aluminum-clad Steel
EM3 - Galvanized Steel with Zinc Coating or Zinc-Aluminum Coating
EM4 - High-strength Steel with Zinc Coating
EM5 - S2-glass Fiber
EM6 - Ceramic Coating
EM7 - Carbon Fiber
EM8 - Polymer-based Coating
EM9 - Stainless Steel
EM10 - 1350 or 1370 Hard Drawn Aluminum Strand
EM11 - 1350 or 1370 Annealed Aluminum Strand
EM12 - Aluminum Zirconium Strand

COMPONENTS

C1 - Aluminum-clad Steel Core or Galvanized Steel Core or High-strength Steel Core
C2 - Carbon Composite Core in Glass Fiber Encapsulation
C3 - Aluminum Metal Matrix Core
C4 - Carbon Composite Core in Aluminum Encapsulation
C5 - Carbon Fiber Core
C6 - Steel Reel
C7 - Wood Reel

CONDUCTOR MANUFACTURINGS

CM1 - Aluminum-conductor Steel Reinforced Cable (ACSR): Hand Drawn Al Strand + Steel Core
CM2 - Aluminum-conductor Steel Supported Cable (ACSS): Annealed Al Strand + Steel Core
CM3 - Aluminum-conductor Composite Core (ACCC): Annealed Al or Al-Zr Strands + Carbon & Glass Fiber Core
CM4 - Aluminum-conductor Composite Reinforced (ACCR): Al-Zr Strand + Al Metal Matrix Core
CM5 - TS: Annealed Al Strand + Carbon Composite Core in Al Encapsulation
CM6 - C7: Al-Zr or Annealed Strand + Carbon Fiber Composite Core

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Figure 4-2. Supply chain segments of the conductor industry with a focus on materials.

4.5.2.1.1 INPUT MATERIAL IMPACT ASSESSMENT METHODOLOGY

The vulnerability of each technology to disruptions in input material supply is described by Figure 4-2. Because most supply of input material was impacted by Covid-19, the assessment was done on materials that have supply chain concerns independent from the pandemic. Material supply chain risks come from three main factors: (1) source, (2) composition complexity, and (3) use volume (or demanded quantity). Regarding sourcing, domestic supply would have lower risk than importing from neighboring countries, which would have lower risk than importing from overseas. Next, a material that has more ingredients would have higher risk than a material with fewer ingredients. For example, high-strength steel is an engineered material with the most ingredients, causing a high-risk potential. Last, use volume/quantity reflects the demand for a material. Also shown in Figure 4-2, aluminum is used in five engineered materials and two components. A supply chain disruption to aluminum could impact these value chain segments, which will eventually affect the production of all six conductor types.

Supply chain impact thresholds are evaluated as follows:

- Green: low low impact (e.g., <25% import reliance)
- Yellow: low to average impact (e.g., 25% - 50% import reliance)
- Orange: average to high impact (e.g., 50% - 75% import reliance)
- Red: high impact (e.g., >75% import reliance)

4.5.2.1.2 WORKFORCE IMPACT ASSESSMENT

The workforce risk is measured in two aspects: (1) availability of workers; and(2) their skill levels. Supply chain impact thresholds are evaluated as follows:

- Green: very high availability and requires no to minimal training from the company
- Yellow: high availability and requires minimal to major training from the company
- Orange: medium availability and requires major to complete training from the company
- Red: low availability and requires complete training from the company

4.5.2.1.3 FORWARD AND REVERSE LOGISTICS

Logistic risk is measured in three aspects: (1) diversity of transportation mode, (2) ease of handling, and (3) cost competitiveness when comparing shipping domestically and internationally. Because the information from the survey is not sufficient to evaluate cost competitiveness, only the first two factors are considered. Supply chain impact thresholds are evaluated as follows:

- Green: two or more modes of transportations are used, and the commodity is easy to handle (no physical or chemical safety concerns as classified by Department of Transportation under Category 1–9 that requires special permits)
- Yellow: two modes of transportations are used, and the commodity is relatively easy to handle (some safety concerns related to size but no special permit required, not a hazardous material to transport)
- Orange: one mode of transportation is used, and the commodity is classified as a hazardous material to transport or special permit is required due to transportation challenges
- Red: one mode of transportation is used, and the commodity is classified as a hazardous material to transport, and multiple special permits are required due to transportation challenges

4.5.2.2 Results

The overall risk score for the conductor supply chain, mostly concentrating on the core and cable production, is in the upper range of green and can easily be pushed to yellow. The highest, second highest, and third highest risk, as shown in the last column of Table 4-2, is from input materials, workforce, and logistics, respectively. However, compared to other industries, the manufacturing and transporting of conductors are not as delicate, complex, or hazardous as those that require special permits to handle. The risk score shows that supply chain risk is not of high concern given the mitigations the industry has put in place. However, this risk score might change to steady yellow if the probabilities of different risk categories go up due to global economic context. Detailed supply chain impact assessment for each manufacturing area/category is explained in Sections 4.4.2.2.1 to 4.4.2.2.7.

Category	Core Manufacturing Impact	Conductor Manufacturing Impact	Probability of Disruptions	Risk From Core & Conductor Manufacturing (Impact x Risk)
Input Materials	3	3	High – 4	12
Manufacturing Process	1	1	Low – 2	2
Manufacturing Equipment	3	3	Very Low – 1	3
Workforce	3	3	Medium – 3	9
Logistics	1	2	Low – 2	2 – 4
Reverse Logistics	1	1	Low – 2	2
Recycling	1	1	Very Low – 1	1
			Total Risk Score	**31 – 33**

Table 4-2 Supply chain risk categories, impacts and risks of the conductor industry.

4.5.2.2.1 INPUT MATERIALS

Of those materials listed in Figure 4-2, zinc and high-strength steel stand out as the top materials of concern. There was a shortage of zinc in 2022 and a shortage of steel in 2021. According to USGS, the average import reliance of refined zinc in the U.S. from 2017 to 2021 was ~83% [34]. The U.S. accounted for ~6% mine production globally in 2021, but much of the ores and concentrates are exported to be refined elsewhere. Import of refined zinc was 3-fold to 7-fold more than domestic refining output. Alternatively, the concern of steel is not with raw materials but the manufacturing of engineered materials. Average import reliance of steel from 2017 to 2021 was ~13% [35], much less than zinc. However, the production of high-strength steel is specialized to the application. There is competing demand from rail, pipe, and rebar applications. In addition, domestic capacity is lower than demand, and domestic prices are not competitive.

Aluminum is of moderate concern in terms of sourcing. The average U.S. import reliance from 2017 to 2021 was ~48%. Globally, the U.S. accounted for 1% of global smelter production and 2% smelting capacity in 2021 [36]. Canada accounted for ~5% of the global smelting output in 2021. This country is the main source for U.S. aluminum imports. Specifically for aluminum alloys and wire with maximum cross-sectional dimension exceeding 7 mm having a harmonized system (HS) Code 760521, U.S. import value ranged between $54M and $93M per year, which is equivalent to 12 thousand metric tons – 19 thousand metric tons per year within the last 5 years [37]. Roughly 80% of imported aluminum wire comes from 10 major countries, including Canada, China, Mexico, Italy, Czech, France, Spain, Japan, Switzerland, and Korea. Germany, Ecuador, and other Asian countries are also occasionally sourced with varied quantities.

There are some minor concerns with carbon fiber related to import reliance. According to the UNComtrade database, the U.S. import of carbon fiber with HS Code 681591 increased from 3,590 metric tons (mt) in 2017 to 10,452 mt in 2022 [37]. The economic value of carbon-fiber imports also increased from $3.2M in 2017 to $11.2M in 2022. Major importing countries include Brazil, Canada, Ecuador, Japan, and other Asian countries.

Aggregating all the risks of these materials, a risk score of orange is assigned to this category and is shown in Table 4-3.

Material	Import Reliance Risk	Composition Complexity Risk	Quantity Risk
Aluminum	Average to High	Low	High
Carbon Fiber	Low to Average	Low	Low
High-Strength Steel	Average to High	High	Average to High
Zinc	High	Low	Low to Average
Overall Material Risk Score			

Table 4-3 Detailed scoring of material risks

4.5.2.2.2 MANUFACTURING PROCESS

From the survey results, manufacturing does not seem to be a concern. Some steps could become the bottleneck, such as wire drawing and galvanization for steel core production or stranding for cable production. Even so, cable manufacturing is not as delicate as semiconductors or as complex as transformers. Therefore, this manufacturing process is rated as green.

4.5.2.2.3 MANUFACTURING EQUIPMENT CAPITAL

Manufacturing equipment is analyzed separately from the manufacturing process. The section above focuses on production steps that could be the bottlenecks causing long lead time. This section focuses on sourcing of the equipment. The frequency of process risk is typically higher than equipment capital risk. Manufacturing process risk arises when production is ongoing, which could be 8–24 hours/day. Alternatively, equipment capital risks arise when a new facility is commissioned, or an existing facility goes through capacity expansion. Major equipment used for core and cable manufacturing includes draw benches, rigid frame standers, precision heated dies, infeed tooling, spooling equipment, annealing ovens, stranding equipment, straighteners, and quality assurance equipment. For composite core manufacturing, additional equipment includes resin and hardener blending equipment, pultrusion machine, pultrusion monitoring equipment, conforming, insulation line, and encapsulating machine. For steel-core manufacturing, pickling equipment and galvanizing line are needed.

Manufacturer surveys showed that, depending on the equipment type, import reliance varies from 20% to 100%. Part of the import profile is because of a company's ownership and their preferred sourcing. Testing equipment has also been reported to source globally. Exporting countries are mostly trade friendly, such as North America or Europe. Because of the average to high-import reliance, this category is rated as orange.

4.5.2.2.4 WORKFORCE

The shop floor requires a wide range of skills, from low to high. Highly specialized workers include pultrusion machine operators, metal work operators, and maintenance workers, such as industrial mechanics and electricians. For the lower skill workers, their availability is high, and companies can train them adequately. For higher skill workers, companies have used incentives to attract them or over hire. The main challenges that these companies reported include night shift challenge, willingness of workers to work in settings requiring physical activities, and concerns for process learning and adoption of the standard operating procedure. Overall, the workforce availability is low to medium and requires major to full training from the companies. The risk level for the workforce is rated as orange.

4.5.2.2.5 LOGISTICS

Multiple modes of transportation are used to transport core and cables. In the U.S., trucks and rail are being used, with trucks being the most common mode. For international shipping, sea and air transportations are also used. There are some minor concerns about truck availability, reliability, and cost. However, the main challenge is with reels having a diameter of 96 in. or over 7 metric tons. Lowboy trucks are used to carry the large reels to go beneath underpasses. It is also challenging to unload the large reel due to crane or forklift capacity. Even so, no special permit is required for transporting the cable. Tarping the cable is recommended by industry to protect it from debris,but this commodity is not hazardous in nature. The risk for forward logistics is yellow for cable and green for core transportation.

4.5.2.2.6 REVERSE LOGISTICS

Reverse logistics refers to the shipping of steel reels and/or defective cable back to the manufacturers. This process is simpler than shipping the original cable. Trucks are mostly used in this process. The impact is rated as green.

4.5.2.2.7 RECYCLING

As mentioned in Section 4.3, while cables composed of aluminum and steel can be easily recycled, cables with composite core are less known due to the technology being relatively new. The recycling impact on the supply chain is positive when it can add more material supply. Alternatively, the impact is negative when materials are locked in end-of-life products that can only be discarded. As a result, new supplies are needed to meet growing demand. However, because composite cores are made from petroleum products, which do not have major shortage concerns, the overall rating for recycling is green.

4.6 U.S. Opportunities & Challenges

Given the aging infrastructure, growth in renewable energy integration and need for electrification infrastructure, demand for conductors is expected to grow between now and 2050. This need offers the opportunity for this industry to expand domestically. However, given the lifetime of grid components of 50 years or longer, domestic manufacturers struggle to plan for production capability expansion. This is because they do not want to idle capability when demand is met. Therefore, the manufacturer's current modus operandi is to maintain existing production capacity of capital equipment and increase the number of shifts and labor when needed. Even so, manufacturers face challenges to find skilled labor and obtain adequate input materials and equipment for production. Key materials, such as aluminum, carbon-fiber, high-strength steel, and zinc, have various levels of import dependence, which are sourced from North America to worldwide. The disruption in any of those material supply chains would have a significant impact on the conductor industry.

An observation from the survey is that most companies are not comfortable providing information on where they are sourcing materials and equipment. It is because they want to claim that their products are made in the USA to be in compliance with "Build America, Buy America Act" [38]. However, based on the U.S. import profile of various materials, this requirement could be a major bottleneck if there are not enough upstream suppliers.

In conclusion, the U.S. conductor industry is in a good position to plan for future growth until 2050. However, further investigation is needed to helps this industry improve their planning. Planning tools that consider component supply chain interdependence for grid buildout, visualize capacity in the next 50 years for various growth scenarios, and prioritize bottlenecks to resolve would ensure a sustainable growth.

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SECTION 5: National Act Adoption Goal Determination/Assessment

5.1 Background

In today's environment where siting and permitting new lines on new routes is difficult and expensive, existing RoWs are a critical asset that should be fully utilized for transmission expansion. Reconductoring of existing lines with higher capacity advanced conductors not only reuses the existing land, but preserves existing transmission structures, which is a lower cost and is a faster way to expand transmission capacity compared to rebuilding lines from the ground up. Rebuilding of structures may be required if line voltages are increased or if existing structures need to be replaced because of their design or condition. Advanced conductors exhibit properties such as high capacity and low sag that make them ideally suited for reconductoring applications. This section will seek to answer how many of the existing miles of transmission lines in the U.S. are candidates for reconductoring using advanced conductors of any type. The methodology used to identify this target will be to consider the total number of existing transmission miles, identify reasons that lines may not be candidates for reconductoring, and then deduct the number of miles that are not suitable from the total number of miles to calculate potential circuit miles that are candidates for reconductoring for rapid capacity expansion.An estimated 600,000 miles of existing transmission lines are in the U.S. The following subsection provides the reasons why reconductoring may not be a good fit.

5.1.1 Reconductoring Challenges

There are two major reasons why a transmission line may not a good candidate for reconductoring. First, existing lines where structures are at the end of life because of degradation or because of design should be rebuilt versus reconductored. Second, replacing the existing conductors with advanced conductors may not increase capacity or may not be feasible. This section primarily focuses on reconductoring to increase line capacity. Lines could be reconductored with advanced conductors specifically for efficiency, but as there are no known projects in the U.S. where lines were lines have been reconductored only for efficiency purposes, so it is assumed here that the cost of taking lines out of service and the resources needed to reconductor only for efficiency gains is not currently viable.

5.1.1.1 Age and Condition of Existing Lines

Over time, transmission line materials degrade as steel rusts, aluminum fatigues, concrete crumbles, and wood decays.

Utilities transmission assets are monitored at least annually for sag and clearance violations, and periodically for asset conditions. If problems are noted from the inspection or other operational indications, utilities prioritize replacement of those assets. There are generally no age-only policy for replacing conductors or transmission assets; therefore, some assets are still operating after over 100 years of service. However, needs prioritization is the basis for replacements outside of noted degradation. A large portion of the transmission system is older than 25 years, much of it installed in the 1960s and 1970s [1]. It is estimated that 30% of transmission lines need to be entirely rebuilt over the next 10 years due to age and condition to prevent use beyond 70 years (based upon American Electric Power data) [2]. If a line, including its structures, are at or near the end of life, the towers and the conductors are likely to be replaced at the same time. With the exception of decommissioning and removing the existing line, rebuilding a line follows the same steps as building a new line and advanced conductors will face the same challenges as they do with new construction.

5.1.1.2 Resiliency of Existing Lines from Extreme Weather Events.

The materials of some transmission lines can still be in good condition and operating as designed; however, the structures may need to be replaced for resiliency purposes. As climate change has increased the frequency and severity of extreme weather events, utilities have responded by increasing the resiliency of line designs. One example would be a utility in a wildfire prone area that has standardized on steel poles for new construction. For existing wooden poles, the utility could take steps to reduce the risk of fire by treating the poles with fire retardant materials, but the utility is likely to have a policy that dictates that any major work, such as capacity expansion, would trigger a full replacement of the line to bring it up to reliability standards. Another example could be a utility planning for increased resiliency from hurricane-force winds [13]. Transmission lines are designed to survive certain conditions, after which they are expected to fail. Some older structures in hurricane-prone areas can be expected to fail at wind speeds in excess of 100 miles per hour. Newer structures in hurricane prone areas are often designed to survive wind speeds of over 150 miles per hour [14] or even 175 miles per hour for critical spans such as hard to replace river crossings [1,2, 15].

The reconductoring of existing structures that do not meet modern design standards for resiliency is a possibility if rapid capacity expansion is needed or project costs must be reduced but is a compromise that could impact reliability in the event of a wildfire, ice storm, hurricane, or other natural disaster. If a transmission line that does not meet current resiliency standards requires more capacity, most utilities would choose to rebuild it with new structures rather than reconductor with advanced conductors.

5.1.1.3 Reconductoring Does Not Increase Thermal Capacity

There are thousands of circuit miles of transmission that have already been built or reconductored with high-temperature conductors since ACSS was introduced over 50 years ago. For older ACSS lines, reconductoring could yield a much lower capacity benefit—closer to a 20% increase versus a capacity doubling. Similar benefits could be achieved by using other grid enhancing technologies such as dynamic line rating or by retrofitting a high-emissivity coating to the existing lines. Because of the limited capacity increase these lines are likely not good candidates for reconductoring. Another situation that could preclude existing lines from being reconductored with advanced conductors is the use of vibration resistant twisted pair conductors. Across the Midwest, lines have used twisted pair conductor to prevent the wind induced vibration phenomena known as galloping, where the conductors can move violently and clash together causing line damage and outages. Because twisted pair conductors do not experience galloping, existing structures are typically designed with closer phase spacing and may be unsuitable for reconductoring with non-vibration resistant advanced conductors except with high-capacity versions of twisted pair conductors. These lines are also not likely candidates for reconductoring.

5.1.1.4 Other Constraints Prevent Conductors from Reaching Thermal Capacity.

Reconductoring with advanced conductors increases a line's thermal capacity. On some lines, thermal ratings may not be the constraint preventing the line from transmitting more power. Line segments that are longer than 30–50 miles are typically not thermally limited but rather have other electrical constraints such as line stability and line voltage drop that limit power flow. While these lines could be reconductored with higher capacity conductors, there would be little to no capacity benefit. Existing lines with voltages of 500 kV or higher are unlikely to be thermally constrained, as their length tends to be longer and because the multiple conductor bundle configurations used on extra high-voltage lines often requires more conductor cross section to be installed than is needed for thermal purposes. Lines that are not thermally limited are not likely candidates for reconductoring [3-5].

5.1.1.5 A larger capacity increase is required than reconductoring can offer

Reconductoring existing lines can double line capacity. Where RoWs permit, rebuilding transmission lines at higher voltages or with double circuits can increase capacity by a factor of 12 or more. Reconductoring is much faster and lower cost, but there will be times when system planners choose to increase capacity even more than that.

Each of these conditions make reconductoring unlikely. None of these conditions preclude the use of advanced conductor for rebuilding the lines, just as any new transmission line constructed could benefit from the capacity and efficiency benefits of advanced conductors, although not at the speed or the cost of reconductoring.

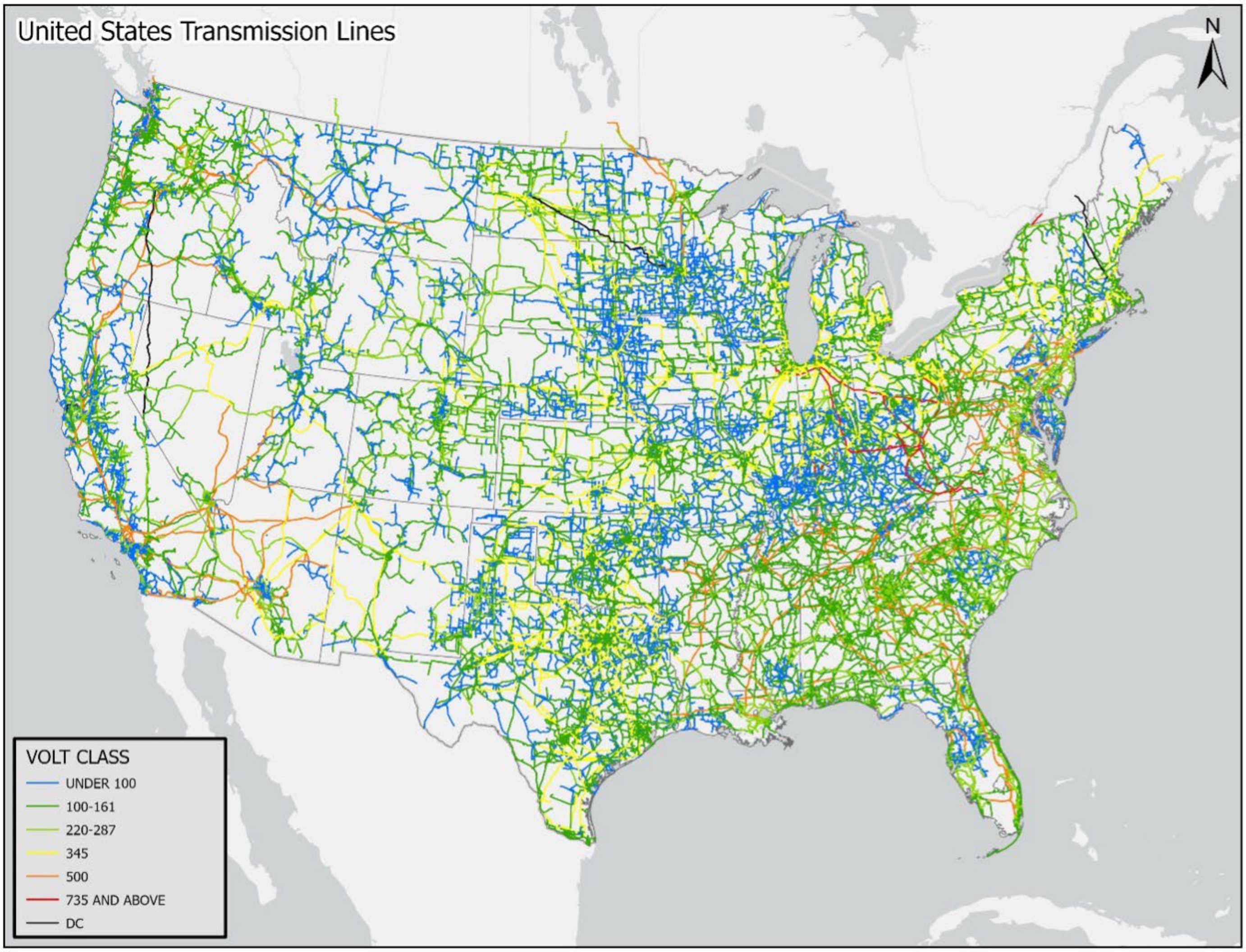

Figure 5- 1. Transmission lines in the USA by voltage level.

Figure 5-1 provides a perspective on the current U.S. transmission system by voltage based upon Homeland Infrastructure Foundation-Level Data (HIFLD) data [6]. Shorter line segments </=345 kV that are thermally limited are more likely candidates for reconductoring with advanced conductors.

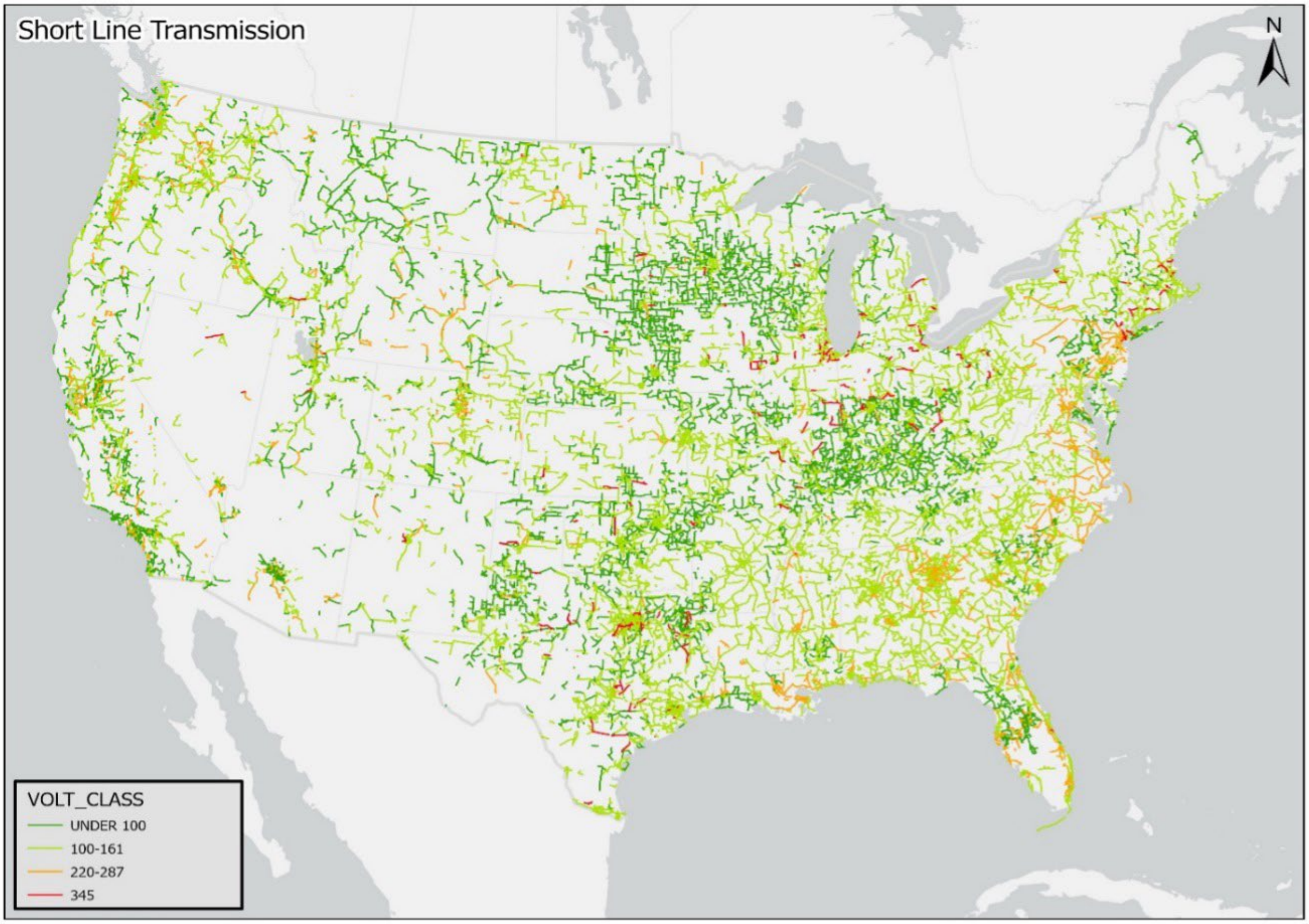

Figure 5- 2. Short transmission lines by voltage.

5.1.2 GIS Analysis of Short Lines

Geographic information system (GIS) analysis of HIFLD data reveals the quantity of short line miles by region and is shown in Figure 5-2. The total length of existing lines that are short enough to be thermally limited and potentially suitable for reconductoring is 236,331 miles, which is comprised of 21,673 short segments. The breakdown of short line miles by region are provided in Table 5-1, based upon the Cybersecurity and Infrastructure Security Agency (CISA) regions shown in Figure 5-3 [12].

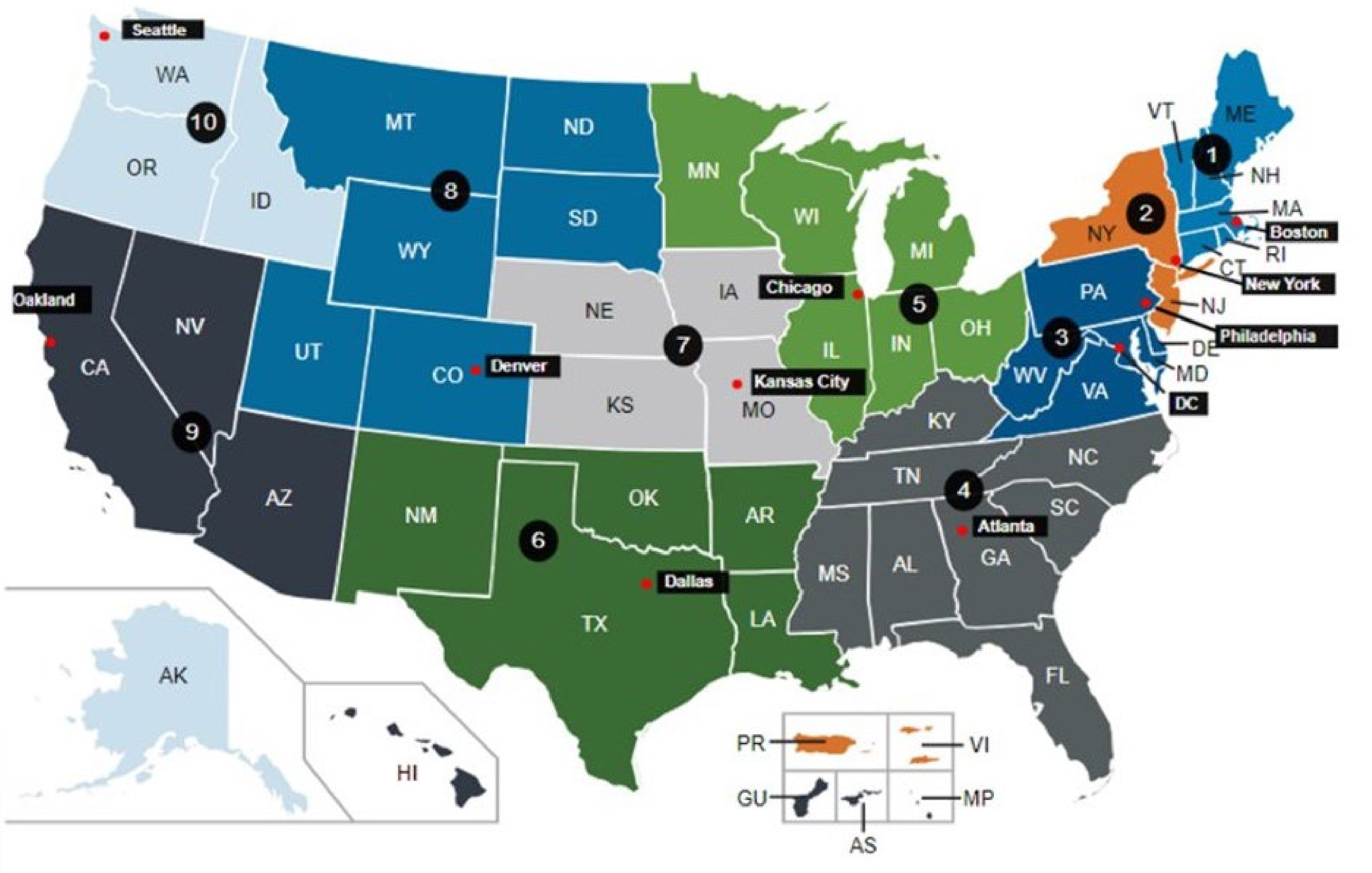

Figure 5- 3. CISA Region (from cisa.gov)

CISA Region	Region Name	Short Line Miles
1	Upper NE	5,979
2	Lower NE	6,364
3	Ea	13,614
4	So	52,585
5	Upper MW	37,809
6	SW	43,250
7	Lower MW	20,217
8	Mountain W	25,858
9	We	14,023
10	Pacific NW	16,632
	Total Short Line Miles	236,331

Table 5-1. Short line miles by region.

5.2 Advancing Opportunity for ACT Reconductoring

A large percentage of the U.S. electrical grid would benefit from immediate reconductoring with advanced conductors. However, as highlighted in section 5.1, there are several reasons why a line may not be an ideal candidate for reconductoring. A primary reason is that many lines are too long to benefit from an increase in the thermal capacity offered by reconductoring. Another primary reason is the age or design of the existing line may make the structures unsuitable for reconductoring. By using the total number of U.S. transmission line miles as a starting point and reducing that amount for each of the conditions listed in Section 5.1, an estimate of existing line miles that are immediate candidates for reconductoring can be produced.

Table 5-2 summarizes seven conditions from Section 5.1 that could exclude a line from being a reconductoring candidate. Of the existing 600,000 miles of transmission lines, roughly half are not candidates based on the listed criteria.

Transmission Segments for Consideration	Total Estimated Miles	% of Total Estimated Miles Excluded
Transmission Line Miles	600,000 [7]	
Needs replacing within 10 years for age/condition	-200,000 [4]	33.3%
Total miles high temperature conductor	-40,000 [8]	6.7%
Twisted pair conductor	-30,000 [5]	5.0%
765 kV transmission	-2,453 [9]	0.4%
500 kV+ transmission	-26,038 [6]	4.3%
HVDC tranmission interconnects	-1,526 [10]	0.3%
345 kV and below not thermally limited	-1,646 [11]	0.3%
% of line miles to be excluded for above reasons		50.3%

Table 5-2. Reconductoring candidates.

Table 5-3 then applies this excluded percentage to the short segment transmission line miles identified in section 5.1.2. When these two filters are applied together to the estimated 600,000 existing miles of transmission lines, 19.6% or 117,510 miles are identified as immediate candidates for reconductoring and the resulting rapid grid capacity additions.

Short Segment Miles from Table 5-3	236,331
Excluded % Miles from Table 5-4	-118,821
Total line miles for possible reconductoring	117,510

Table 5-3. Short segment reconductoring candidates.

5.2.1 Other Conditions

In generally considering areas of threat from hurricanes, earthquakes and wildfire by overlaying the short conductor map Figure 5-2, Figure 5-4, Figure 5-5, and Figure 5-6 illustrates conductors that might be prioritized for replacement. Short lines affected by hurricanes include approximately 31,638 miles, earthquakes at 34,671 miles, and wildfires at 42,584 miles. As can be recognized in Table 5-2, each region of the country has a threat that could be considered as a resilience factor that prioritizes where replacement might occur where dictated for renewables integration, load growth, and age.

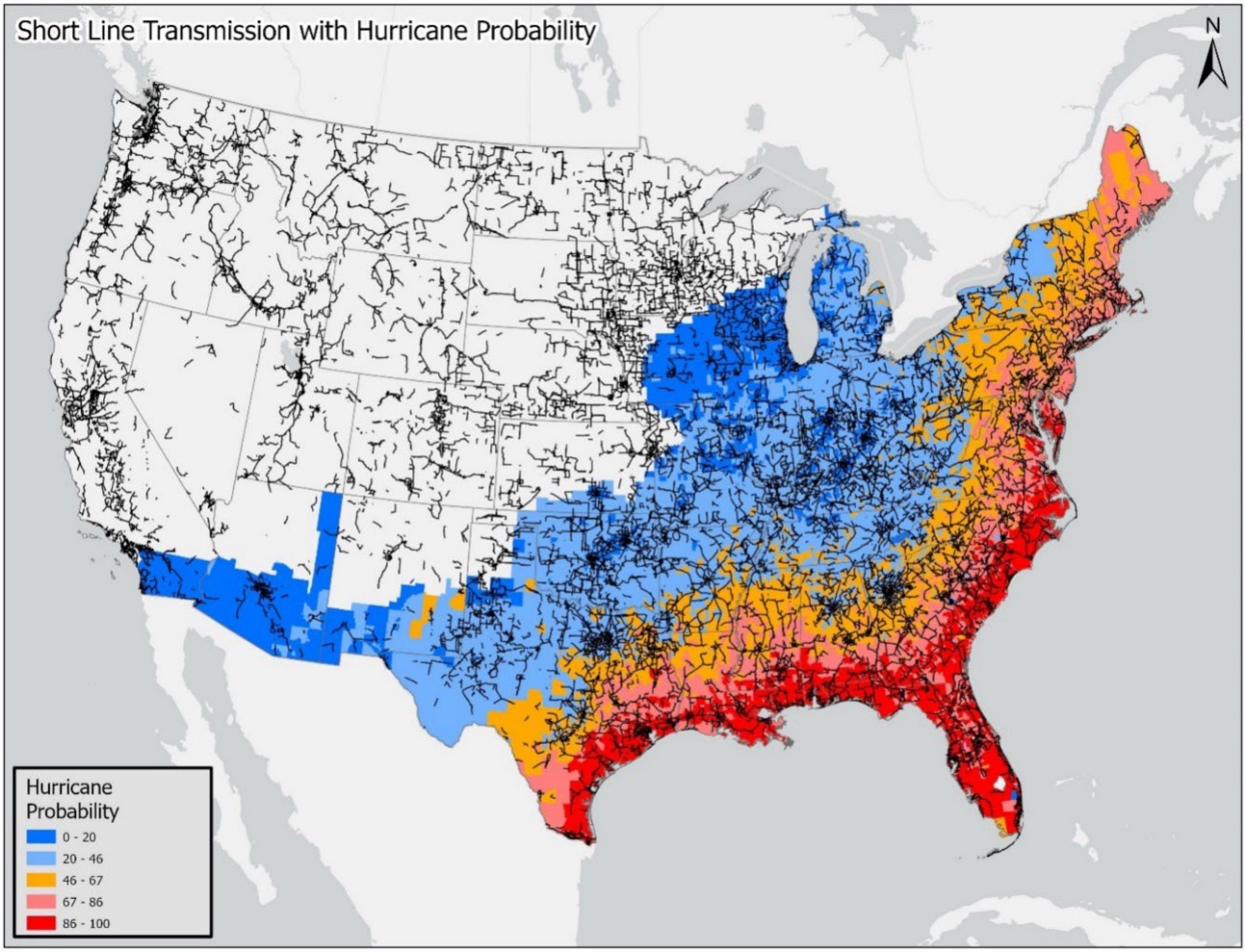

Figure 5-4. Short lines with hurricane probability.

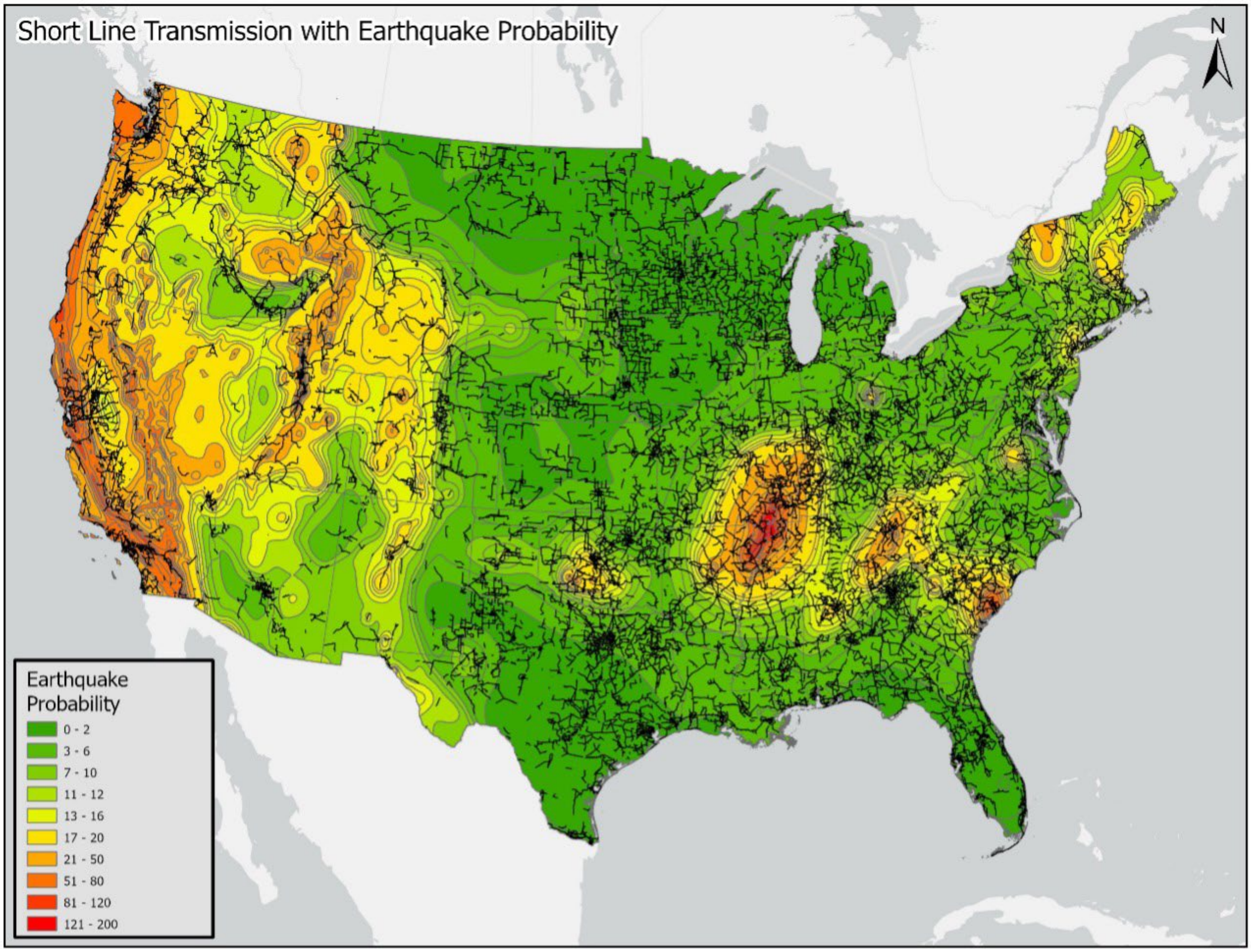

Figure 5-5. Short lines with earthquake probability.

CISA Region	Short Lines: High Hurricane Threat	Short Lines: High Earthquake Threat	Short Lines: High Wildfire Threat
1	501		
2	209		
3	1,608		778
4	19,042	1,624	6,859
5		440	386
6	8,957	632	12,665
7		551	444
8		4,139	5,739
9		9,994	8,460
10		7,757	7,253

Table 5-4. Short lines in hurricane, earthquake, and wildfire high-threat areas.

Table 5-4 lists the total number of miles of short line per CISA region that are in a high-threat area for hurricanes, wildfires, or earthquakes. Of the 236,331 short segment line miles, 127,577 miles fall in a high-threat area. Utilities, states, or reliability coordinators could decide at any time to increase the reliability requirements of these or other lines, which would require more rebuilding of structures and less reconductoring with advanced conductors. Utilities could also decide to or be forced to convert overhead transmission lines to underground insulated lines, which would increase resiliency from fires and hurricanes, although at a reported ten times the cost of overhead transmission construction. As extreme weather events become more common, it is hard to predict how resiliency requirements might change.

It is also worth noting that a substantial portion of transmission lines are currently not candidates for reconductoring because of the line distances between substations. Should substations be added at intermediate points, these lines would be broken up into smaller segments and could more effectively be reconductored.

5.2.2 Informing Decisions through Results Disseminations

With independent results and existing champions, results can be more widely distributed and inform the transmission community. Supplementing current workshops and working groups with sessions facilitated by champions of the technologies, notably those in industry that provide their justification and experience could also contribute to broader acceptance. Motivating this advancement may be benefited by government incentives but significant acceptance will come from individual experience.

5.3 Summary

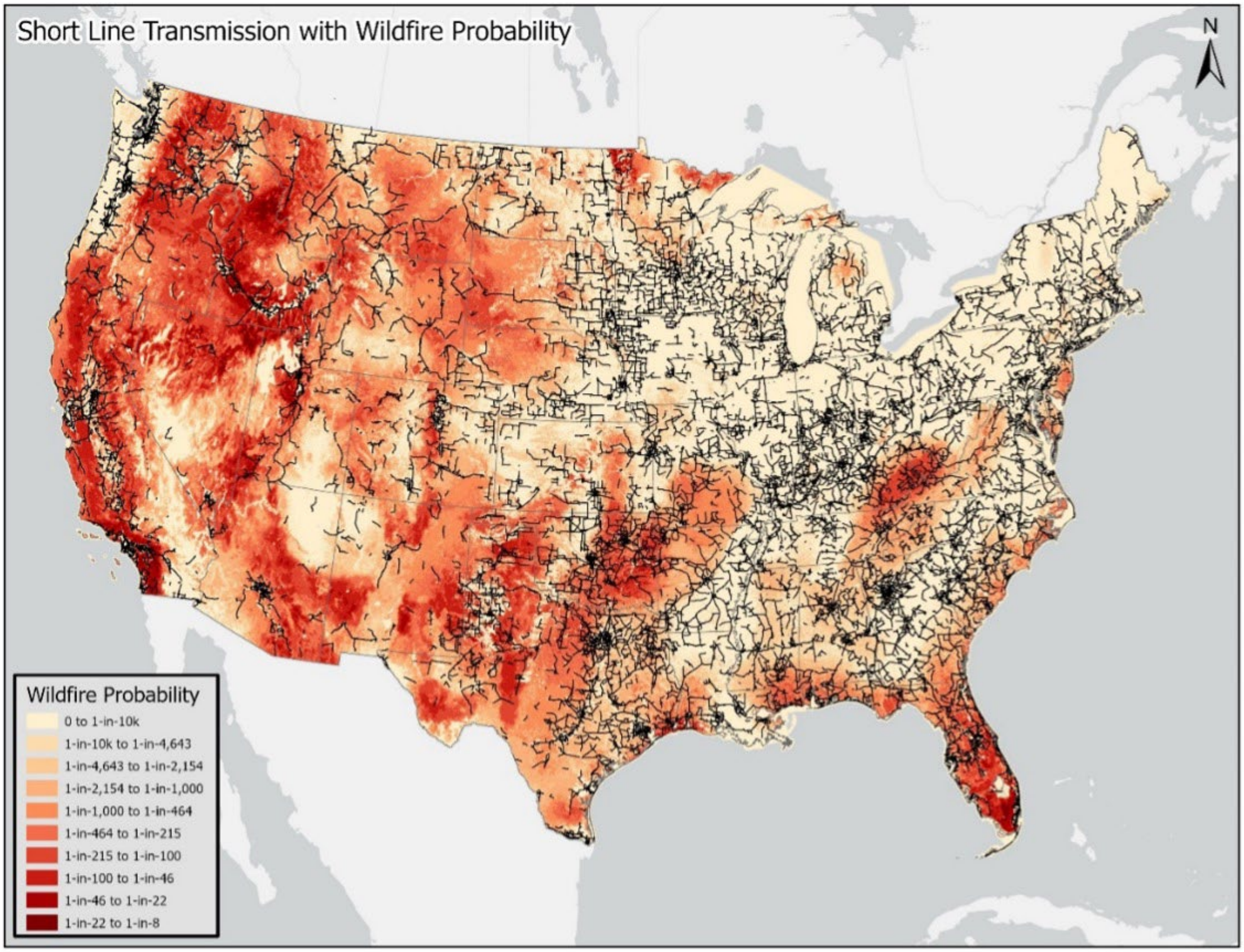

Figure 5-6. Short lines with wildfire probability.

Noting sensitive areas as a further motivator for adoption of advanced conductors, further evaluation of specific locations where increased load or significant renewables generation exist or are planned would be an additional modifier. Further analysis of weather, age- and threat-related considerations may further drive adoption, noting that areas of constant threat like Florida have already invested in such changes to reduce recovery time resilience.

Based upon age and condition of existing lines and taking into account the factors that might limit reconductoring, a near term goal of 118,821 miles of transmission lines could be reconductored with advanced conductors, rapidly bringing new transmission capacity to the grid. A more detailed analysis could include age and condition of existing transmission lines assets, including conductor types used, line ratings, thermally limited lines, and structural design limits, such as ability to withstand different levels of hurricane-force winds.

This analysis would confirm specific opportunities and these areas may also be candidates for shared investment by government and private industry.

While industry has many sharing mechanisms, leveraging the nature of the government to independently analyze and share unbiased information on advanced conductor performance would greatly inform and enhance these sharing mechanisms. These include the confirmation of the improved capacity, resilience against damaging storms or climate, and the cost. Investing in both the infrastructure in the national laboratory system leveraging current, and establishing new sharing mechanisms would further inform and aid acceptance by industry.

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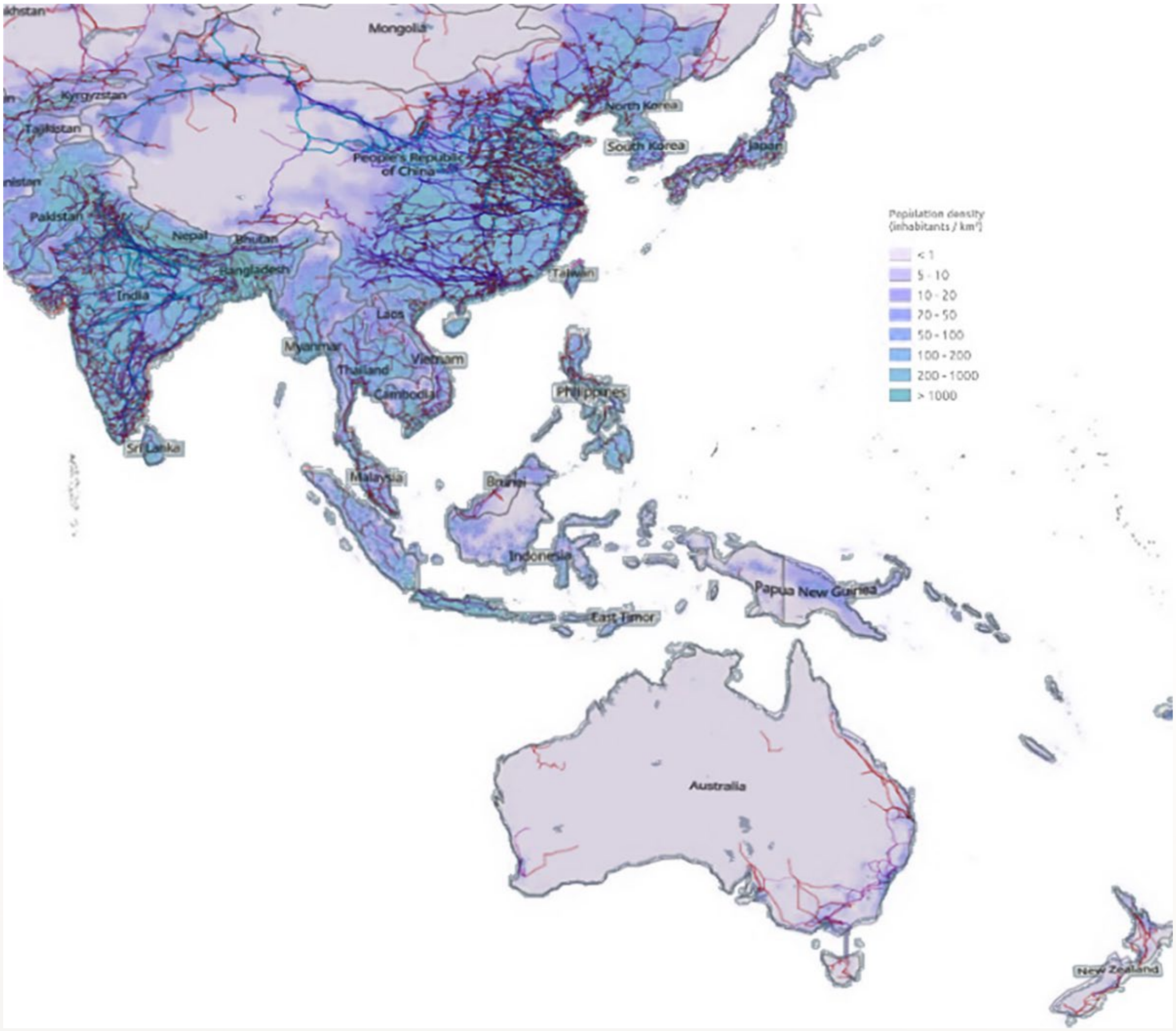
SECTION 6: Global Trends for ACT Adoption

6.1 Introduction

Up to this point, this report has described the adoption of ACTs exclusively from the perspective of the American power system. However, an investigation of the use of these technologies globally provides insight into opportunities and applications that may not have been previously considered. A full characterization of how ACTs are being used around the world would be quite lengthy and is beyond the scope of this report. Rather, the intent of this section is to consider the similarities and differences between the use of ACTs domestically and internationally. Handling procedures and training for installation crews depends on the technology being used and is standardized by the conductor manufacturers rather than regulators.

In this section, the general trends regarding the use of advanced conductors are assessed for different regions of the globe outside of the U.S. and Canada. These regions are internally quite diverse; however, they are broadly grouped as follows; Asia-Pacific, Middle East and Africa, Europe, and Latin America. The characteristics of each region that affect adoption of advanced conductors are described, along with illustrative examples of how the conductors are being used in these areas. This is then followed by an overview of the common applications for advanced conductors and the regions where examples can be found. This section concludes with a discussion of the unrealized opportunities for the use of advanced conductors in the U.S., based on the examples presented.

6.2 Asia Pacific



The first region considered is the Asia-Pacific. This is the largest and most populous region in the world with a combined population of ~4.8 billion people as of 2023, ~60% of the total global population [1]. This region includes many technologically advanced societies with high levels of electrification, such as Japan and Australia; many emerging economies, like India and China; and many developing countries, like Nepal and more. The power systems of east Asia and Australia tend to be the most mature, while new line constructions are more common in the south and among the islands as part of rural electrification efforts. In the Asia-Pacific region, electric utilities have found their choices regarding HTLS adoption affected by many of the same considerations as in the United States. Procuring RoWs and permitting processes tend to vary from country to country, but in general these costs, along with tower construction, remain the biggest considerations for transmission line projects.

6.2.1 China

China is the second largest nation in Asia by both population and geographic area. The total landmass of China is ~9.4 million km^2 and the total population as of 2023 is 1.4 billion people [2]. China is one of several nations to have recently achieved 100% access to electricity for their population, having reached this milestone in 2013 [3]. The largest sources of electricity in China are fossil fuels at 66% and hydroelectric at 18% of total generation in 2020 [4]. The Chinese electrical grid is enormous and constantly expanding. Consequently, they have used advanced conductors in a wide range of applications for decades. China was an early adopter of ACCC. In 2007, the Chinese state grid company ordered over 370 miles of ACCC conductor for various projects [5]. At the time, this order alone represented over one-fourth of all ACCC conductors that had been sold in the world. China is not only one of the leading users of ACCC conductor, they are also a leading supplier as well. In 2013, the manufacturer of ACCC conductor entered a joint venture with the Chinese state-owned company NARI to manufacture their core material in China [6]. More recently, ACCC conductor has been used in China for novel HVDC transmission lines as well [7].

6.2.2 Nepal

A new line construction in Nepal is using the HTLS conductors. Nepal is a country with a rapidly growing power industry. The population of Nepal is 31 million as of 2023 [8]. In 2015, Nepal had ~780 MW of installed generation with another 1300 MW under construction [9].

In 2015, ~65% of the country had access to grid electricity and the annual growth rate of energy production was 8.5%. As of 2023, the access to electricity has increased to almost 90% [10]. The country of Nepal spans two large river valleys, which has a combined yield over 83 GW of potential hydroelectric generating capacity. This potential, combined with rapid growth, makes Nepal an attractive country for the deployment of advanced grid technologies. The local climate in Nepal has conditions that must be accounted for to derate the capacity of certain HTLS technologies for local use [11]; however, despite this, advanced conductors remain attractive in this system. Nepal has fully embraced HTLS conductors with over a dozen reconductor projects in 2023 alone [12]. These projects consist primarily of varying sizes of ACCC conductor; however, there are projects using ACCR and

Aluminum Conductor Invar Reinforced (ACIR) as well. In addition to these projects, Nepal has two entirely new lines being constructed with ACCC. These lines have higher MW loading and more than twice the ampacity of the alternative ACSR designs at ~75% of the cost per km. Additionally, the new lines achieve these benefits at only 220 kV, as opposed to the 400-kV rating required by the alternative design. This is a significant advantage as Nepal has seen rapidly growing land prices and environmental regulations. The lower voltage rating allowed the lines to be constructed on smaller RoWs with a lower overall environmental impact.

6.2.3 India

Another country in this region with extensive use of advanced conductors is India. As of 2023, India is the most populous country on earth and is home to more than 1.4 billion people [13]. Of these, more than 99.5% have access to electricity [14]. The total electrical power consumed in India is ~1,700 TWh/year [15]and is the third-largest consumer of electricity in the world [16]. In total, India has ~14 million circuit km of transmission and distribution lines [17]. The rapid population growth and rate of electrification in India makes it one of the largest markets for HTLS conductors, and all conductors generally, in the world. A full description of the use of HTLS conductors in such a large power system is beyond the scope of this report; however, several examples have received media attention in recent years. One example for the use of ACCR conductor in India was on two 110-kV lines near Mumbai [18]. Like most other cases, the utility needed to increase the capacity of the lines to meet load growth, but modifying towers or securing new RoWs would have proven prohibitively expensive. The existing structures were in good condition, so reconductoring with ACCR allowed the utility to increase capacity while maintaining sag limits without structure modifications or new construction. An example where ACCC was used was a 17.2-km stretch of 132-kV line between Eklahare and Ozar. Again, the reason cited by the utility for choosing the HTLS conductor was the ability to retain the existing structures while increasing capacity.

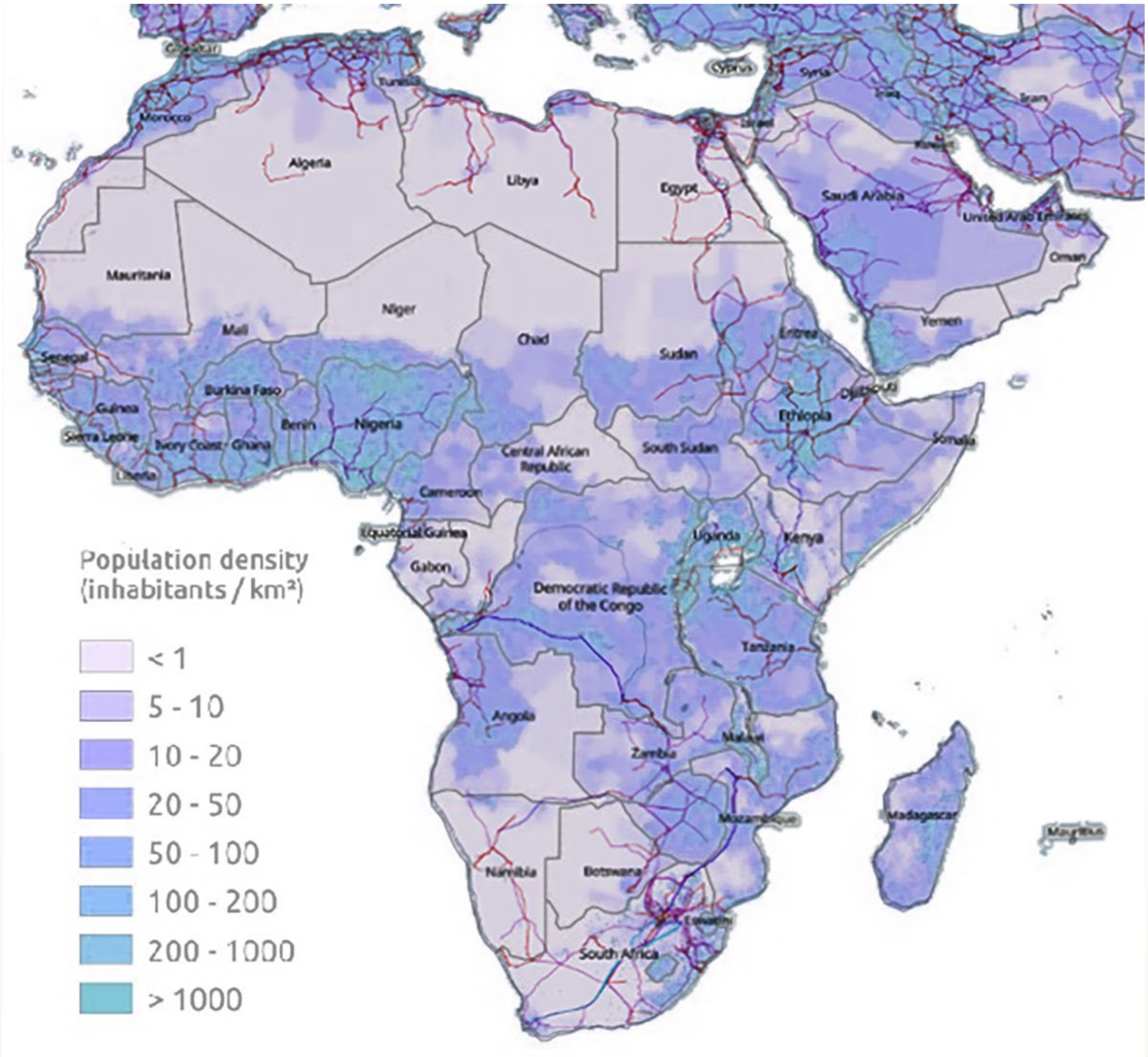
6.2.4 Japan

No discussion of advanced conductors would be complete without mentioning Japan. Japan is a dense urban country with a population of 123 million people, 93% of which live in an urban area [19]. This population is concentrated in a landmass of only 378 thousand km^2 [20]. Japan has been at the forefront of advanced conductor technology development for decades. Both the gap-type and invar-reinforced conductor families were developed in Japan as well as early carbon-fiber designs [21]. Invar is an alloy of steel and nickel that has less thermal expansion than other steel types. Invar-reinforced conductors have lower strength ratings than steel-reinforced equivalents, and so are mostly only found in southern Japan and other parts of Asia where ice loading is not a significant concern. Gap-type conductors feature a gap between the core and conductor strands, which is filled with a corrosion-resistant lubricant. This allows these conductors to be pre-tensioned during stringing which reduces their sag during normal operation. Gap-type conductors and their variants have found widespread adoption throughout Asia, the Middle East, and Europe. They are generally very similar to ACSS in terms of performance, which is the preferred technology in the U.S. Prior to the development of composite cores, gap-type conductors were one of the most popular conductors for reconductoring. As of 2016, 27,000 km of gap-type ACSR variants had been installed in 25 different countries around the world [22]. Prior to the advent of composite cores, ACSS and gap-type conductors were the main competing technologies for reconductoring projects. While gap-type conductors are still used in some regions, ultra-strength ACSS and composite core conductors have become the new standard for these projects.

6.2.5 Australia

Australia, located in this region, is notable for its lack of use of advanced conductors. In 2023, the population of Australia was just shy of 27 million people [23] . The total area of Australia is 7.7 million km^2 [24], roughly the same as the mainland U.S. Australia is a wealthy country with a high standard of living and a well-established power system, ranked 18th in the world for gross domestic product (GDP) per capita [25]. Despite this, Australian utilities have only recently begun to consider using advanced conductor technologies in their power system, with the first use of an ACSS conductor being as recent as 2021. Other utilities in Australia have only just begun the process of considering advanced grid technologies [26]. This lack of widespread adoption in the Australian system can be attributed to the fact that despite the Australian power system being relatively old, Australia's load demand has remained mostly constant for decades [27]. Australia has one of the lowest population densities in the world [28], which makes the procurement of RoWs for new constructions much easier than in other power systems. As a result, it is generally more economical to use the conventional ACSR to meet the load demands in the Australian system with new line constructions, and reconductoring is generally not necessary. The situation in Australia is very similar to some of the more rural interconnections within the U.S.

6.3 Africa/Middle East



Like the other regions in this section, the region described by the combination of Africa and the Middle East covers an enormous geographic region with many different nations, each with a unique culture, geography, demography, and economy. These differences all play a factor in the use of advanced conductors and the overall maturity of the power system in these countries and subregions. The purpose of this report is not to navigate these nuances, but rather to describe the ways advanced conductors are being used in this part of the world. This report will seek to accomplish this by showcasing examples that describe the various trends and attitudes towards these conductors in various power systems in the region.

The total population of this region is estimated to be ~1.6 billion people as of 2023. These people are primarily located in a relatively small number of population centers, which in turn affects how the power system has evolved in this region. This is a region of sharp contrasts containing some of the most developed nations in the world as well as some of the least. The coastal regions tend to be the most densely populated and have the most advanced power systems. It is in these regions where advanced conductors have seen applications in reconductoring projects, similar to how they are commonly used in other parts of the world. However, other parts of this region are seeing increasing rates of electrification, particularly the rural regions, and in these regions advanced conductors are being used for their benefits in new constructions.

6.3.1 Nigeria

Nigeria is a particularly interesting country in this region that has experience with reconductoring. Nigeria is the fourth most populous country in the world at 218 million people and one of the fastest growing with an average annual population growth of 2.5% [29]. It is also a developing country with increasing rates of industrialization, urbanization, and electrification. The percentage of citizens living in urban areas was 53% in 2023 [30]. As of 2019, 62% of the Nigerian population had access to electricity with 91% of urban citizens having access and 30% of rural citizens having access [31]. Increasing electrification in Nigeria is seen as the solution to many of the country's problems by local leaders [32]. The combination of ambitious electrification goals and a growing population places immense stress on the Nigerian power system. In recent years, capacity constraints on transmission lines presented a significant barrier to meeting their electrification goals. In response to these constraints caused by the population growth of urban centers as well as anticipated future loading as a result of rural electrification, the Transmission Company of Nigeria (TCN) has engaged in the ambitious project to reconductor all of their 132-kV transmission lines. As of 2021, Nigeria had ~23,600 circuit km of transmission lines and it is estimated they will have 26,500 circuit km by 2027 [33]. If Nigeria were to reconductor this entire system with advanced conductors, they would become one of the largest users of advanced conductors in the world. This announcement was made late in 2023, and as of this writing the conductor technology they will use remains unknown. Regardless, such an ambitious reconductoring project will no doubt shape the entire advanced conductor industry for years to come.

6.3.2 Israel

One country in the region with a mature power system is Israel. The population of Israel was 9.1 million in 2023 [34]. Israel is a small country with a total land area of only 22,000 km^2, slightly larger than the state of New Jersey [35]. The population of Israel has been growing at a steady rate of ~2% for decades [36]. The total energy consumption in Israel was 300 TWh in 2023 and has been steadily increasing [37]. Due to the age of the Israeli power system and its continued population growth, Israel has begun to see many of the same problems with congestion as the U.S. and has begun to turn to reconductoring to alleviate some of these issues. Newer transmission lines in Israel have used the AAAC conductor, while older lines were typically ACSR [38]. Beginning around 2013, the incredible increase in electric demand (~3.5% per annum at the time) and the increasing difficulty in securing RoWs drove the Israel Electric Corp (IEC) to consider reconductoring with HTLS [39]. The ACSR lines had already been uprated to higher operating temperatures in a prior capacity expansion project, so the lines were already operating at their maximum allowable sag. A 12-km double-circuit 161-kV line was chosen as a pilot project. To meet the project requirements, IEC ultimately decided to use ACSS conductor. They had originally considered using ACSS/TW, but the added weight from the extra aluminum would have required significant tower modifications. To compensate for the increased sag at high temperatures, the conductor was pretensioned above its rated sag tension to shift the load from the aluminum fully to the core prior to stringing. Aluminum expands more than steel, so at low temperatures when the aluminum supports part of the tension, the sag will increase more with an increase in temperature. By pretensioning the core, the weight is supported almost entirely by the steel and the increase in sag with temperature will only be the result of the expansion of the steel core. The final sag at 200°C was found to be less than the original ACSR at 100°C. Ultimately, IEC achieved a 50% increase in ampacity without the need to perform significant tower upgrades and while maintaining their sag limits.

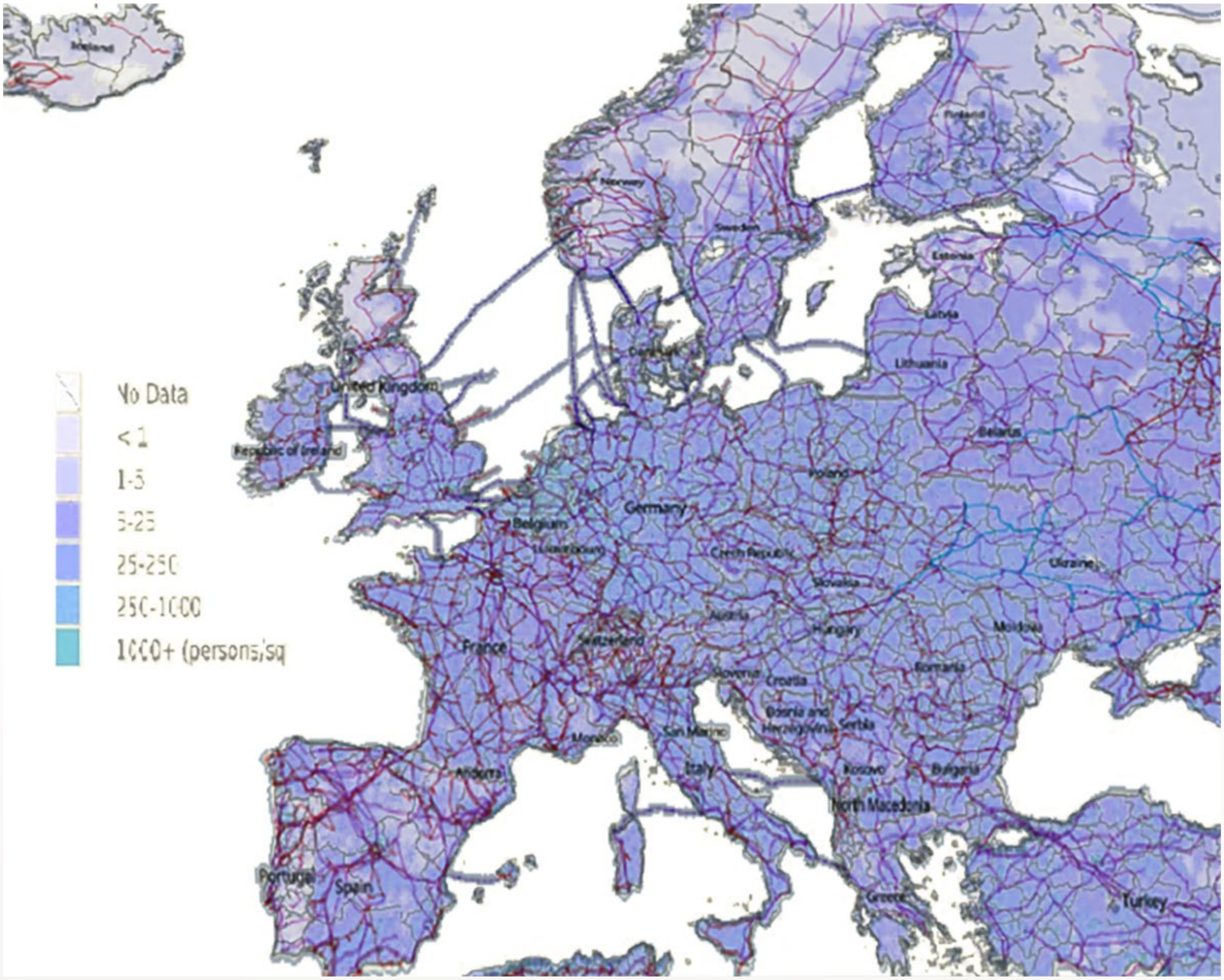
6.3.3 Congo

The Democratic Republic of the Congo (DRC) is another country in the region that has used advanced conductors. In 2023, the population of the DRC was 102 million [40]. The area of the DRC is 2.3 million km^2[41]. Much of the Congolese population is rural, with only 44% living in urban areas in 2018 [42]. The DRC has one of the lowest rates of electrification in the world, with only 20% of the population having access to electricity in 2021 [43]. However, electrification has increased considerably in recent years as the rate of electricity access was only 9% just 2 years earlier in 2019 [44]. Most of the electricity in the DRC comes from hydroelectric sources at 2.8 GW of the country's 2.84 GWtotal [45]. Hydroelectric generation will likely remain the primary source of energy in the Congo, as it is estimated the nation has over 100 GW of hydroelectric potential [45]. In 2013, an ultra-low sag ACCC conductor was chosen for a span on a new double circuit 120-kV line [46]. The span length is ~1.4 km across lake Nzilo. The conductor was chosen due to its high-tensile strength (~2.6 MPa versus ACSR's ~1.4 MPa) and low weight (~70% lighter than ACSR), which made the span possible. In addition to this project, ACCC has been used on numerous projects in South Africa, as well as another long span in Mozambique.

6.3.4 South Africa

South Africa is a nation of 59 million people [47] and spans an area of 1.2 million km^2 [48]. 69% of the population is urban as of 2023 [49]. As of 2021, 89% of the people in South Africa had access to electricity [50]. The total electricity consumption in South Africa was 202 billion kWh in 2021 [51]. In South Africa, significant sources of renewable generation potential exist in the northern, western, and eastern cape provinces. Much of the population lives in the northern province, and the transmission lines in this area are severely congested [52]. In South Africa, it is often difficult to bring lines out of service due to reliability constraints. To address this challenge South Africa has turned to reconductoring with advanced conductors. They have deployed this technique since at least 2010, when they used ACCC to upgrade their 88-kV grid in preparation for the FIFA World Cup [53]. As of 2022, ACCC had been used in nearly two dozen reconductoring projects in South Africa and other countries in southern Africa. One project in particular, which has received media attention was the reconductoring of an 11 km stretch of a 132-kV line by Buffalo City Metropolitan Utility on the eastern coast of the country with ACCC conductor [54]. The objective of this project was to double the capacity of the small line servicing the rural community of East London. The conductor used is only 350 kcmil, and this project is noteworthy because it shows how advanced conductors can provide value even on small capacity lines.

6.4 Europe



Geographically, Europe is the smallest region considered in this study at only ~10 million km^2. It also has the second smallest total population at ~740 million people [55]. Despite this, Europe contains the largest synchronous interconnection in the world, known as the Continental Synchronous Area, which is a single power system covering the majority of continental Europe and providing power to roughly 400 million people. This region includes many asynchronous HVDC links that connect with the other European power systems, as well as portions of the African and middle eastern power systems. Further expansion of these connections is anticipated in the near future.

Europe contains one of the most mature power systems in the world, which is roughly equivalent to the maturity of the U.S. system. Indeed, many of the early milestones in the power industry occurred in Europe, including the first demonstration of the long-distance transmission of AC power and the first demonstration of the transmission of three-phase power. Today, ACSS is a popular technology for transmission lines in Europe. This is partly because conductor manufacturers in Europe offer higher grade steel for the core material of ACSS than manufacturers in the U.S. This enables utilities to string ACSS at much higher tensions, like the Israeli case mentioned above, which mitigates some of the sag concerns of this conductor technology.

On average, Europe has a higher population density than the U.S. Consequently, many of the factors that drive reconductoring projects in the U.S. are even bigger drivers in Europe. These include considerations like environmental permitting and the securing of RoWs. This has resulted in a trend toward the adoption of advanced conductors like that of the more densely populated regions of the U.S., but on a much larger scale. Examples of reconductoring projects using advanced HTLS conductors in the European region are numerous with case studies from almost every country and interconnection. The remainder of this section will showcase examples from Scotland, Germany, and Romania.

6.4.1 United Kingdom

The population of the UK was ~68 million people in 2023 [56] and the nation spans a geographic area of 243,000 kilometers^2 [57]. The total amount of electrical energy consumed in the UK was 270 TWh in 2022 and has been steadily declining for the last two decades [58]. In the UK, reconductoring is often driven by a need to meet environmental constraints. The Scottish and Southern Electricity Networks (SSEN) undertook a reconductoring project beginning in 2017 and ending in 2020, which has received considerable press attention within the power system community [59-61]. The line is a 44-km double circuit 132-kV line running from Fort Augusts to Fort William. The original capacity of the line was 89 MVA and needed to be increased to 198 MVA to meet increasing industrial demand in the area. Major factors considered in this project included the need to maintain a minimum clearance of 6.7 m in every section of the line and difficult terrain that would make tower modifications costly and time consuming. While many different conductors were considered, ultimately, ULS ACCC Monte Carlo was chosen for its high ampacity and ultra-low sag characteristics. This choice enabled SSEN to double the capacity of the line while retaining 97% of the original structures.

6.4.2 Germany

Germany is a country of 83 million people [62]. In 2021, 77% of the German population was urban. In 2022, Germany consumed a total of 582 TWh of electrical energy [63]. In Germany, a reconductoring project was undertaken between 2011 and 2012 [64]. Around 2011 the German utility Westnetz had started to experience issues in the Hunsruk region due to increased penetration of wind generation in the area during off-peak hours. It was decided to deal with the excess generation by transmitting it toward the substation at Waldlaubersheim. To meet the increased power transfer, the existing transmission line needed to upgraded. Several options were considered, including reconductoring with a high-temperature ACSR or rebuilding the line to support a double-circuit ACSR. Ultimately, the utility decided to reconductor the line with ACCC based on several factors. First, while the conductor price was much higher than ACSR, using ACCC allowed the utility to avoid refurbishing all but one of the towers, which made the project cost roughly equal to the other reconductoring option considered. Second, while the costs were roughly the same between both reconductoring options, the project timelines were not. Avoiding tower modifications would reduce the project timeline considerably, which was crucial since additional wind generation was scheduled to come into service at the end of 2012.

Finally, the ACCC conductor has more conductivity than ACSR, which would enable the utility to profit more from the new wind turbines. The installation of the conductor took place between June and August 2012—remarkably short for most reconductoring projects.

6.4.3 Romania

Romania is a country in eastern Europe comprised of slightly less than 20 million people [65]. The urban population of Romania is low compared to other European nations, with only ~54% of the population living in urban centers [66]. The total electrical energy consumed was 50 billion kWh as of 2023 [67]. In 2011, a detailed case study was performed by researchers in Romania on the feasibility of reconductoring a 24-km 220-kV transmission line from South Bucharest to Fundeni [68]. A wide range of different conductor technologies used in power systems around the world at the time were considered. The technologies considered were ACSS, ZTACIR, GTACSR, TACSR, ACCR, and ACCC/TW. The case study included a full analysis of the mechanical, electrical, and economic factors for the project. Each potential solution was ranked according to its attractiveness to the utility based on multiple factors, including cost, capacity, sag, and efficiency. The study found that any of the considered conductors would likely meet the technical needs of the project. Therefore, despite many of these technologies not being used in the U.S. this study shows that they should be considered as viable options. Both ACCC and ACCR had higher capital costs than the other options. Combined with their novelty at the time, they were not seen as attractive options. Mostly used in Korea and Japan, ZTACIR was considered viable due to the low tension of the project and the relatively low ice loading in Bucharest. The increased cost of installation and maintenance from the special handling required by GZTACSR made it an unattractive option. Ultimately, the project concluded the most attractive options were ACCC/TW or ACSS. The TSO decided to use ACSS due to their low experience in maintaining ACCC and its higher cost. This study represents one of the most exhaustive public studies on the choice of advanced conductors for reconductoring and serves as an example of the considerations and methodology that should be employed by all utilities when planning these projects.

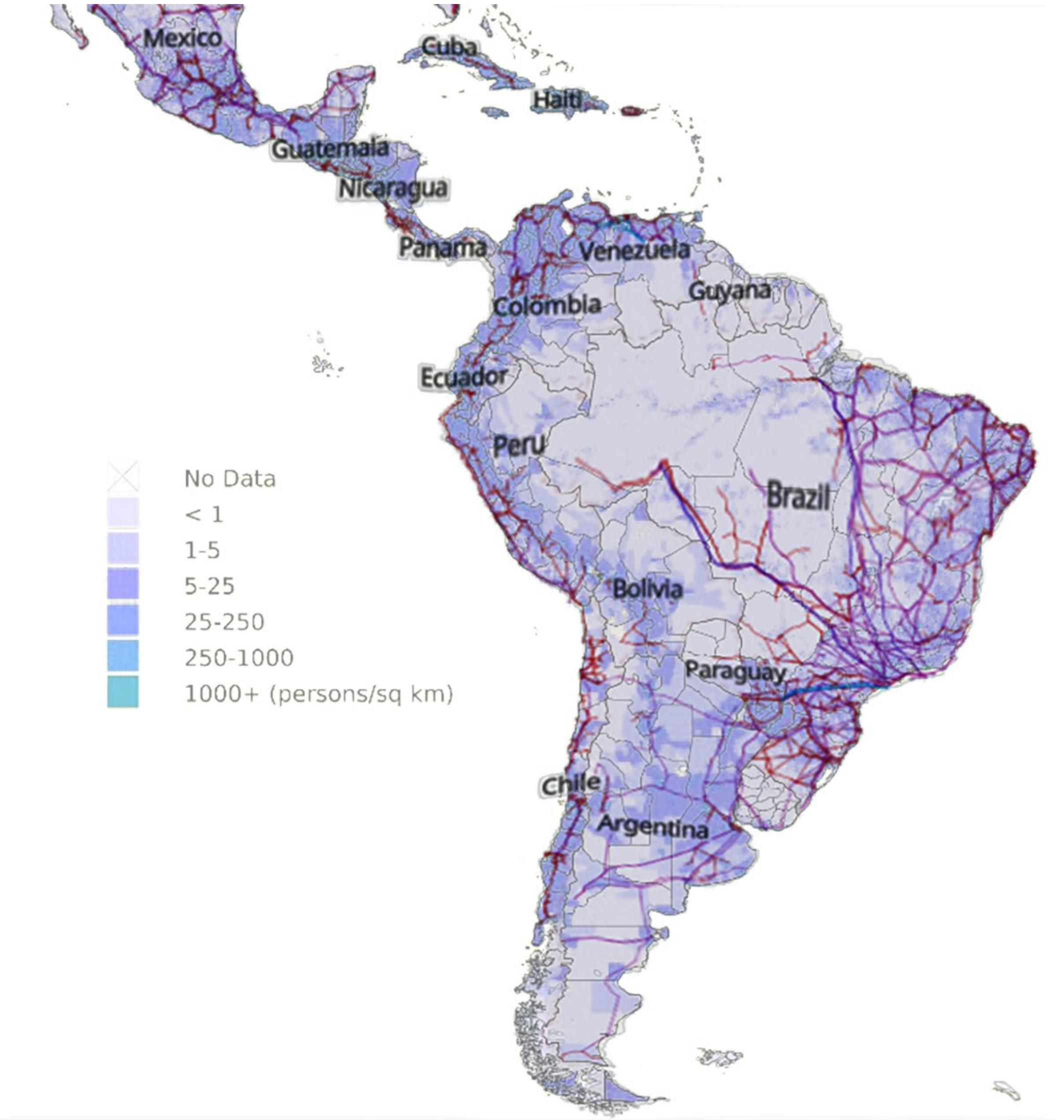
6.4.4 Belgium

Belgium is centrally located within the European power system. It is one of the smallest countries in Europe at only ~30 thousand km^2 [69]. It also has one of the highest population densities of any European nation at 382 people per km^2 [70] The total power consumed in Belgium was 81 billion kWh annually as of 2023 [71]. Consequently, the Belgian power system supports considerable transfers of power. This power not only supplies local loads but serves to transfer power between the surrounding regions. This situation is similar to the power systems of southern Oregon and northern California that facilitate large transfers of power between the generation centers in the north and the load centers in the south. Combined with the planned closure of all nuclear plants in the country by 2025, the Belgian transmission utility Elia saw a need to double the capacity of the existing 380-kV transmission system beginning in 2013 [72]. This utility already had some experience with advanced conductors having installed ACCC for the first time in 2009. The project began in 2013 with the use of an ACCC conductor on a 19-mile stretch of line. Between 2015 and 2017, the utility installed another 14 miles of advanced conductors including ACCC as well as the Lo-Sag ACPR conductor produced by the French company Nexans [73]. ACPR is similar to ACCC or TS conductor in design but features Z-shaped conductor strands designed to minimize wind loading and is not sold in the U.S. See the section on Brazil below for more information about ACPR conductor. Elia also installed an additional 71 miles of advanced conductors between 2017 and 2022, including a river crossing that used specialized ZTACSR, a type of ACSR that uses a high-temperature aluminum alloy.

6.4.5 Russia

Russia is the largest country in the world by area, spanning a region of 17 million km^2 in both Europe and Asia [74]. Russia is the ninth largest country in the world by population with a total of 146 million inhabitants [75]. They are the fourth largest consumer of electricity in the world with a total production of 943 billion kWh in 2019 [76]. The Russian power system was developed relatively late compared to the power systems of America and the rest of Europe. Electrification was a top priority during the Soviet era, and the Russian power system expanded rapidly during this time [77]. Access to electricity in Russia was at 100% in 2021; however, this number has fluctuated over the past few decades with a low of 95% in 2015 [78]. The Russian power system is largely state owned; however, it has progressed toward privatization since the early 2000s [79]. Russia has adopted advanced conductors at a comparable rate to the U.S. By 2012, ACCR had been deployed on two different lines to relieve congestion in Moscow and a total of eight lines in the country as a whole [80]. At the time, Russia had the second most deployments of ACCR, following the U.S. [81] and has continued to use the conductor extensively. ACCC has also been installed in the Russian system in recent years. This conductor has primarily been installed in the northern regions where temperature variations, wind loads, and ice loading are the main concern. This includes projects in Siberia in 2014 [82] and in Tatarstan in 2021 [83]. One novel application of an advanced conductor undertaken in the Russian system was the use of ACCC for an overhead ground wire system in 2019 [84]. This installation was part of a pilot project to test a de-icing system where overhead protective ground wires are heated to over 100°C to melt ice on the transmission wires.

6.5 Latin America



The term "Latin America" does not have a rigid definition. For the purposes of this work, it refers to the predominately Spanish- and Portuguese-speaking nations to the south of the United States and includes the nations in South and Central America including Mexico and the Caribbean islands. This region comprises an area ~7.5 million miles^2 and a population of ~650 million people [85]. The power system is relatively mature in this part of the world, with over 90% of households having access to electricity in most urban centers [86]. Even in the rural parts of this region, electricity is available in more than

90% of homes in the upper- and middle-income nations and is still over 50% in the lowest income nations. Overall, Latin America is a success story for electrification. In 1970, only ~50% of the population had access to electricity compared to 98% in 2021 [87, 88]. Latin America is a global leader in green energy with 63% of the energy in the region coming from renewable sources, mostly hydroelectric (45%) [89].

Electrification efforts in Latin America have slowed in recent years. This is largely due to the difficult terrain in the more remote population centers [87]. This includes natural barriers, such as the Amazon rainforest, remote Caribbean islands, and the Andes Mountains. In these cases, building traditional transmission and distribution networks is often not practical, so local electrification is achieved with microgrids. Due to the recent electrification push, the grid in this region does not have the same problems with aging infrastructure or congestion as Europe, Asia, and the United States. Regardless, HTLS conductors have still found uses in this region in a number of applications.

6.5.1 Argentina

Argentina has one of the older power systems in this region. Argentina is the 9th largest country in the world by area at 2.8 million km^2 [90]. Argentina is a heavily urbanized country with a total population of 45 million people, 92% of which live in an urban area [91]. It is the thirty-third most populous country in the world [92]. Argentina is another country that has seen rapid electrification in recent years, first reaching 100% electricity access in 2014 [93]. They have begun to adopt HTLS conductors for many of the same reasons as the rest of the world. One recent project was the reconductoring of a 14-km 132-kV line in Mendoza City [94]. The purpose of this project was to increase the capacity of this critical line. This line was so critical that much of the reconductoring work had to be performed at night and on the weekends to minimize outages, and in some cases the lines were energized before they had even been clipped off. EDEMSA (the utility that owns the line) opted to use ACCC because it allowed them to complete the upgrade in a short amount of time and provided the best economic benefit. This project was the 12th in Argentina to utilize ACCC, and brought the total amount of ACCC installed in the Argentinian power system to ~350 km. This makes Argentina competitive with many other power systems in their relative level of adoption of advanced conductors. Like in other systems, the motivation for reconductoring is the need to meet increasing demand while preserving existing structures and RoWs.

6.5.2 Panama

Another example of the use of ACCC conductor in this region is in Panama [95]. Panama is located in central America with a total area of 75 thousand km^2 [96] and a population of 4.3 million people [97]. As of 2021, 95% of the population in Panama had access to electricity [98]. The Panamanian system is unique; not because of the specific conductor application, but because of the regulatory incentive driving the choice of conductors. Power transmission in Panama is provided by a single state-owned utility called Empresa de Transmision Electrica (ETESA) [99]. The law that created this utility includes two provisions that have directly driven capacity expansion and the use of efficient conductors [100]. The first provision guarantees the utility will earn a 13.7% return on new assets and the second allows the utility to retain any profits when the system efficiency is >96%. As a result, ETESA has been actively pursuing advanced conductor technologies with higher efficiencies, because the regulatory incentives allow them to offset the higher capital costs with increased profits.

6.5.3 Brazil

Brazil is the largest country in Latin America, with an area of 8.5 million km^2 and a population of 217 million people [101] as of 2023. Most of the population is concentrated along the coast in a few major population centers [102]. Roughly one-tenth of the entire population lives in Rio de Janeiro—or its greater metro area [103]. Historically, Brazil was one of the fastest growing nations in the western hemisphere, though its growth has begun to slow considerably [103]. Brazil is a rapidly developing country. Electricity access in Brazil reached 100% for the first time in 2020 [104]. Roughly two-thirds of the electricity in Brazil comes from hydroelectric generators [105]. To meet increased load demand and in anticipation of several world events being hosted in Brazil, the utility company Light began a project in the late 2000s in collaboration with the French cable manufacturer Nexans to develop a new advanced conductor that would be ideal to meet the needs of the Brazilian power system [106]. The result of this collaboration was the Lo-Sag ACPR conductor, which has been used on multiple reconductoring projects in Brazil and in Europe [107]. This conductor is similar to the other composite core technologies profiled in this report. The finished conductor is produced by Nexans but the core material is produced by Mercury Cable. Beginning in the early 2010s, a series of lawsuits were filed between CTC Global, Nexans, and Mercury in both the U.S. and Europe over patent infringement claims. Rulings in the U.S. have tended to uphold the patent claims of CTC, while rulings in Europe have tended to favor Nexans and Mercury. As a result, ACPR is not available in the U.S., but can be found in many other parts of the world.

6.6 General Trends

As has been shown, advanced conductor technologies have been used in power systems around the world and are often used in ways that are different from in the U.S. While every power system is different and every transmission or distribution line project is different with its own unique considerations, some broad trends can be observed. From these general trends, several common use cases can be extrapolated. The rest of this section describes each of these use cases and the regions where they are most commonly found.

6.6.1 Permitting Concerns/Securing RoWs

When utilities need to increase the capacity of a particular line, the biggest challenge (and cost) is often obtaining the necessary approval for the work. Even when permitting is not a significant constraint, acquiring RoWs and tower construction costs dominate the budget of most projects. Comparatively, the cost of the conductor itself is usually small, regardless of the technology used. When an advanced conductor enables an increased capacity through a simple reconductoring instead of a rebuild, most utilities will choose that option regardless of global region.

6.6.2 New Constructions

New lines are designed to meet current and projected demands. For most lines, by the time load increases have grown to exceed line capacity, the line needs to be rebuilt anyway. Because advanced conductors are more expensive than ACSR, they are rarely used in new construction. The exception to this rule is in places where the projected capacity for the new line is such that using an advanced conductor in the design can save more on tower costs than the additional cost of the conductor. Examples of this can be seen primarily in Asia where there is significant demand for new transmission lines.

6.6.3 Old Structures/RoW Constraints

Advanced conductors are almost never used to reconductor old lines. Such lines often need to be replaced anyway. This is again because of the cost of tower construction and permitting. If a line has aging structures and is overloaded, it is usually a good candidate for a full rebuild. However, exceptions exist to this rule as well. Often in developed regions, it can be difficult or costly for utilities to acquire the permits or RoWs to rebuild a line at a larger size. When more capacity is needed, but the utility is tightly constrained by their RoW, advanced conductors can be an attractive option even if tower rebuilds are required. Examples of these types of projects can be found in some of the more tightly regulated power systems in Europe as well as the United States.

6.6.4 Long spans

Because advanced conductors are designed for similar sag and tension ratings as an ACSR, the number and size of towers is usually the same regardless of the conductor. The notable exception to this rule, where advanced conductors have seen applications, is for long spans. In these cases, the lower conductor weight can be utilized to reduce tensions, enabling longer spans and saving cost on structures. There are examples of advanced conductors being used for this purpose in all power systems but is particularly common in remote areas of developing regions.

6.6.5 Efficiency

Most advanced conductor technologies have smaller cores than equivalently sized ACSR. Additionally, these technologies often use trapezoidal wires or similar shapes for the conductor strands. This allows more aluminum to be concentrated in the same wire diameter. Some of these technologies also use annealed aluminum, which is more conductive. All of these factors make most advanced conductors more conductive, and consequently more efficient than ACSR of the same diameter during most operating conditions. Some countries around the world have enacted regulatory structures that incentivize utilities to consider efficiency in transmission line design. Examples of advanced conductors being used in transmission line projects for their efficiency can be found in Latin America, Asia, and Europe, as well as the U.S.

6.6.6 Primary use case

While the above scenarios are all examples of advanced conductor applications, there is one scenario where advanced conductor use is most common. This is when the load profile of a line has increased in a way that was not anticipated by the original design. Changes in economic conditions, such as new technologies, environmental conditions, and wars, can all drive mass migrations of populations. As a result, sudden population shifts or the creation of new industrial centers can dramatically increase the loading on relatively new lines, and sometimes in unexpected places.

The ideal situation for reconductoring is one where there is a line with relatively new structures, either a new build or recent rebuild, and shifting demand has been such that the line is now overloaded. In this situation the option for the utility is to either rebuild the line to a higher rating, build a parallel line, or reconductor with a higher capacity wire. The first option is very expensive because the existing line must be removed in addition to the cost of building the new line. Furthermore, the new line may not fit in the existing RoW and expanding the RoW may be impossible. In general, this is an unattractive option for most utilities. The second option is essentially the same as building a new line in terms of costs, permits, and RoWs. Compared with the first two options, the third option will usually be much cheaper, faster, and easier to get approval. This is true regardless of the region in which the utility operates and examples of advanced conductors being used for this purpose can be found in every region of the globe.

6.7 Lessons for the U.S.

This section has showcased examples of how ACTs are being used around the world. While in general the factors utilities consider when planning T&D projects are the same globally, this section has featured some examples of advanced conductors being used in ways that are different from how they are used domestically. Not all of these situations may be directly applicable to the U.S.; however, there are still some opportunities that can be identified. First, while most projects tend to be on lines with nominal voltages between 100 kV and 200 kV, this section provides examples of advanced conductors being used on distribution voltages as well as transmission voltages, meaning these technologies should at least be considered for any project. Second, advanced conductors are primarily used in the U.S. for reconductoring projects; however, this section has described several examples of advanced conductors being used on new constructions. This is usually only seen on lines with much larger capacities than those typically found in the U.S.; however, if the transmission system is to be expanded appreciably, these technologies may be good options. Third, this report has focused on ACSS, ACCC, ACCR, TS, and C7 because these are the most prominent technologies in the U.S. However, as this section shows, there are many other technologies available globally. There are many reasons why these technologies are not used in the U.S.; however, if these barriers can be overcome, the availability of these technologies could give domestic utilities more options and the increased competition may lower conductor costs overall. Finally, this section has showcased novel applications for advanced conductors not commonly found in the U.S., including overhead ground wires and HVDC lines. The main take-away is that domestic utilities and regulators should not constrain themselves only to domestic examples when considering ACTs, since a broader range of experiences exists globally.

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SECTION 7: Future of Advanced Conductors

7.1 Introduction

The future market position of advanced conductor technologies (ACTs) is a complex question. Most of the utilities interviewed for this report agree that advanced conductors are gaining steady ground with some moving from trial adoption to general acceptance. ACT technologies offer a scattered mix of new and advanced capabilities while also presenting a range of unknown performance characteristics in highly demanding environments.

Each of these new technologies must compete in a complex technological ecosystem with extremely diverse environmental and economic demands. It is likely that the proliferation of new conductor technologies currently being presented to the US and global utilities will experience a process of natural selection where less competitive technologies will be eliminated over time. The surviving technologies will either find an enduring market niche or exceed the performance of currently accepted technologies and become the dominant system deployed for conductoring/reconductoring projects.

During the scan, many descriptions of industry limiting factors for deployment of ACTs were identified. Some the concerns were skilled work force, conductor aging/durability, incomplete test data, installation challenges, service support, value proposition, special tooling, specialized connectors and equipment, technology maturity, maintenance, lead time, etc. However, the two most common reoccurring categories that the issues could be grouped into were ease of installation and credible life expectancy of the conductor. Utilities are looking for conductors that are easy to install and last a very long time.

The appetite for new technologies among the utilities is real, as most of the utilities profiled have tried one or more ACTs. Initial deployments have been met with a mix of good and bad experiences that have shaped their ongoing conductor selection. Projects are assessed with a range of new technologies in mind working toward the goal of improving operations and customer service, reliability, and cost.

7.2 Technology Competition

Today, a rich ecosystem of technologies exists all competing to solve the complex balancing problems utilities have with environmental stewardship, accountability to ratepayers, durability, stability and efficiency of the system, maintainability, renewable generation integration, etc. The systems available include new advanced conductors, new line sensors, dynamic rating schemes, storage, power flow control, enhanced safety, etc. In addition to the technologies currently available, there is an even larger number of technologies being developed. The utility engineers must understand the interoperability, cost, durability, maintenance requirements, security, etc., and ultimately the value proposition for each of these new technologies. When faced with a technical problem, all the available options are typically considered against the specific needs of the project.

Several Advanced Conductors technologies are competing in the marketplace, along with other grid enhancing technologies. For conductors, there are technologies that range from aluminum and steel systems to carbon-fiber, carbon-composites, and carbon nano-material additives mixed with aluminum or steel, and even nitrogen-cooled superconductors. The list of existing technologies and technologies being developed is impressive.

Currently ACSR, ACSS, ACCR, ACCC, TS, C7 E3X, and 3Ms ceramic metal core are conductors that are on the market and have been reviewed for this report. One very interesting new technology in the competitive space is superconducting power lines. After the discovery of superconductors that could operate at temperatures far above absolute zero (in the range of liquid nitrogen), applications emerged for magnets, MRI machines and more exotically the magnets for the CERN Large Hadron Collider and the ITER fusion reactor. Work to develop power line conductor systems that could practically eliminate line losses has continued and superconducting power lines are a cutting-edge technology currently competing in the market. One notable example is a 1 km installation of Nexans super conducting cable in Essen Germany. None of the utilities we interviewed specifically discussed any intentions to use superconductor technology; however, the systems do offer some incredible capabilities, including five to ten times the capacity.

The technologies Achilles heel is the need to operate at -320°F. The historic solution has been to create a flow circuit of liquid nitrogen to cool the line. This has technologically limited the application of superconducting power lines to relatively short runs. A new technology from Veir offers a system with an open loop liquid nitrogen cooling system. The technology divorces superconducting power lines from the closed loop nitrogen system, which creates the potential for long line operation. Veir's system also offers a vacuum jacket that removes the conduction and convection heat transfer from the environment into the cooled line, which massively reduces the cooling burden and improves the efficiency of the nitrogen cooling system. The utilities interviewed were overwhelmingly bullish on ACTs but were not completely sure about which one would prove to be most effective over the long haul.

Unique design factors can significantly impact conductor selection. While the ACSS system enjoys the widest acceptance so far, 3Ms technology ACCR, and TS have some very strong supporters among utilities. ACCC can provide some incredible performance value but also has historically had ice loading issues that often lead to early removal from consideration for cold climates. Ice loading performance has been improved for the technology; however, lingering perceptions of those icing issues remain.

The technological evolution of the power grid and other industries have repeatedly shown when a host of new technologies is presented to the U.S. or global industry, the process of natural selection will down select to the most competitive technologies over time. It is reasonable to draw parallels to the current technological landscape for technologies designed to manage congestion, improve capacity, efficiency, and renewable penetration. Because utilities need to streamline and standardize their equipment to the greatest extent possible, the competitive environment will naturally down select the options to the systems that present the best value proposition.

7.3 Future Demand

There is a need expand transmission capacity rapidly and to replace/upgrade a large portion of the transmission grid that is aging. The U.S. and the rest of the world need technological solutions commercially available to renew, enhance, and harden critical infrastructure. Utilities have overwhelmingly indicated a positive attitude toward ACTs; however, they are also very concerned about the responsibility they have to their customers and the environment. A conductor that fails can cause catastrophic fire or other significant harm to the community; a conductor that must be replaced too often or is difficult to install or maintain can create undue financial hardships on the customers they serve. One very prominent theme that presented itself during the scan was the need for extended pilots. While the ACTs have excellent potential and some of them have been in the market for 20 years, the interviewees expressed desire to see more trials and testing through pilot programs in low-risk corridors. Most utilities desire multiple pilots and test programs to enhance the body of data needed to move to large scale deployments of ACTs. A lack of industry standards for most advanced conductor technologies and their accessories is also a barrier to adoption. Industry standards are typically developed with collaboration between manufactures, utilities, and other stakeholders. Very few standards exist for advanced conductors, leaving it up to utility engineers to individually evaluate manufacturer performance claims. As the future unfolds for individual technologies, there are three potential paths. First a technology can fall into niche applications where its attributes make it an ideal solution for problem. For many advanced conductors, reconductoring is the ideal use where ACSR conductor on existing structures can quickly be replaced with higher capacity conductors with minimal modification to the structures. Because every line has different characteristics, a variety of conductors will find lasting niches based on differing mechanical and electrical performance requirements, so long as the technologies meet the basic needs of reliability.

The second technology path leads to market dominance. Currently, ACSR is still the most widely deployed conductor and has been the dominant overhead transmission conductor technology for decades. Prior to the increased use of aluminum conductors, many different designs of copper conductor competed in the market. ACSR has achieved a position of dominance slowly and because of decades of positive performance and a reliable track record. Many types of ACSR such as self-damping conductor, oval-profile conductors, and expanded-diameter conductors have fallen out of use while ACSS has taken a significant amount of the market from ACSR with many utilities even standardizing on its use for specific voltages or applications. Continued improvement of ACSS technology to improve on its deficiencies in strength have expanded its range of applications. Now, newer composite core conductors are attempting to take market share from both the ACSR and the latest advancements of ACSS. The wide adoption of ACSS has created momentum that will be difficult for other technologies to overcome in the short term, even with equivalent performance. Today, there are some attributes where composite core conductors show clear advantages, such as lower sag, weight, and efficiency. ACSS still dominates in capacity, cost, and familiarity.

Should a new technology or iteration of an existing technology enter the marketplace that can outperform ACSR and ACSS on the myriad of competing design factors, the new conductor may ultimately achieve dominance. While it will be met will initial cautious optimism, it will first be tested and deployed in limited low impact locations until sufficient data proves the superiority of the technology. At that point adoptions should accelerate.

The third and final path leads to extinction. As the evolutionary process reduces the diverse menu of conductor technologies to a smaller list of products, there will also be technologies that fail to dominate or find market niches. The selection process is constantly occurring, different utilities are trying the different ACTs in highly diverse scenarios. Some utilities are moving forward with wider deployments, while some are pulling back after disappointing results after pilot projects. It is unclear what path each technology will take but it is clear that few utilities will widely adopt a system that cannot satisfy the basic requirements of longevity, robust operability, and maintainability.

Today, there is ongoing research and continual progress being made on ACT technologies. In the past two decades, both composite core and steel core conductors have gotten stronger, and for steel core conductors still stronger cores are being used in Europe. New composite core conductor designs, such as ACCC Infocore and TS Conductor, promise the reduce the risk of conductor breaks during installation. High-emissivity coatings, such as E3X, are being deployed on a wide variety of conductors to increase capacity and improve efficiency. Overhead superconductors, such as those offered by a Veir, are cooled with liquid nitrogen and can offer five to ten times the capacity of tradition conductors. Advancements in alloys and technologies like carbon nanotubes are expected to further enhance performance of conductors.

Ultimately, there is ample demand for conductors now and in the future. Even where a conductor technology achieves dominance, the search for new technologies and materials will not stop; and if a superior product is developed, it will eventually replace the old technologies. Given the challenges of the modern grid, advanced conductor technology is expected to play a major role.

7.4 Conclusion

Advancement in conductor technology has generated a great deal of excitement because it offers the potential to remove and replace existing conductors with advanced conductors while avoiding a long permitting cycle. Grid capacity is needed quickly to accommodate shifting demand, renewable generation, and resiliency. Advanced reconductoring is a great way to do this.

Widely deploying advanced conductors in the immediate future is not without risk as most of the advanced conductor systems have not been deployed long enough to fully understand every drawback or how technologies will perform in the long term in the varied environments in which they must operate. The future is not certain, but society must balance the risks of sticking to standard practices versus the risks of challenging and deploying new technologies that have not been fully vetted. Advanced conductor usage is expected to continue to increase while the technologies continue evolve to offer improvements in durability, deployability, efficiency, capacity, and cost.

SECTION 8: Conclusions

Overhead conductor manufactures are investing in technologies to add the capacity and efficiency to the grid that is so urgently needed to accommodate decarbonization policies. Most utilities have at least limited deployments of advanced conductors, with a few taking steps to broadly deploy these technologies on a wider basis. Reconductoring with advanced conductors is an important tool to rapidly add transmission capacity to the existing grid and can often bypass long permitting approval periods. Reconductoring also reduces costs compared to rebuilding lines. The costs and benefits of both reconductoring and rebuilding on existing line routes should both be considered. Reconductoring can typically double transmission capacity, although losses may increase because of increased current flow and increased resistance from operating advanced conductors at higher temperatures. Rebuilding can increase capacity on a route by 12 times or more where line voltage is increased. Other project types, such as new construction of regional and interregional lines, would be very valuable; however, these projects may not be feasible, at least in the short term. Conductor performance has advanced dramatically in this century and further performance increases are expected. To be widely deployed, some conductor types will need to address industry concerns about fragility during installation and long-term performance. New technologies are being introduced to enhance durability and to verify that conductors have not been damaged . Industry standards must be developed to address questions around performance and compatibility of both conductors and the associated splices and hardware. The challenges to the transmission grid posed by the energy transition are immense, and advanced conductors will play an important role.

Appendix A: Advanced Conductor Use Case Studies

Acknowledgments

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Contents

Utility Scan Introduction

Utility Profiles

The following document includes conductor selection profiles of 44 of the largest transmission operating utilities in the United States (U.S.). Federal power marketing agencies were also included. For each utility, available information on their conductor deployments and technology strategy is included, and exemplary project details for each conductor type are listed. Profiles are based on interviews as well as publicly available documents, such as those from regional planning processes or regulatory filings.

Conductor Application Successes

Of the profiled utilities, a high number have taken advantage of conductor technology advancements beyond ACSR. 95% of the utilities have deployed or have plans to deploy Aluminum Conductor Steel Supported (ACSS) conductors including products with ultra-high-strength steel cores. Seventy percent of utilities had deployed or have plans to deploy other advanced conductor technologies, including ACCR from 3M, ACCC from CTC Global, E3X from Prysmian, TS Conductor, and C7 from Southwire. Many utilities have installed more than one of the technologies. Figure A-1 shows adoption rates for scanned utilities.

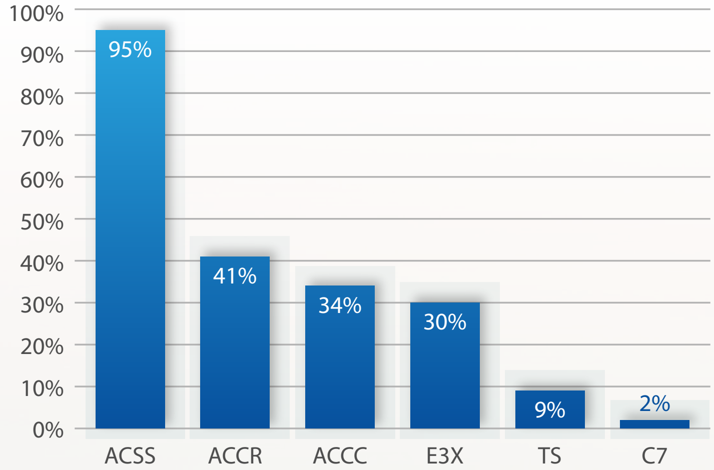

Figure A-1. Percentage of profiled utilities deploying transmission technology.

In the U.S., experience with advanced conductor technologies appears to be high, although many utilities have only limited deployments of any given technology. It seems common for a utility to perform only one or two projects with a given conductor without adopting it more broadly. Other than ACSS, 3M's ACCR was the most commonly deployed technology, followed by ACCC from CTC Global and E3X from Prysmian. Both TS Conductor and Southwire's C7 technology have relatively low acceptance, likely because of the newness of the technologies.

Utility Profile Summary

For the utilities profiled, some have standardized on a given conductor technology for a specific application, such as for a transmission voltage level or for reconductoring. Many other utilities appear to have used a technology for only one or two projects without more broadly adopting it in their system. A few utilities have used composite core conductors but no longer consider them after negative experiences either on their own projects or in the area. This indicates that U.S. utilities are willing to try a new technology but may be hesitant to widely deploy until it has a long track record of positive performance both in their network and at other utilities. The broad adoption of ACSS is likely due to the 50+ year track record, plus its continued evolution to improve performance with advancements, such as trapezoidal aluminum wires, mischmetal coated steel, ultra-high-strength steel, and availability with high-emissivity coatings. Likewise, in the two decades since introduction, composite core conductors have evolved with a proliferation of designs, including higher modulus cores, stronger aluminum alloys, high-emissivity coatings, and technologies to prevent and detect damage to the composite cores during installation and operation. The U.S. grid is built with hundreds of interconnected utilities each making their own engineering and financial decisions on what technology choices are prudent. Conductor performance in the years to come will determine which technologies become dominant and which may fade into obsolescence.

Figure A-2 shows a summary of the deployments by each of the profiled utilities.

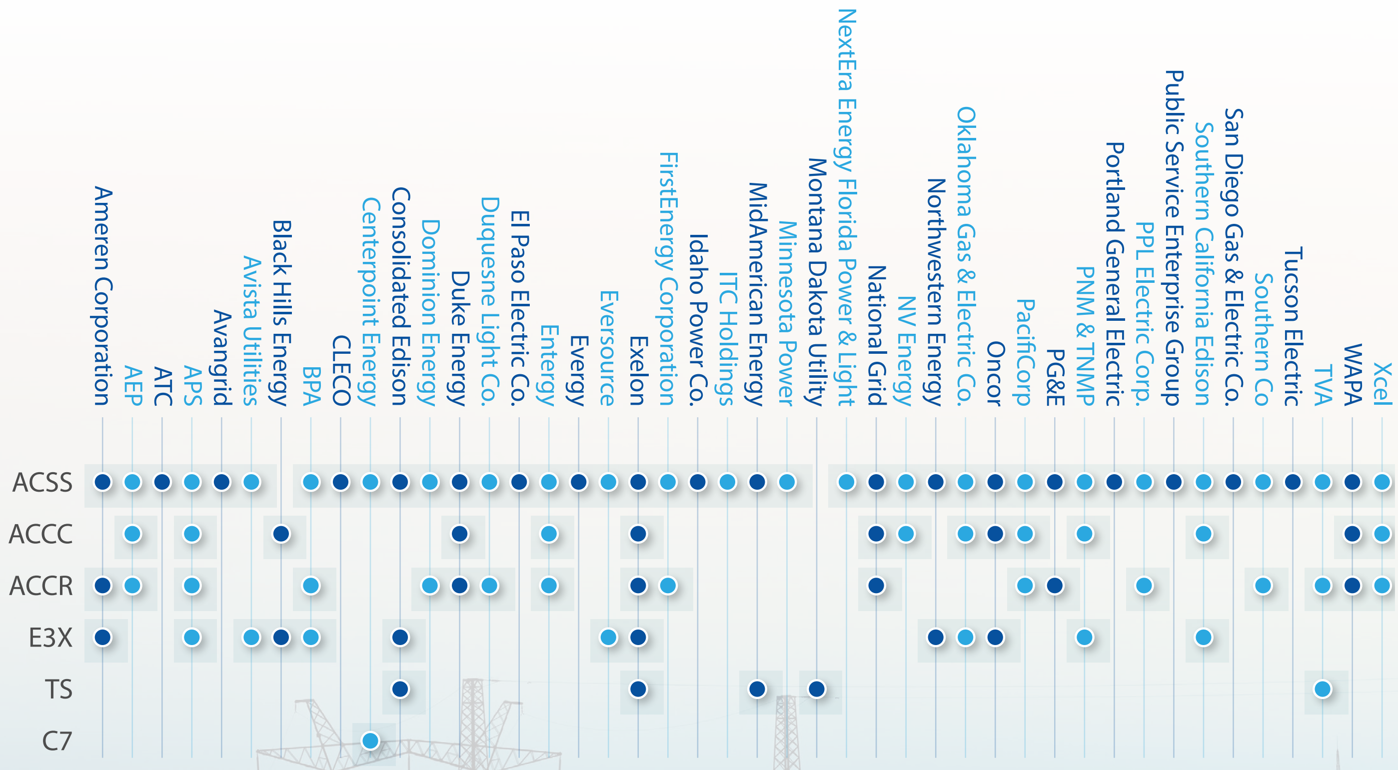

Figure A-2. Summary of the deployments by each of the profiled utilities.

Ameren Corporation

(ACSS, ACCR, ACSS/E3X)

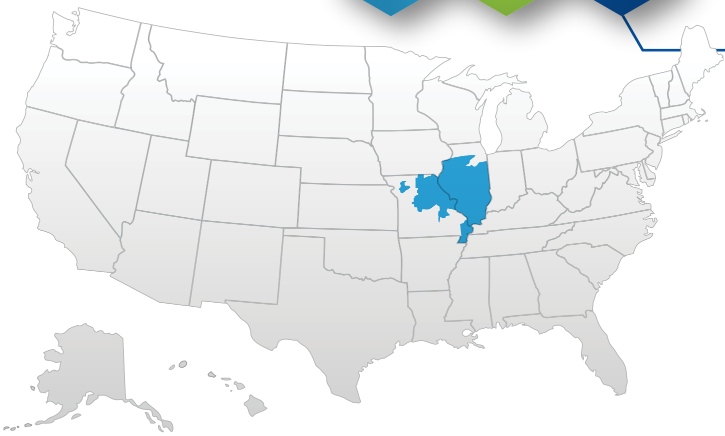

Figure A-3. Ameren cooperation service area (serves Missouri and Illinois).

Utility Profile

Ameren Corporation serves a 64,000 mile^2 area located in central eastern Missouri and southern Illinois (Figure A-3). They serve 2.4 million electric and 900,000 natural gas customers. They operate more than 7,500 miles of transmission lines and own approximately 10,200 MW of generation capacity.

Conductor Application Successes

Ameren Utilites has used ACSS extensively as well as ACCR (Figure A-32) and has designed at least one new line with ACSS with E3X. Ameren's Illinois River project spanned 375 miles and used ACSS for the new 345-kV lines. The ACCR conductor was used for the Page-Berkeley line which was reconductored to increase ground clearances and increase capacity. Ameren has proposed to use ACSS with ultra-high strength steel and E3X coating for a 3,548-foot crossing over the Missouri River.

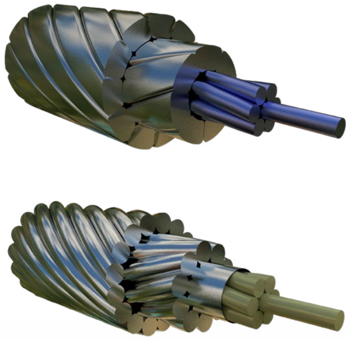

Figure A-4. ACSS conductor (top) and ACCR conductor (bottom).

Exemplary Projects

Year	Project Name	Project Type	Conductor Used	Voltage Level	Line Length	Project Purpose
2020	Illinois Rivers	New Construction	ACSS	345 kV	375 miles	Capacity
2022	Page-Berkely	Reconductor	ACCR	138 kV	unknown	Sag, capacity
Planned	Missouri River Crossing	Rebuild	ACSS/MA5/E3X	138 kV	2 miles	Capacity

American Electric Power

(ACSS, ACCC)

Utility Profile

American Electric Power (AEP) spans over 11 states with 40,000 miles of transmission lines and serves over 400,000 residential and business customers (Figure A-5). They are also one of the largest generators of power with over 25,000 MW of power, 7100 of which is renewable energy and the largest operator of transmission lines in the U.S.

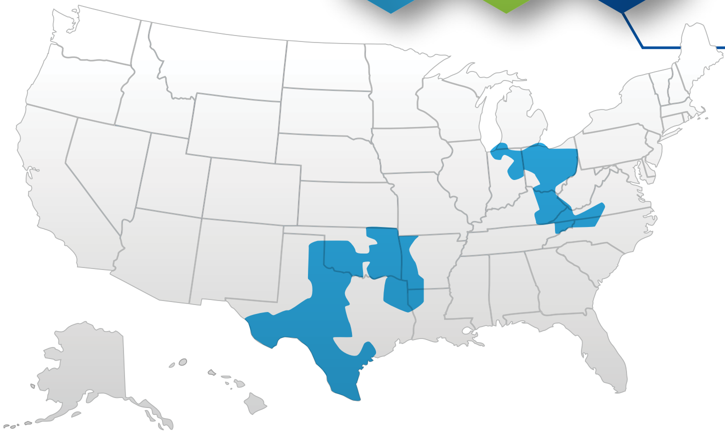

Figure A-5. American Electric Power region.

Conductor Application Successes

AEP is believed to be the largest domestic user of ACCC conductors, having installed ACCC on 26 lines for a total of 447 circuit miles of transmission. In 2015, AEP completed the largest ACCC reconductoring project in the U.S., which was 240 miles of 345-kV circuits. Because of grid constraints this reconductoring project was performed without deenergizing the existing line.

AEP has also used ACCR on two lines for a total of 27 circuit miles. AEP widely uses ACSS conductor for reconductoring and for new construction. In 2021, AEP also indicated a 30-mile 345-kV line reconductor with ACSS conductor (Figure A-7).

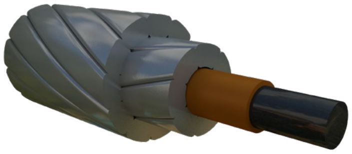

Figure A-6. ACCC conductor.

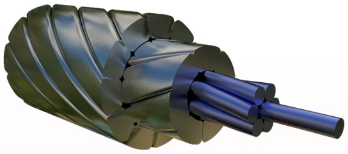

Figure A-7. ACSS conductor.

Exemplary Projects

Year	Project Name	Project Type	Conductor Used	Voltage Level	Line Length	Project Purpose
2015	Lower Rio Grand Valley	Reconductor	ACCC	345 kV	240 miles	Capacity
2021	East Lima to Maddox Creek	Reconductor	ACSS	345 kV	30 miles	Capacity

American Transmission Company

(ACSS)

Utility Profile

American Transmission Company serves parts of Michigan, Wisconsin, and Illinois (Figure A-8). They operate over 10,000 miles of transmission lines and 582 substations.

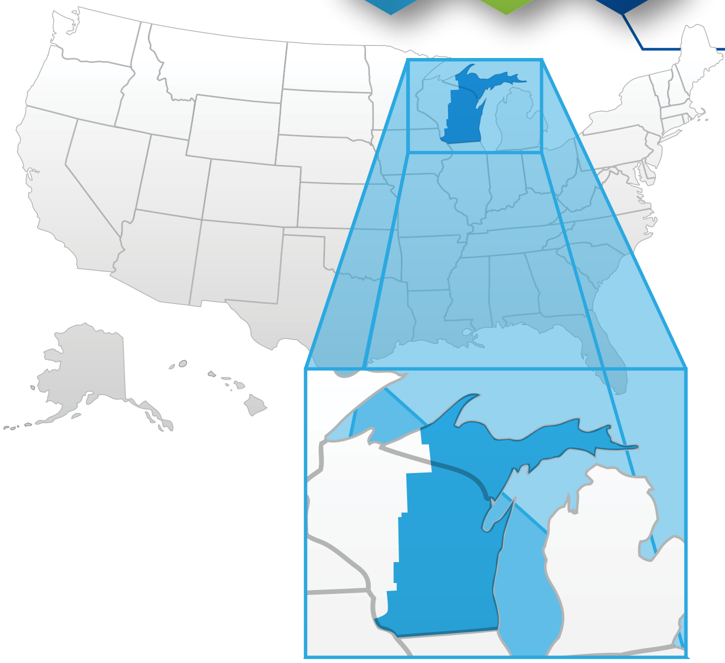

Figure A-8. American Transmission Company service region.

Conductor Application Successes

American Transmission Company constructed the 180-mile 345 kV Badger-Coulee project, which was part of the MISO region MVP project portfolio. This project was primarily constructed with twisted pair ACSR (Figure A-9, top), but portions were constructed with Aluminum Zirconium Alloy stranded ACSR, which is capable of higher temperature operations, and with ACSS (Figure A-9, bottom). Twisted pair ACSR is used to prevent conductor galloping, ACSR with aluminum zirconium alloy (ZTACSR) has higher current carrying capabilities, and ACSS has lower sag than ZTACSR and uses annealed aluminum.

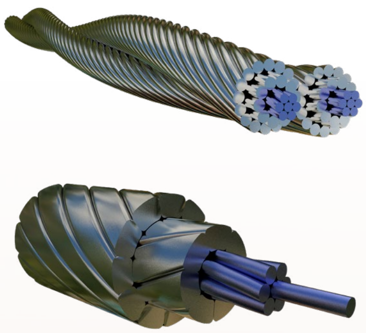

Figure A-9. Image of twisted pair ACSR (top) and ACSS (bottom).

Exemplary Projects						
Year	Project Name	Project Type	Conductor Used	Voltage Level	Line Length	Project Purpose
2018	Badger-Coulee	New construction	ACSR-TP, ACSS, ZTACSR	345 kV	180 miles	MVP project

Arizona Public Service

(ACSS, ACCR, ACCC/E3X)

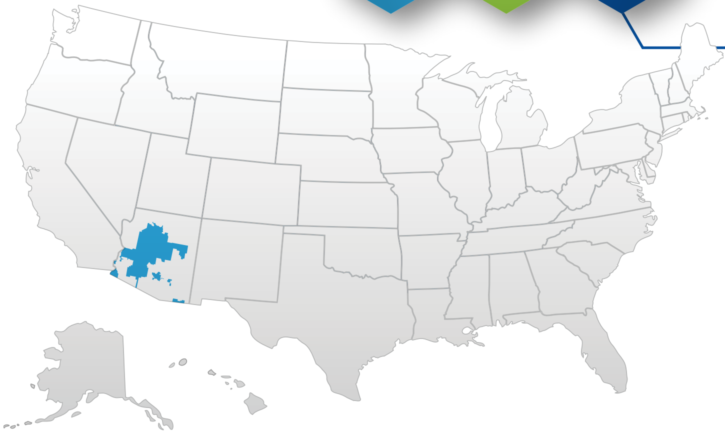

Figure A-10. APS Electric Service territory boundary.

Utility Profile

Arizona Public Service (APS) Provides Electric to 15 counties in Arizona. The transmission system covered for this region is illustrated in Figure A-10.

Conductor Application Successes

APS uses ACSS and ACSR (Figure A-11) for new construction and reconductoring projects. APS has used ACCC with E3X (Figure A-12) and ACCR (Figure A-13) for reconductoring projects in dense urban environments. The urban environments to increase capacity without worrying about clearance issues and replace structures tends leading them to use a composite core conductors.

Figure A-11. ACSS/ACSR.

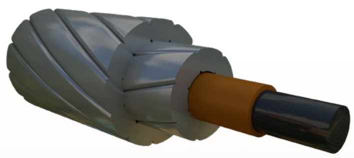

Figure A-12. ACCC.

Figure A-13. ACCR.

Exemplary Projects

Year	Project Name	Project Type	Conductor Used	Voltage Level	Line Length	Project Purpose
Prior to 2010	Phoenix Metro Trunkline	Reconductor	3M ACCR	230 kV	5.5 miles	Capacity increase
2020	Tempe Upgrade Project	Reconductor	ACCC with E3X Coating	69 kV	2 miles	Capacity increase
2015	Palm Valley-Trilby Wash	New construction	ACSS	230 kV	16 miles	Capacity increase

Avangrid

(ACSS)

Utility Profile

Avangrid's has two main operations. Avangrid renewables, which operates renewable energy power plants over 24 different states from the east to west coasts (Figure A-14). Avangrid Networks owns and operates eight electric utilities, which serves over 3.3 million customers from New York to New England. Avangrid Renewables is the third-largest renewable energy company, which includes both onshore and offshore assets. Avangrid Networks electric utility companies include Central Maine Power, United Illuminating, New York State Electric and Gas, and Rochester Electric and Gas Company.

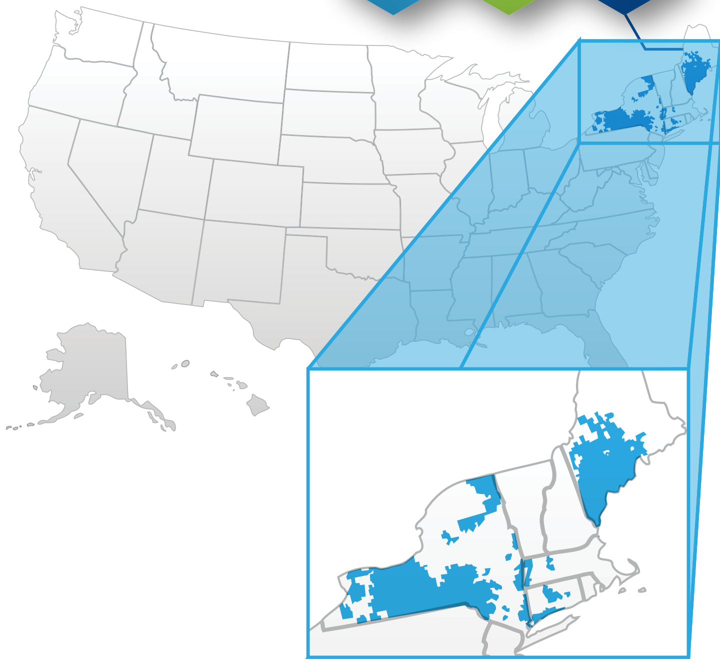

Figure A-14. Avangrid service area.

Conductor Application Successes

Avangrid had previously used ACSS (Figure A-15) in their system on a long span over the Housatonic River. The Derby Junction-Ansonia project is an example of how utilities have been increasing capacity on existing corridors for close to 100 years. The line had originally been built in 1924 of steel lattice towers and operated at 13.8 kV. In the 1930s, the line was upgraded to 69 kV and in the 1960's, upgraded to 115 kV. An eight-fold increase in voltage would have increased capacity by the same factor of eight. United Illuminating, the Avangrid operating company in Connecticut, considered upgrading the line one more time to further increase capacity by reconductoring with an ACSR with E3X, but upon inspection realized a high percentage of the lattice structures and foundations would need significant work and opted for a rebuild instead.

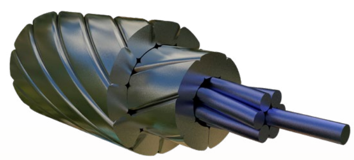

Figure A-15. ACSS conductor.

The rebuild considered ACSR and ACSS, and ultimately selected ACSR to meet future needs. Should future demands require increasing capacity again, advanced conductors will be able to double the capacity again on the same route.

Exemplary Projects

Year	Project Name	Project Type	Conductor Used	Voltage Level	Line Length	Project Purpose
1930's and 1960s	Derby Junction-Ansonia	Voltage uprate	Copper	13.8 to 69 to 115 kV	8.2 miles	Capacity increase
Planned	Derby Junction-Ansonia	Rebuild	ACSR	115 kV	8.2 miles	Capacity increase and reliability

Avista Utilities

(ACSS, ACSS/E3X)

Utility Profile

Avista operates over 30,000 miles[2] spanning from Washington, Oregon, Idaho, and Alaska (Figure A-16). Their grid is powered by 59% of renewable energy largely due to the vast hydro resources available in the Washington area, but also has wind, biomass, natural gas, and coal.

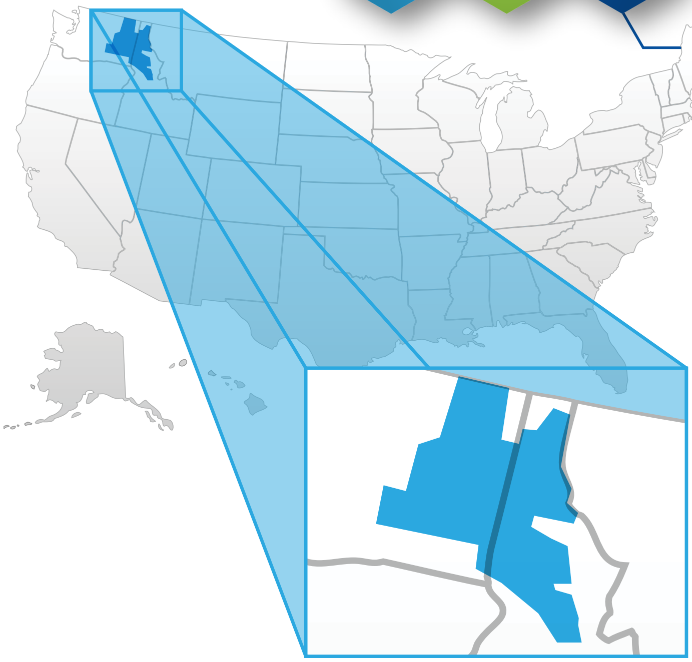

Figure A-16. Avista service area.

Conductor Application Successes

Avista Utilities has used ACSS (Figure A-17) in their system. Generally, projects considering this conductor involve building new towers to add redundancy and additional capacity into narrow corridors. E3X is a special coating placed on conductors that facilitates faster heat transfer away from the conductor. This results in the conductors being able to cool faster from electrical resistance heat generation. Thus, the E3X coating enables power lines to support power loading up to 25% beyond their normal rating. For example, ACSS without E3X coating can double power capacity in comparison to traditional ACSR. E3X can add an additional 25% capacity.

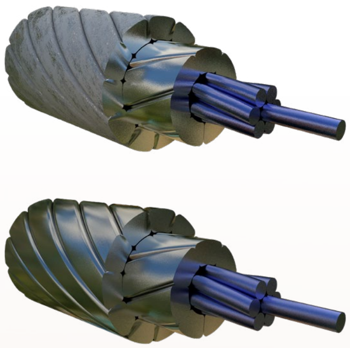

Figure A-17. ACSS cable with (top) and without (bottom) E3X emissivity coating.

Upgrading the Benton–Othello line was deemed necessary after engineering analysis revealed increased peak loading during the summer could exceed capacity. If the Benton–Othello line was lost, it could affect other areas in the system resulting in blackouts or increased system fragility.

The Ninth and Central project replaced wood poles from the 1940s while increasing line capacity through a residential area. ACSS with E3X coating was leveraged, which increased the ACSS conductor capacity by 15% beyond the upgrade the project had already planned with standard ACSS. The E3X coating dulled the wire just like a non-specular conductor (i.e., it does not reflect the sunlight) to reduce the visual impact of the new installation. The previous lines lasted over 70 years, and Avista hopes to achieve a similar longevity out of this line upgrade without disturbing the residents along the right of way.

Exemplary Projects

Year	Project Name	Project Type	Conductor Used	Voltage Level	Line Length	Project Purpose
2020	Benton-Othello	Rebuild	ACSS	115 kV	26 miles	Capacity
Ongoing	Ninth & Central-Sunset	Rebuild	ACSS/E3X	115 kV	7 miles	Capacity

Black Hills Energy

(ACCC, ACCC/E3X)

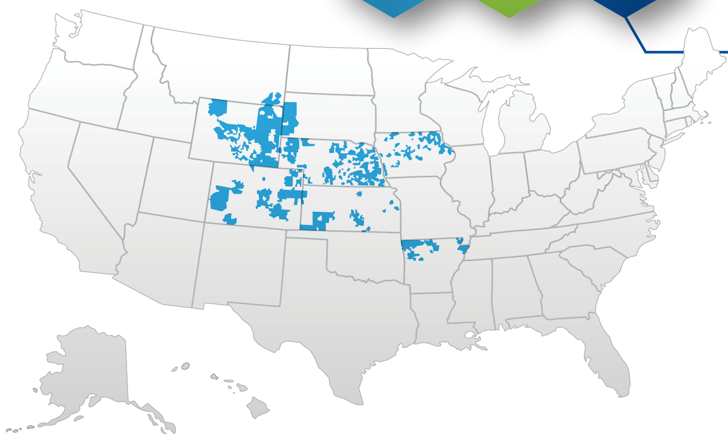

Figure A-18. Black Hills Energy region.

Utility Profile

Black Hills Energy provides electricity and natural gas to approximately 1.3 million customers (Figure 18).

Conductor Application Successes

In 2014, Black Hills Energy completed their first reconductoring with ACCC to increase the capacity in Spearfish, South Dakota. The ACCC conductor (Figure A-19) provided increased capacity without the need to add new structures or reinforce existing transmission towers. In 2018, Black Hills reconductored a 115-kV line in Cheyenne, Wyoming that had been built in 2013 using ACSR. Because of heavy growth from data centers in the area, more capacity was needed.

The conductor used was ACCC with E3X coating, which was the industry's first installation of a composite core conductor with high-emissivity coating.

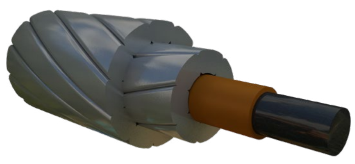

Figure A-19. ACCC conductor.

Exemplary Projects

Year	Project Name	Project Type	Conductor Used	Voltage Level	Line Length	Project Purpose
2014	Spearfish, SD	Reconductor	ACCC	69 kV	Unknown	Capacity
2018	Cheyenne, WY	Reconductor	ACCC/E3X	115 kV	Unknown	Capacity

Bonneville Power Administration

(ACSS, ACCR)

Utility Profile

The Bonneville Power Administration (BPA) delivers hydropower produced in the Columbia River Basin to communities across the Northwest. The BPA service area is illustrated in Figure A-20.

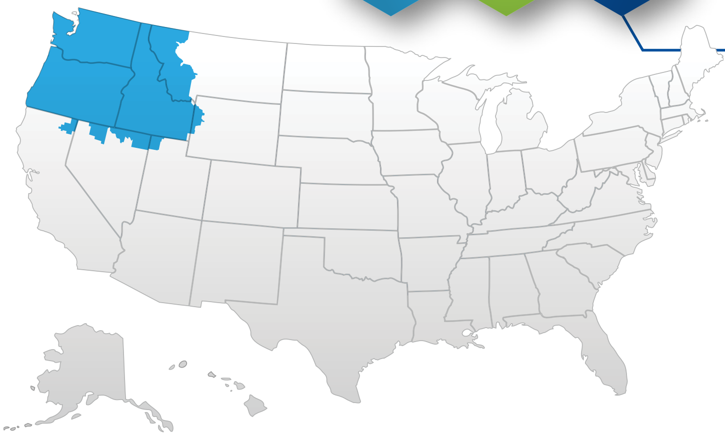

Figure A-20. BPA region.

Conductor Application Successes

BPA has installed ACSS, ACCR (Figures A-21 and A-22) for test and new construction, recognizing the importance of the application and the resulting benefits.

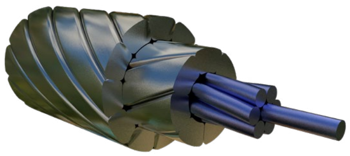

Figure A-21. ACSS conductor.

Figure A-22. ACCR conductor.

Exemplary Projects

Year	Project Name	Project Type	Conductor Used	Voltage Level	Line Length	Project Purpose
2004	Pascal, Washington	Reconductor	ACCR	115 kV	Unknown	Test line

CenterPoint Energy

(ACCR, ACCS, ACSS/TW)

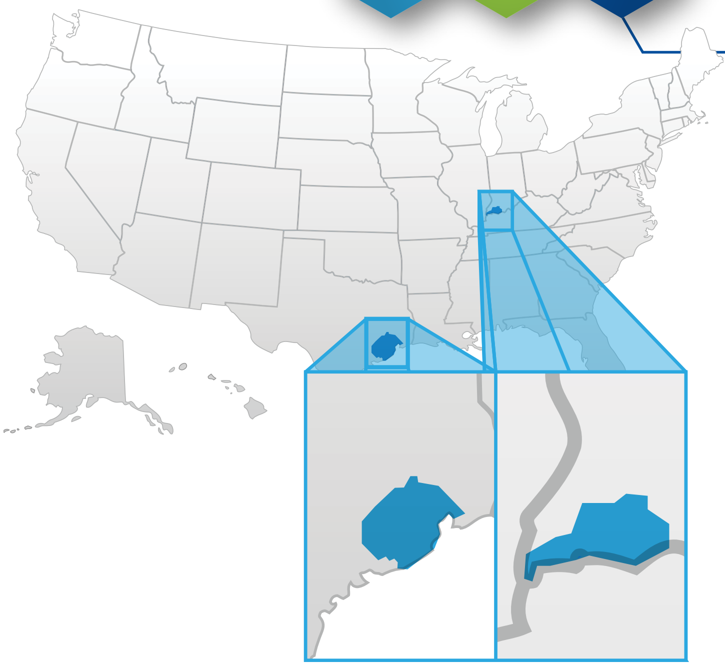

Figure A-23. Region served by CenterPoint Energy.

Utility Profile

CenterPoint Energy supplies electricity and natural gas to several states in the Midwest and Southern United States (Figure A-23). Their electricity footprint lies primarily in the Houston, Texas area, where transmission and distribution infrastructure provide service to approximately 2.6 million customers.

Conductor Application Successes

CenterPoint Energy (CPE) installed over 3000 miles of ACSS between 2000 and 2007, and in 2007 pioneered the implementation of ACSS/TW MA5 with an ultra-high strength steel core.

In 2014, CNP built projects using C7 composite core conductors. The CNP implementation used two types of conductors with a C7 core: an ACCS/TW (Figure A-24) and ACCR/TW. The ACCS/TW/C7 provided less sag at higher temperature, but the ACCS/TW/C7 (Figure A-25) provided better robustness to extreme wind and ice loads. The application provided an operational performance basis to inform appropriate application in future transmission reconductoring upgrades and new line construction.

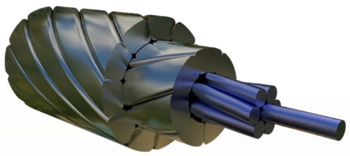

Figure A-24. ACSS/TW conductor.

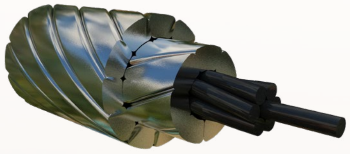

Figure A-25. ACCS/TW/C7 conductor.

Exemplary Projects

Year	Project Name	Project Type	Conductor Used	Voltage Level	Line Length	Project Purpose
2013	Crosby-Mt Belvieu	Reconductor	ACCR/C7	138 kV	2.6 miles	Pilot project capacity addition
2013	Crosby-Mt Belvieu	Reconductor	ACCS/C7	138 kV	3.3 miles	Pilot project capacity addition
2007	Bay City-Rosenberg	New construction	ACSS/TW/HS285	345 kV	40 miles	Capacity

CLECO

(ACSS)

Utility Profile

Cleco provides electricity to serve approximately 293,000 customers in Louisiana (Figure A-26).

Conductor Application Successes

Cleco has utilized ACSS conductor (Figure A-27) within its transmission area.

Figure A-26. CLECO region.

Figure A-27. ACSS conductor.

Exemplary Projects

Year	Project Name	Project Type	Conductor Used	Voltage Level	Line Length	Project Purpose
2021	Unknown	Unknown	ACSS	Unknown	3 miles	Unknown

Consolidated Edison

(ACSS, ACSS/E3X)

Utility Profile

Consolidated Edison (ConEd) provides electricity and natural gas to New York City and Westchester County (Figure A-28). Electricity service is provided to approximately 3.6 million customers. Most of ConEd's transmission system uses underground cables; however, ConEd owns 45.7% of New York Transco, LLC, which is a transmission developer for the state of New York.

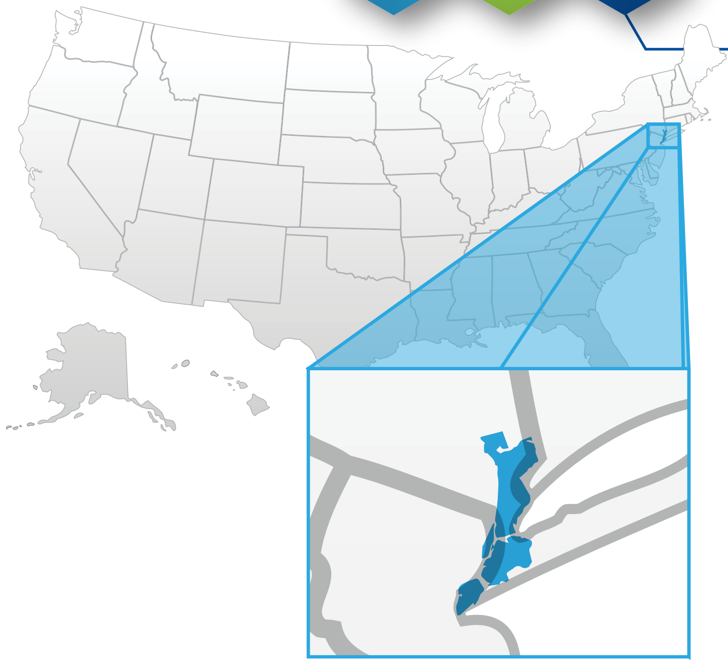

Figure A-28. Consolidated Edison region.

Conductor Application Successes

Con Edison is a partner in a 17.5-mile transmission project that ties the Cricket Valley Energy Center to one of its substations. The ACSS conductor was selected for the New York Energy Solution project and for Cricket Valley Energy Center transmission based upon consideration of construction costs, line losses, and line performance for the line rating. New York is aggressively building capacity to connect lower cost renewable generation in the upstate region to the city. NY Transco completed a 54-mile 345-kV rebuild project along existing 115-kV corridors using ACSS. ACSS/E3X was (Figure A-29) selected for a short section of the line, which enabled reconductoring of existing 345-kV structures.

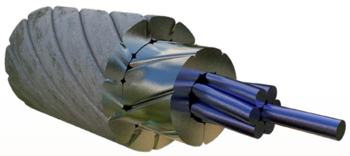

Figure A-29. ACSS conductor with E3X coating.

Exemplary Projects

Year	Project Name	Project Type	Conductor Used	Voltage Level	Line Length	Project Purpose
2017	Cricket Valley	New build	ACSS	345 kV	17.5 miles	New generation interconnection
2020-2023	New York Energy Solution	Rebuild and reconductor	ACSS for rebuild ACSS/E3X for reconductor	345 kV	54.5 miles	Capacity to connect to upstate

Dominion Energy

(ACSS/TW, ACCR)

Utility Profile

Dominion Energy operates electricity in Virginia, North Carolina, and West Virginia, and includes the dense northern Virginia cluster of data centers where power demand is expected to grow by over 200% in the next 4years. The transmission system covered for this region is illustrated in Figure A-30.

Figure A-30. Dominion Transmission region.

Conductor Application Successes

In 2009, Dominion completed the Loudoun-Brambleton line in close proximity to the Dulles airport in Loudoun County, VA. The conductor increased capacity on an existing line by 90%.

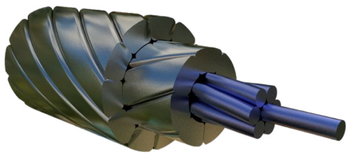

Figure A-31. ACSS/TW conductor.

Dominion Energy has used ACSS for high-capacity lines and has a standard to use ACSS/TW (Figure A-31) for new and reconductored 230-kV circuits. Recognized benefits of using ACSS for high-capacity applications has been codified in Dominion Energy's strategy. Dominion uses triple-bundle ACSR (three conductors per phase) for construction of 500-kV lines, presumably because 500-kV systems are less likely to be thermally limited.

Exemplary Projects						
Year	**Project Name**	**Project Type**	**Conductor Used**	**Voltage Level**	**Line Length**	**Project Purpose**
2022	Beaumeade Belmont	Reconductor	ACSS/TW	230 kV	6.7 miles	Capacity
2009	Loudoun-Brambleton	Reconductor	ACCR	230 kV	5 miles	Capacity

Duke Energy

(ACSS, ACSS/TW, ACCR, ACCC)

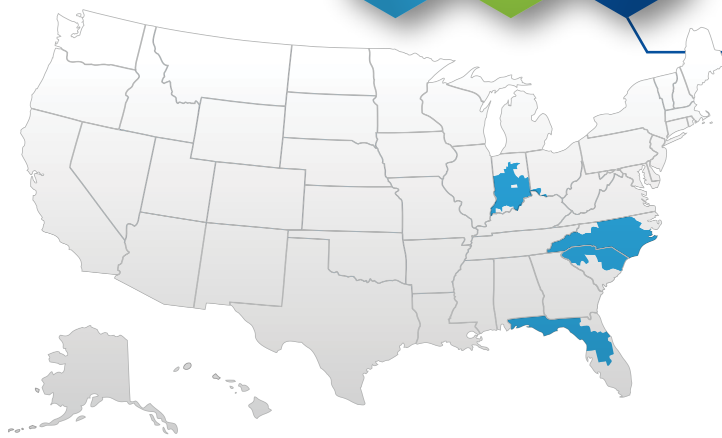

Figure A-32. APS Electric Service territory boundary.

Utility Profile

Duke Energy is based in Charlotte, North Carolina, they support 7.2 million and own 58,200 megawatts of generation (Figure A-32). Duke Energy's service territory covers 104,000 miles^2 in IN, OH, KY, WV, VA, NC, and SC. A large majority of Dukes' power generation in the Midwest comes from coal, natural gas, or oil. In the Carolinas, a large portion (~1/2) comes from nuclear power. Duke has made a commitment to installing more renewables and is looking for ways to improve efficiency, reduce costs and reduce greenhouse gas emissions. Figure A-31 shows Duke's current Transmission line project.

Conductor Application Successes

Duke commonly uses ACSS (Figure A-33) and ACSS/TW. Duke has experience with ACCC (Figure A-34) and ACCR (Figure A-35) composite core conductors but in 2022, testified to the North Carolina Utilities Commission that Duke no longer considers composite core conductors due to recent installation concerns.

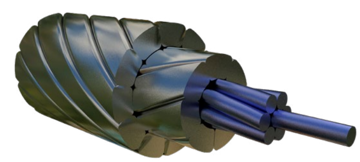

Figure A-33. ACSS conductor.

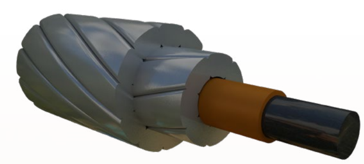

Figure A-34. ACCC conductor.

Figure A-35. ACCR conductor.

Exemplary Projects

Year	Project Name	Project Type	Conductor Used	Voltage Level	Line Length	Project Purpose
2013	Pisgah Tie to Shiloh Station	Reconductor	ACSS	230 kV	22 miles	Capacity
2019	North Carolina State Port Authority	Reconductor	ACCR	230 kV	2 miles	Reduced Sag for larger container ships
Unknown	Florida	Unknown	ACCC	Unknown	Unknown	Unknown

Duquesne Light Company

(ACCR, ACSS/TW)

Utility Profile

Duquesne Light company has more than 600,000 customers, 1700 employees, 7700 miles of transmission and distribution lines, and 150 EV charging stations (Figure A-36). The customer base is ~90% residential. The service area is in the Pittsburg region.

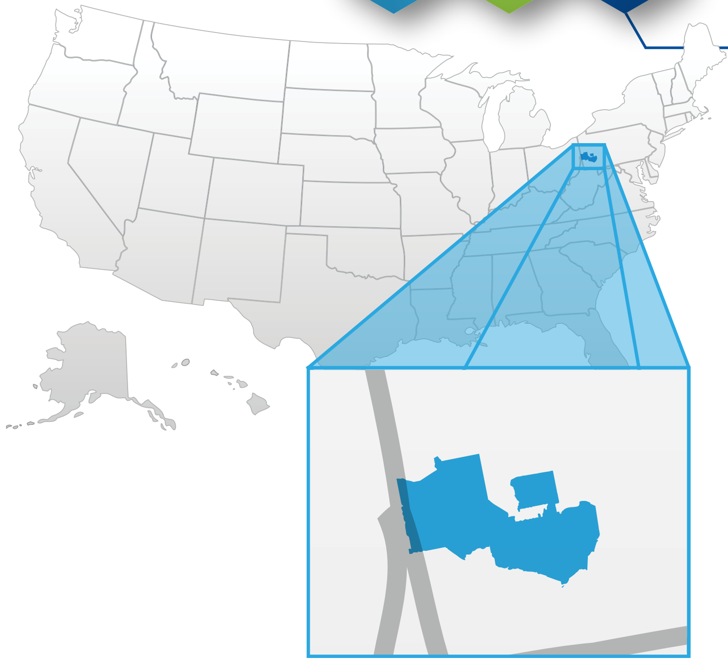

Figure A-36. Duquesne Light service area.

Conductor Application Successes

Duquesne Light has used ACSS/TW (Figure A-37) to reconductor multiple projects, including a 7-mile transmission line installed on towers constructed in the 1960s.

To solve the congestion on this line, only a single side needed to be reconductored; however the structural imbalance would have created issues with the line-to-line clearance and resulted in unacceptable mechanical loading on the towers (Figure A-38).

Replacing towers to mitigate loading issues was not desirable because the towers had not reached their end of life.

The project also had a long span with a diagonal crossing of the Ohio River. A single span was required that could stretch 3700 feet that required new structures. To comply with Federal Aviation Administration rules on tower height as well as clearance to the river below, the ACCR conductor (Figure A-39) was selected for its low-sag properties.

In this project, a mix of conductors helped match the historic mechanical loading characteristics for tower stability on existing structures while using a composite core conductor for very low-sag characteristics on the river crossing.

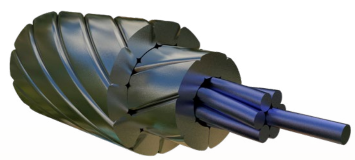

Figure A-37. ACSS/TW conductor.

Figure A-38. Tower reconductoring.

Figure A-39. ACCR conductor.

Exemplary Projects

Year	Project Name	Project Type	Conductor Used	Voltage Level	Line Length	Project Purpose
2018	Ohio River Crossing	Rebuild	ACCR	138 kV	3700-foot span	Capacity
2018	Pittsburgh project	Reconductor	ACSS/TW	138 kV	7 miles	Capacity

El Paso Electric Company

(ACSS)

Utility Profile

El Paso Electric company is based in Texas. The generation portfolio is very diverse including, nuclear, natural gas, solar, and wind turbines. The company also has transmission, and distribution line in west Texas and southern New Mexico (Figure A-40). The company owns 2010 MW of base load generation from six generation facilities. El Paso Electric Company serves ~437,000 customers. The company's retail customers are primarily in El Paso, Texas, and Las Cruces, New Mexico.

Figure A-40. El Paso Electric service area.

Conductor Application Successes

In the El Paso Electric Company 2020–2029 System Expansion Plan, the utility has enumerated a list of projects; all the projects will use ACSR. Only a single 2-mile span has been modeled with ACSS (Figure A-41). The company seem to currently be leveraging other technologies like smart meters and improved electric vehicle infrastructure to improve efficiency, stability, and reduce emissions. The company also seems to have put a great deal of resources into developing solar generation.

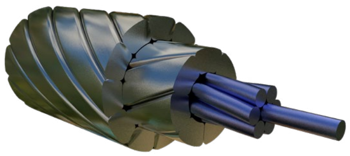

Figure A-41. ACSS conductor.

Exemplary Projects

Year	Project Name	Project Type	Conductor Used	Voltage Level	Line Length	Project Purpose
2019 planned	Newman East	New construction	ACSS	115 kV	2 miles	Capacity

Entergy

(ACCC, ACCR, ACSS)

Figure A-42. Entergy service area.

Utility Profile

Entergy headquarters is in New Orleans and the company services areas in Arkansas, Louisiana, Mississippi, and Texas. The company provides generation, transmission, and distribution to their customers (Figure A-42).

Conductor Application Successes

A reconductoring project "Hartburg-Inland Orange" using ACCC (Figure A-43) was studied by EPRI and a report was published in 2011, which showed reconductoring with ACCC reduced a project cost from $18.1 million for rebuilding with ACSS to $8.5 million with ACCC while also improving efficiency versus ACSS. A draft Entergy specification from 2021 states, "It is generally preferential to develop a custom conductor solution using an ACCR conductor in lieu of the ACCC conductors. Use of the ACCC standards will generally be limited to extension of existing ACCC lines or other similar circumstances" so Entergy appears to have changed preference from ACCC to ACCR for composite core conductors. In 2016, Entergy completed the Ninemile-Napolean reconductoring project with ACCR in the City of New Orleans.

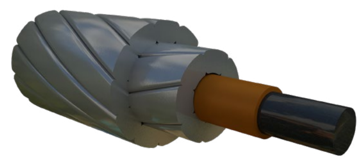

Figure A-43. ACCC conductor.

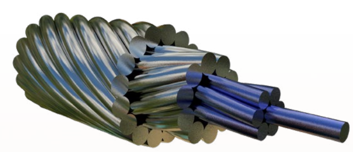

Figure A-44. ACSS conductor.

Entergy has been using ACSS (Figure A-44) at least since 2010 with projects to connect main transmission to new substations. Entergy has been upgrading much of their system for better storm resiliency. A typical example was a new substation being linked to the McLewis line and the Helbig line. Multiple projects of this kind are present in the public record. One of the more interesting documents from Entergy is a recently released scope book for solar generation providers, giving guidance on how to link to Entergy. In this book there is a fairly comprehensive enumeration of conductor technologies presented as viable options for use.

Exemplary Projects

Year	Project Name	Project Type	Conductor Used	Voltage Level	Line Length	Project Purpose
Prior to 2011	Hartburg-Inland Orange	Reconductor	ACCC	230 kV	4 miles	Capacity
2016	Ninemile-Napolean	Reconductor	ACCR	230 kV	12 miles	Capacity and decreased sag
2018	Southeast Louisiana Improvement Project	New construction	ACSS	230 kV	10 miles	Capacity and reliability

Evergy

(ACSS, ACSS/TW)

Utility Profile

Evergy is an electric utility serving Kansas and Missouri formed by the combination of Kansas City Power and Light and Westar in 2019. The company serves ~1.7 million customers including residential, commercial, and industrial (Figure A-45). Evergy has a generating capacity of 16,000-megawatt electricity in Kansas and Missouri. Evergy owns >10,100 miles of transmission and ~52,000 miles of distribution.

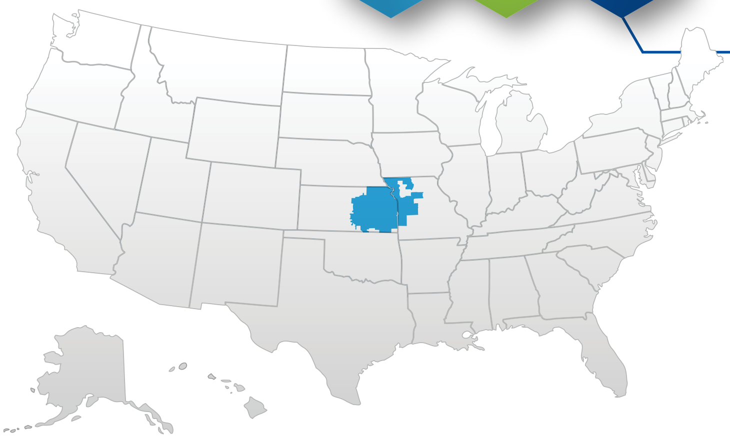

Figure A-45. Evergy service area.

Conductor Application Successes

In 2003, Evergy predecessor company KCP&L performed a live line reconductoring using ACSS on a 32-mile line connecting the LaCygne power station. The project used an ACSS/TW conductor (Figure 46) to replace the existing ACSR conductor. The cost savings of the added transmission capacity paid for the cost of the upgrade in 14 months. There are other reconductoring projects in the queue for Evergy along with several historic use cases. The Maryville to Creston 161-kV Rebuild (GIA-61) (143691) is a typical case and is a reconductoring effort for 62.4 miles using 556.5 ACSS Parakeet conductor costing ~$14,900,000. Evergy has made their analytic process for selecting candidate corridors and technologies for reconductoring open to the public. The company is clearly forward-thinking regarding new technology but is looking for the best design fit for their system and geography.

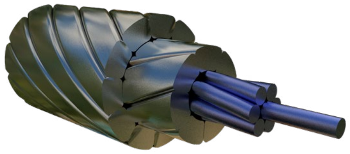

Figure A-46. ACSS/TW conductor.

Exemplary Projects

Year	Project Name	Project Type	Conductor Used	Voltage Level	Line Length	Project Purpose
2003	LaCygne to Stillwell	Live reconductor	ACSS/TW	345 kV	32 miles	Capacity

Eversource

(ACSS ACSS/E3X)

Utility Profile

Eversource covers several states in the Northeast (Figure A-47) with electricity and natural gas. Within this region approximately 4 million customers are served.

Conductor Application Successes

Eversource uses ACSS (Figure A-48) in transmission systems and had previously standardized on its use. Eversource prefers to use ACSS instead of ACSR because of the increased current carrying capacity. In 2023, Eversource and Prysmian announced that Eversource would be using ACSS with E3X coating as an enhancement to the ACSS for improved efficiency.

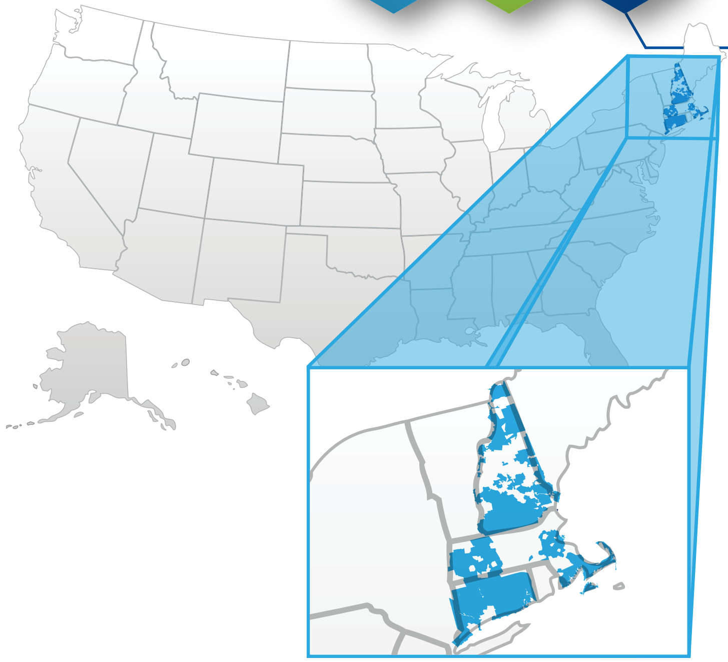

Figure A-47. Eversource region.

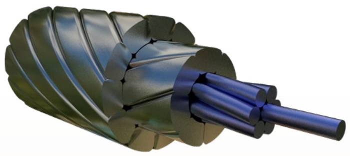

Figure A-48. ACSS conductor.

Exemplary Projects

Year	Project Name	Project Type	Conductor Used	Voltage Level	Line Length	Project Purpose
Prior to 2022	Various	Rebuild and new construction	ACSS	115 kv 345 kv	Various	New capacity and wood pole replacement
2023	Various	Rebuild and new construction	ACSS/E3X	115 kv 345 kv	Various	New capacity and wood pole replacement

Exelon

(ACSS, ACSS/TW, ACCC, ACCR, E3X)

Utility Profile

Exelon covers a family of companies across several states in the Midwest and Northeast (Figure A-49) with electricity and natural gas. These companies include Commonwealth Edison (ComEd), Philadelphia Electric Company (PECO) and others. Within this region approximately 8.8 million electric customers are served. Exelon has adopted a wide range of different transmission technologies to increase capacity on transmission lines.

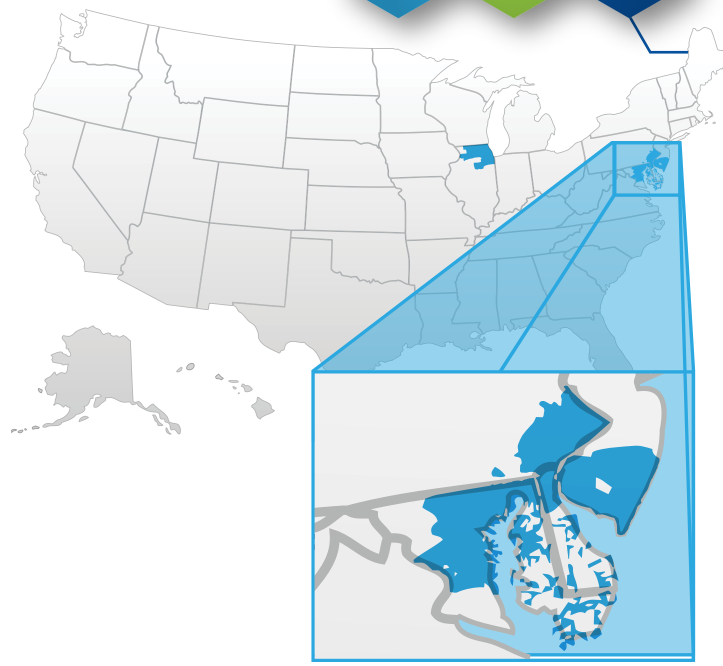

Figure A-49. Exelon region.

Conductor Application Successes

Exelon has used ACSS conductor (Figure A-50) and ACSS/TW and has it listed as an optional conductor for application, as noted in a 2006 interconnection guide, for several voltage levels.

Exelon utility ComEd used ACCC conductor (Figure A-51) on projects in 2014 and 2015 in Illinois and Wisconsin. The Rockford project used ACCC/ULS, which is the stronger carbon-fiber core option for ACCC, typically used for heavy ice load conditions. ComEd also used ACSS to reconductor 4.5 miles of 138-kV lines from the Lisle to York Tap in 2012.

ACCR conductor (Figure A-52) was used for a large reconductoring project connecting two Exelon utilities, PECO, and Baltimore Gas and Electric. Reconductoring occurred on a 500-kV line that was 54 years old.

TS Conductor also notes that TS Conductor has been installed by Exelon.

Exelon has demonstrated an interest in advancing the application of transmission conductors and has continued to innovate in this field. Exelon has been working with Prysmian to retrofit existing transmission lines with E3X coating using robots. E3X works by improving heat dissipation and can increase line ratings on existing lines without reconductoring (Figure A-53).

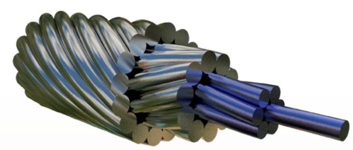

Figure A-50. ACSS conductor.

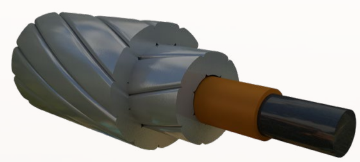

Figure A-51. ACCC conductor.

Figure A-52. ACCR conductor.

Figure A-53. E3X robot.

Exelon

(ACSS, ACSS/TW, ACCC, ACCR, E3X)

Exemplary Projects						
Year	Project Name	Project Type	Conductor Used	Voltage Level	Line Length	Project Purpose
2014	T Line 1607	Reconductor	ACCC	138 kV	3 miles	Capacity
2018	Conastone Area projects	Reconductor	ACCR	500 kV	26.4 miles	Capacity
2015	Lisle to York Tap	Reconductor	ACSS	138 kV	4.5 miles	Capacity
2021	ComEd	Robot E3X retrofit	ACSR	138 kV	1 mile	Pilot

FirstEnergy Corporation

(ACSS, ACSS/TW, ACCR)

Figure A-54. FirstEnergy Corporation region.

Utility Profile

FirstEnergy Corporation covers several states in the Midwest/Eastern United States. (Figure A-54). Within this region, approximately 6 million electric customers are served.

Conductor Application Successes

Allegheny Power, which is now part of First Energy, installed 3M ACCR on a 1.7-mile line in West Virginia. The conductor increased capacity while matching sag of the ACSR to maintain clearance to the distribution lines on the same structures. FirstEnergy has utilized ACSS (Figure A-55) and ACSS/TW (Figure A-56) in several different reconductoring, rebuild, and new applications. ACSS conductor was designated for projects noted in 2016, 2017, 2019, 2022, and 2023 for lengths under 20 miles on 138-kV and 345-kV transmission lines. On the Dowling-Midway project, a 336.4-kcmil ACSR conductor was replaced with a 336.5-kcmil ACSS conductor without replacing the existing lattice structures. This indicates the existing structures had sufficient clearance for the higher sag from the ACSS. On the Black River-Carlisle-Lorain project, a 954-kcmil ACSR was replaced with a smaller 795-kcmil ACSS/TW. It was noted in planning documents that while the ACSS conductor was physically smaller, it had larger current carrying capacity. It is not noted but can be concluded the smaller ACSS conductor would have higher line losses than the larger ACSR it replaces.

Figure A-55. ACSS conductor.

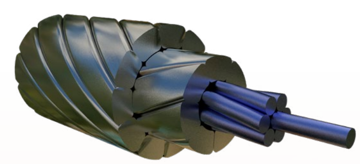

Figure A-56. ACSS/TW conductor.

Exemplary Projects

Year	Project Name	Project Type	Conductor Used	Voltage Level	Line Length	Project Purpose
2016	Black River-Carlisle-Lorain	Reconductor	ACSS/TW	138 kV	6 miles	Capacity
2017	Dowling-Midway	Reconductor	ACSS	138 kV	15 miles	Capacity
2007	Bedington-Nipetown	Reconductor	ACCR	138 kV	1.7 miles	Capacity

Idaho Power Company

(ACSS)

Utility Profile

Idaho Power Company (IPCo) is a vertically integrated utility that covers southern Idaho and eastern Oregon. (Figure A-57). Within this region approximately 620,000 electric customers are served.

Figure A-57. Idaho Power region.

Conductor Application Successes

There is some indication from community sources that IPCo has used ACSS (Figure A-58) in transmission systems. As with other users, ACSS has been available in various versions for years, and as such, it has been an option for use in various reconductoring applications.

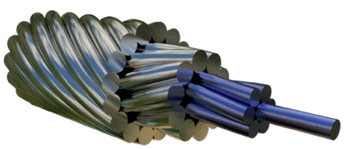

Figure A-58. ACSS conductor.

ITC Holdings

(ACSS)

Utility Profile

ITC Holdings provides electric transmission in several states in the Midwest United States (Figure A-59).

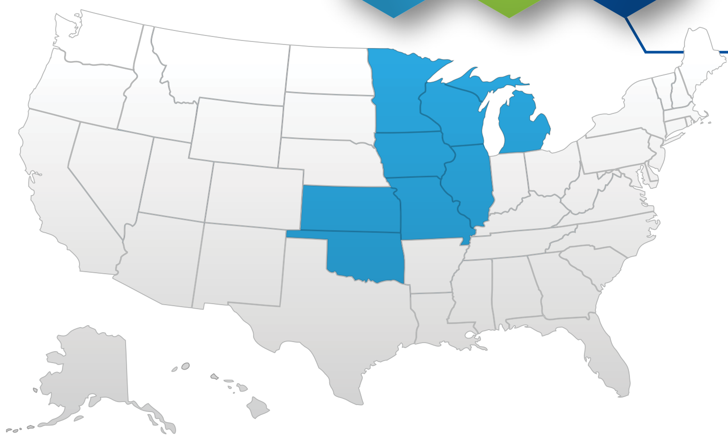

Figure A-59. ITC Holdings service area.

Conductor Application Successes

ITC Holdings has used ACSS conductor (Figure A-60) for some time and has future plans to continue using ACSS conductors on many lines in Michigan. The Wayne-Newburgh project in the Detroit area was previously constructed with a 795-kcmil ACSS conductor has now been rebuilt with a much larger 2156-kcmil ACSS conductor.

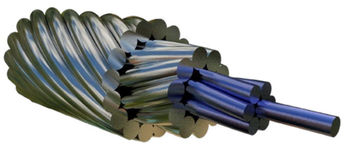

Figure A-60. ACSS conductor.

Exemplary Projects

Year	Project Name	Project Type	Conductor Used	Voltage Level	Line Length	Project Purpose
2022	Wayne-Newburgh #1	Rebuild	ACSS	120 kV	2.7 miles	Increased capacity

MidAmerican Energy

(ACSS, TS Conductor)

Utility Profile

MidAmerican Energy is a Berkshire Hathaway Energy company that operates across the Midwest in the states of Iowa, South Dakota, and Illinois (Figure A-61).

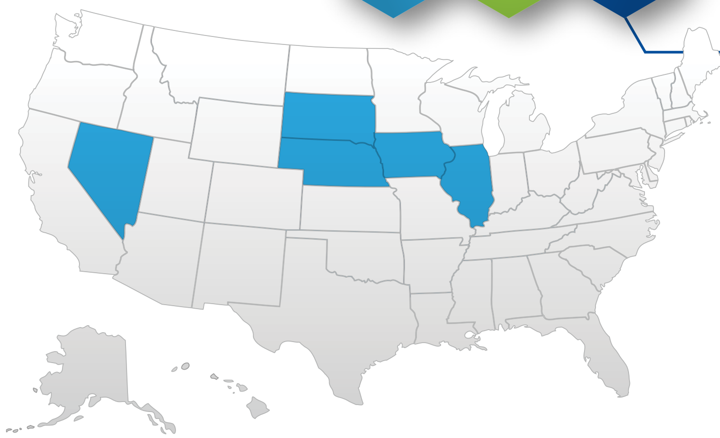

Figure A-61. MidAmerican Energy region.

Conductor Application Successes

MidAmerican's area of operation is in the portion of the upper Midwest that experiences both high winds as well as freezing rains. These concurrent weather conditions can cause the damaging impact of conductor galloping, where suspended conductors can vibrate with very large amplitudes, causing outages and damages to lines. Because of this, many of the conductors used by MidAmerican are T2 twisted pair conductors, where each conductor is composed of two individual ACSR conductors, twisted together in a loose helix. The varying profile and low-lateral stiffness of the conductor prevents galloping. MidAmerican has installed small amounts of both ACSS (Figure A-62) and recently completed a project with TS Conductor (Figure A-63) crossing the Mississippi River.

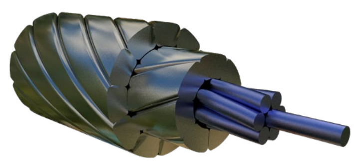

Figure A-62. ACSS conductor.

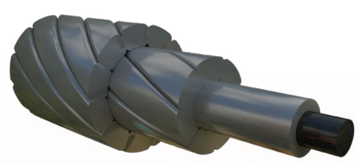

Figure A-63. TS conductor.

Exemplary Projects

Year	Project Name	Project Type	Conductor Used	Voltage Level	Line Length	Project Purpose
2023	Iowa-Illinois Border	River Crossing	TS conductor	Unknown	Unknown	Unknown

Minnesota Power

(ACSS)

Figure A-64. Minnesota Power service area.

Utility Profile

Minnesota Power serves over 150,000 residential and commercial customers in a 26,000 mile^2 area in northeastern Minnesota (Figure A-64). They operate over 3,000 miles of transmission voltages ranging from 500 kV to 115 kV and over 6000 miles of lines less than 115 kV. Minnesota Power operatesa variety of energy generation plants, ranging from coal, biomass, hydro, wind, natural gas, and solar.

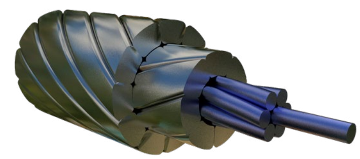

Figure A-65. ACSS conductor.

Conductor Application Successes

Minnesota Power has used ACSS (Figure A-65) on several projects and plans to use it on the upcoming 115-kV Duluth Loop project. Generally, projects considering this conductor involve building new towers to add redundancy and additional capacity into narrow corridors, such as the Elk River-Beck area. Concerns regarding the predicted load growth on Elk River area have spurred Minnesota Power to consider increasing power flow capacity. If not addressed and loads grow high enough, the loss of a power transformer could impact other parts of their grid. ACSS has been used in the industry for over 40 years and is widely considered a good option when building new towers as it has more capacity than traditional ACSR.

Exemplary Projects

Year	Project Name	Project Type	Conductor Used	Voltage Level	Line Length	Project Purpose
Planned	Duluth Loop	New and rebuild	ACSS	115 kV	14 miles	Reliability

Montana Dakota Utility

(ACSS, TS)

Utility Profile

Montana Dakota Utility (MDU) is a vertically integrated utility that covers a four-state region, which includes electric and natural gas service and coal and renewable generation (Figure A-66). Within this region approximately 144,000 electric and a total of 431,000 customers are served.

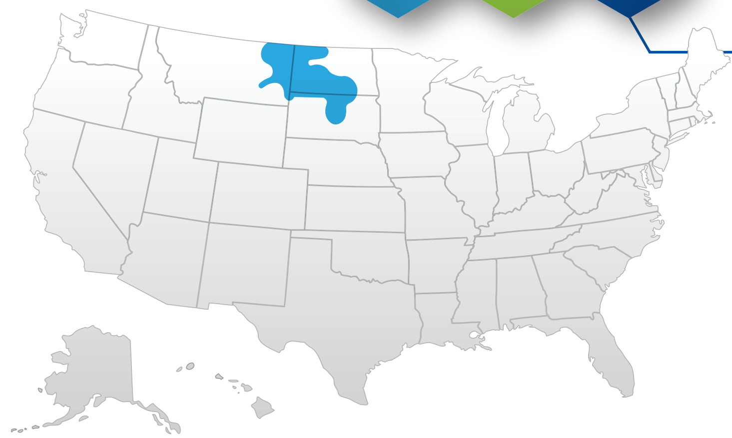

Figure A-66. MDU region.

Conductor Application Successes

MDU was the first utility to use TS Conductor (Figure A-67) in the U.S. The Bismark to Napolean project used TS for an 11-mile section, which allowed the project to reuse 60 existing structures. Reconductoring saved $1.8 million and a year of construction time versus rebuilding.

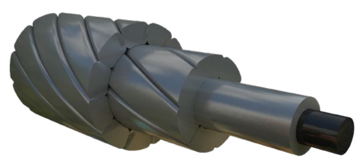

Figure A-67. TS conductor.

Exemplary Projects

Year	Project Name	Project Type	Conductor Used	Voltage Level	Line Length	Project Purpose
2021	Bismark to Napolean	Reconductor	TS conductor	230 kV	11 miles	Renewable energy

National Grid

(ACCC and ACCR)

Utility Profile

National Grid (NG) supplies electricity and natural gas to portions of Massachusetts and New York in the Northeastern U.S. (Figure A-68), as well as portions of England and Wales in the United Kingdom. In the U.S., they serve ~20 million utility customers.

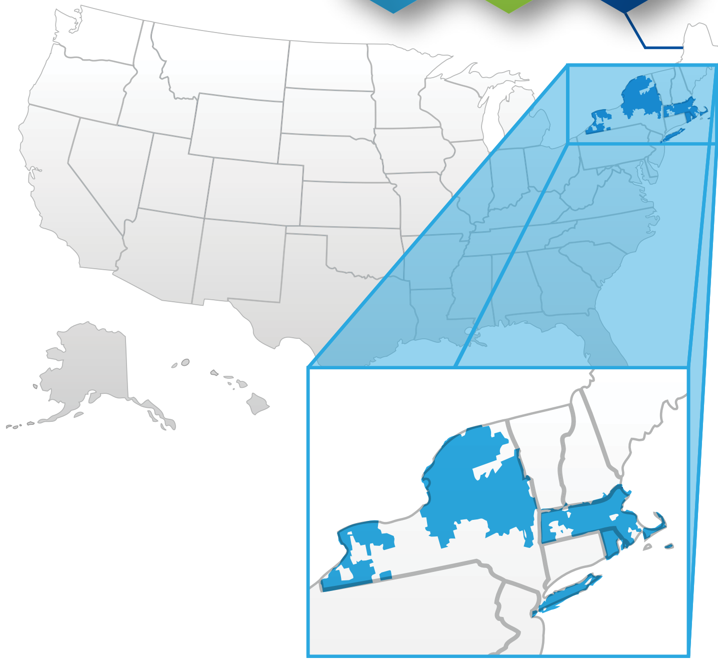

Figure A-68. National grid Region.

Conductor Application Successes

In 2022, NG commenced an upgrade of 157 miles of transmission line from Edic to New Scotland and from New Scotland to Leeds with 954-kcmil ACSS Cardinal and 795-kcmil ACSS Drake conductors. The upgraded line is set to enter service in 2023.

In 2018, NG rebuilt the Somerset-Fall River line which had originally been constructed in 1923. In addition to being 100 years old, the very large structures were occupying a large amount of valuable real estate on the Taunton River. During the rebuild, smaller structures were used that not only took up less space on the ground but were also considerably shorter, which reduced the risk to aviation. To enable the shorter, smaller structures, NG evaluated multiple conductor types and selected 3M ACCR because of its light weight and low-sag profile.

National Grid Ventures is an investor in the startup advanced conductor provider, TS Conductor.

Exemplary Projects

Year	Project Name	Project Type	Conductor Used	Voltage Level	Line Length	Project Purpose
2018	Sommerset-Fall River	Rebuild	ACCR	115 kV	< 1 mile	Reduced Sag, reduced tower height
2023	Edic-New Scotland-Leeds	Reconductor/rebuild	ACSS	345 kV	157 miles	Regional upgrade
2005	Packard-Zimmerman	Reconductor	ACCC	230 kV	1 mile	Unknown

NextEra Energy Florida Power & Light

(ACSS)

Figure A-69. Region served by NextEra FPL Energy.

Utility Profile

NextEra Energy Florida Power and Light (NEFPL) is a utility company primarily based in the coastal regions of Florida. Florida Power and Light (FPL) Company provides electricity to approximately 5.8 million accounts, or more than 12 million people.

NextEra also has several divisions focused on energy generation and transmission assets across the country. NextEra has a transmission only called LoneStar Transmission, which operates in Texas.

Conductor Application Successes

FPL has a proven track record of power system reliability, having been recognized numerous times in recent years with various industry rewards. In 2021, FPL won the ReliabilityOne® National Reliability Award for the sixth time in 7 years and has been in the process of upgrading and rebuilding much of the Florida grid. FPL customers have seen a 45% improvement in reliability because of these grid hardening efforts. Consequently, this region has not experienced many issues with congestion and there has been no need to deploy advanced conductors to uprate existing lines in Florida. Lonestar built 330 miles of the 345-kV Texas CREZ lines using ACSS. NextEra has also invested venture capital funds in the startup, TS Conductor.

Exemplary Projects

Year	Project Name	Project Type	Conductor Used	Voltage Level	Line Length	Project Purpose
2013	CREZ	New build	ACSS	345 kV	330 miles	Renewable energy transmission

NorthWestern Energy

(ACSS/TW)

Utility Profile

NorthWestern Energy is a utility company providing electricity to western Montana and eastern South Dakota. They have approximately 750,000 customers throughout this region (Figure A-70).

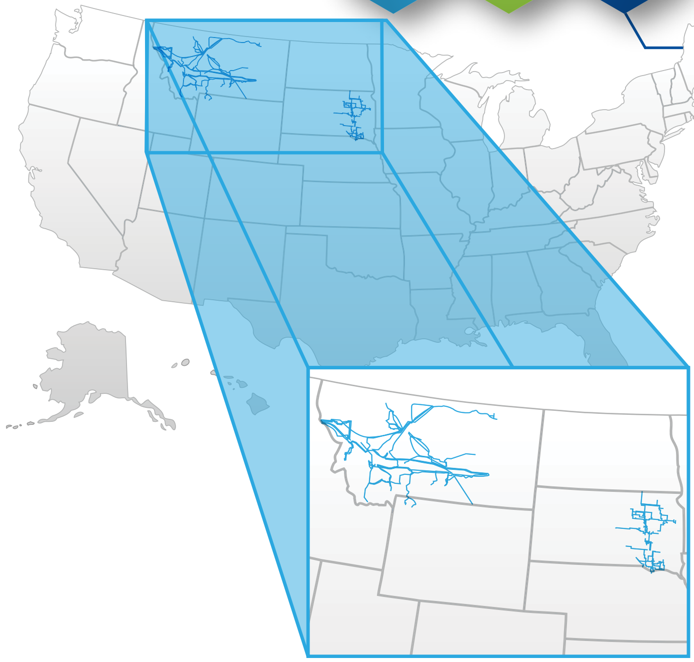

Figure A-70. NorthWestern Energy service area.

Conductor Application Successes

One 20-mile section of a 100-kV line between the cities of Great Falls and Two Dot was constructed with an ACSS/TW/MA5 conductor with ultra high-strength steel in a project, which has received national media attention as an example of a utility choosing a lower loss conductor. The annealed aluminum of the ACSS conductor increases conductivity compared to ACSR and the trapezoidal shaped wires allow more aluminum to be packed in the same diameter as a traditional ACSR. This project was undertaken in 2021. One of the primary motivating factors for the project between Great Falls and Two Dot was wildfire prevention. The ~20-mile section was through a heavily wooded area so the reduced sag of the ACSS conductor, in addition to the use of modern steel structures, reduced the risk of fires in this historically wildfire prone region.

Additionally, the conductor has increased efficiency, which provides more value to the utility and ratepayers. It was estimated if the entire 105-mile line was replaced with this ACSS/TW conductor the total savings could be as much as $440,000 per year. This project was recently used as an example for state regulators to argue for increased incentives for utilities to adopt advanced conductors in the state of Montana.

Exemplary Projects

Year	Project Name	Project Type	Conductor Used	Voltage Level	Line Length	Project Purpose
2021	Great Falls-Two Dot	Rebuild	ACSS/TW/MA5	100 kV	20 miles	Capacity and reliability

NV Energy

(ACCC, ACSS)

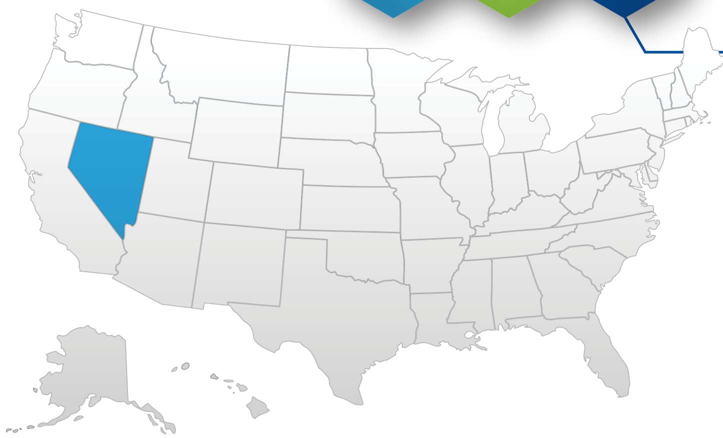

Figure A-71. NV Energy region.

Utility Profile

NV Energy is a Berkshire Hathaway Energy company serving the state of Nevada (Figure A-71).

Conductor Application Successes

NV Energy has performed at least 25 installations of ACCC conductor (Figure A-72) on 128-circuit miles starting in 2009 and has reported excellent experience with the conductor. This experience includes conductors surviving a wildfire that destroyed the wooden poles that were supporting. The applications include segments for 69 kV and 120 kV. NV Energy reports using ACCC for both reconductoring as well as new builds. To accommodate the large industrial end-user growth in the Reno area, NV Energy is using ACCC for new lines, which installation crews prefer to install versus multiple conductor bundles per phase. NV Energy has continued to apply ACCC for enhanced capacity where reconductoring or new line is desired at voltages 120 kV and under. This has been especially important where modification of structures would normally be required through sensitive areas, whereas reconductoring with ACCC allows for reuse of the existing structures and less disturbance to the environment.

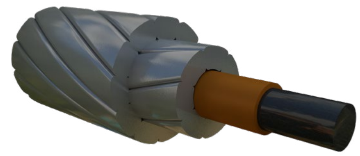

Figure A-72. ACCC conductor.

NV Energy has also used ACSS conductor (Figure A-73) in other applications and plans to continue using it for reconductoring.

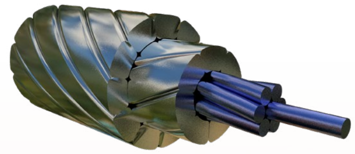

Figure A-73. ACSS conductor.

Exemplary Projects

Year	Project Name	Project Type	Conductor Used	Voltage Level	Line Length	Project Purpose
2009	107 Line	Reconductor	ACCC	120 kV	17.9 miles	Capacity
2020	Wild Horse to Comstock Meadows	New build	ACCC	120 kV	Unknown	Capacity
2023	Northwest to El Capitan	Reconductor	ACSS	138 kV	Unknown	Capacity for solar project interconnection

Oklahoma Gas & Electric Company

(ACCC, ACSS, ACSR/E3X)

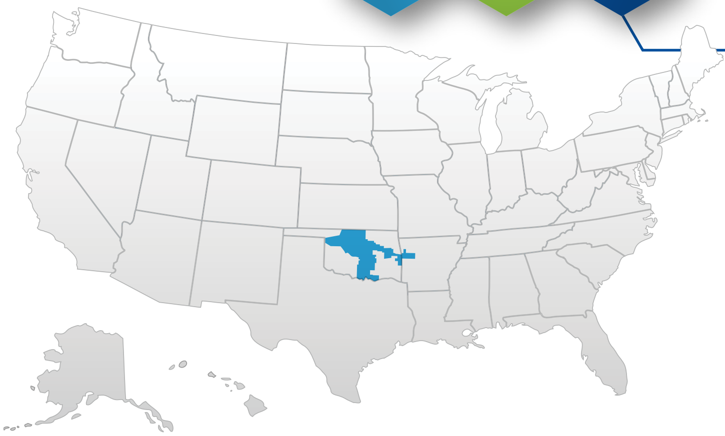

Figure A-74. Region served by Oklahoma Gas and Electric Company.

Utility Profile

Oklahoma Gas and Electric (OG&E) is a utility covering most of central Oklahoma and part of Western Arkansas (Figure A-74). OG&E has ~890,000 customers and operates just over 7 GW of generation. They own ~5200 circuit miles of transmission lines and over 55,000 circuit miles of distribution lines.

Conductor Application Successes

OG&E installed a 35-mile section of ACCC Drake on a section of line between Oklahoma City and the McClain power plant in 2006. In 2013 an F5 tornado passed directly over the stretch of ACCC conductor OG&E had strung in 2006. During this event, it is surmised that a piece of flying debris struck one of the steel monopole structures, leaving it bent at a 45-degree angle. The tension placed on the conductor as a result caused the aluminum strands to snap in one location. However, the composite core remained fully intact (Figure A-75). Line crews were able to repair this section within 24 hours and ultimately bring the entire line back into service within about a week. OG&E was also the first utility to pilot E3X technology in 2013 and the first to use it on a major line in 2015.

Figure A-75. Damaged conductor following the 2013 tornado.

Exemplary Projects

Year	Project Name	Project Type	Conductor Used	Voltage Level	Line Length	Project Purpose
2006	OKC- McClain	New construction	ACCC	138 kV	35 miles	Unknown
2015	Cimarron-Matthewson	New construction	ACSR/E3X	345 kV	16 miles	Unknown
2013	Five Tribes-Pecan Creek	New construction	ACSR/E3X	161 kV	4 miles	Unknown

Oncor

(ACCC ACSS/TW, ACSS/TW E3X)

Utility Profile

Oncor is a public utility company located in the northern part of Texas. They operate over 140,000 miles of transmission and distribution lines and serve more than 400 communities in 98 counties. This service area encompasses more than 3 million people (Figure A-76).

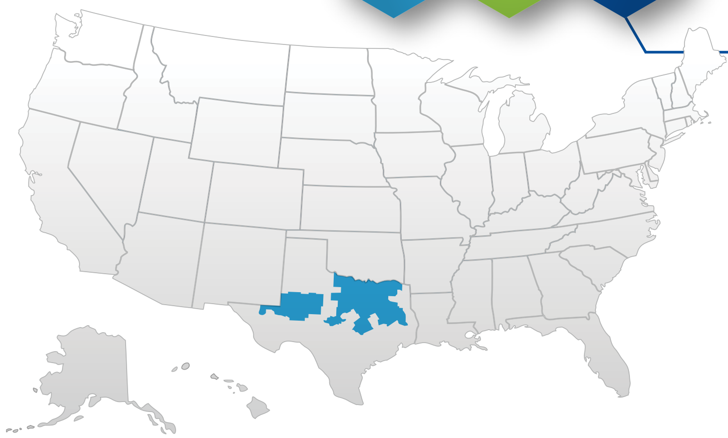

Figure A-76. Region served by Oncor.

Conductor Application Successes

In 2013 Oncor undertook a project to reconductor a 138-kV line from Odessa to Odessa North with ACCC.

Oncor has also experienced success with the use of ACSS/TW conductor in reconductoring and new lines. Additional examples include Old Country 345 kV, Ivy League 138 kV, Flat Iron–Barr Ranch 138 kV, Nacogdoches Southeast–Redland 345 kV, Ramhorn Hill–Dunham 345 kV, Sandlake–North McCamey 345 kV, and Redland–Lufkin 345 kV.

Oncor has also deployed ACSS/TW with E3X coating on several projects for reconductoring, new lines, and rebuilds. Most recently this was done on the Keller Wall Price – Keller Magnolia 138-kV project. Oncor performed a pilot project, installing DLR equipment on parallel lines to validate performance of the E3X coating. Results were favorable and presented at IEEE. Benefits noted were extra capacity and risk management of thermal line rating variables, as heat dissipation varies significantly over the life of standard conductors but with E3X the surface conditions are expected to have insignificant change with aging.

Oncor built approximately 850 miles of new transmission lines as part of the Texas Competitive Renewable Energy Zone projects, known as CREZ. This was state wide project to proactively increase transmission capacity across the state which resulted in several thousand miles of new transmission and helped enable Texas to become the leading renewable energy producer. Oncor used ACSS/TW for their portion of these project.

Oncor found reconductoring with ACCC to provide the best trade-off between cost and capacity improvement to relieve congestion in the Odessa region. Other options like Dynamic Line Rating (DLR) were considered, but ultimately due to the projected long-term load growth, they found reconductoring was the cheapest option for providing the needed capacity increase.

Within Oncor's service area ACSS/TW has become standard. Indeed, every ongoing Oncor project as of this writing is using the ACSS/TW conductor.

These projects range in purpose from improving system resilience following disturbances to meeting increased customer demand as a result of population growth and new customers. Where additional capacity beyond ACSS/TW is required for project growth, ACSS/TW/E3X is used

Oncor

(ACCC ACSS/TW, ACSS/TW E3X)

Exemplary Projects						
Year	Project Name	Project Type	Conductor Used	Voltage Level	Line Length	Project Purpose
2013	Odessa North	Reconductor	ACCC	138 kV	Unknown	Unknown
2018	Apollo-East Richardson	Reconductor	ACSS/TW with E3X	138 kV	Unknown	Capacity increase for data centers
2015	Various CREZ lines	New construction	ACSS/TW	138 kV 345 kV	850 miles	Renewable energy interconnection

Otter Tail Power

(Twisted Pair)

Utility Profile

Otter Tail Power (OTP) is an investor-owned electric utility that provides electricity and energy services for approximately 133,000 residential, commercial, and industrial customers across 70,000 miles^2 in Minnesota, North Dakota, and South Dakota (Figure A-77).

Figure A-77. Region Served by OTP.

Conductor Application Successes

OTP has largely not used HTLS conductor technologies in reconductoring projects. OTP has used a vibration resistant conductor known as Twisted Pair or T2 ACSR for both new construction and reconductoring. This variation on ACSR is constructed in a cable manufacturing process that twists two ACSR conductors into a single conductor and is known by the trade names of T2 or VR2. It is used widely in the ice prone region from the panhandle of Texas throughout the upper midwestern states. Twisted Pair ACSR is designed to prevent a phenomenon called galloping where conductors move violently in the wind, with the entire span of conductor, possibly weighing thousands of pounds moving up and down with amplitudes of up to 40 feet. Galloping can cause outages when conductors from different phases contact if not sufficiently spaced. Over time, galloping can break insulators and transmission towers. The reconductoring projects found for OTP replaced round conductor with T2 twisted pair conductor for reliability reasons.

Exemplary Projects

Year	Project Name	Project Type	Conductor Used	Voltage Level	Line Length	Project Purpose
2013	Buffalo-Enderlin	Reconductor	Twisted Pair ACSR (T2)	115 kV	7 miles	Reliability

Pacific Gas & Electric Company

(ACSS, ACCR)

Utility Profile

Pacific Gas and Electric Company (PG&E) provides Electric in the Northern two-thirds of California, from Bakersfield to northern Santa Barbara County. The transmission system covered for this region is illustrated in Figure A-78.

Figure A-78. PG&E Electric Service territory boundary.

Conductor Application Successes

PG&E ACSR and ACSS (Figure A-79) are commonly used conductors. For reconductoring PG&E has many projects where they have used ACSS and ACCR (Figure A-80). PG&E may make modifications to existing structures or may replace a portion of line structures when reconductoring with ACSS.

Figure A-79. ACSR/ACSS.

Figure A-80. ACCR.

Exemplary Projects

Year	Project Name	Project Type	Conductor Used	Voltage Level	Line Length	Project Purpose
Prior to 2010	NRS to Scott	Reconductor	3M ACCR	115 kV	<1 mile	Capacity increase
Unknown	Morro Bay-Midway	Reconductor	ACSS	230 kV	35 miles	Solar project integration

PacifiCorp

(ACCC, ACSS/TW)

Utility Profile

Pacificorp is a Berkshire Hathaway Energy company that consists of Rocky Mountain Power and Pacific Power (Figure A-81).

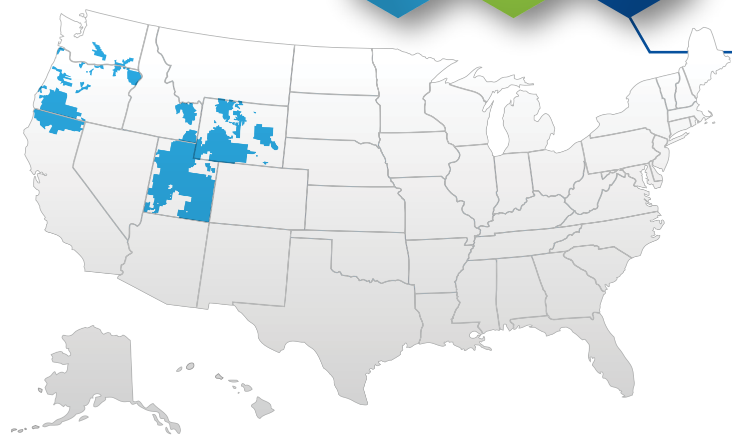

Figure A-81. PacifiCorp region.

Conductor Application Successes

PacifiCorp widely utilizes ACSS conductor including for its new Aeolus Shirley Basin 230-kV line that was built as part of the Energy Vision 2020 project. Their new Aeolus Freezeout 2 230-kV line will also be built with an ACSS conductor. PacifiCorp was an early adopter of ACCC conductor, energizing a 6.7-mile section in 2006 in the Salt Lake City area. Pacificorp has used ACCC conductor in multiple projects (Figure A-82), including to a roughly 20-mile section of the 345-kV Populus-Terminal project.

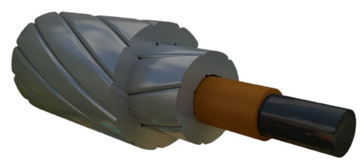

Figure A-82. ACCC conductor.

Exemplary Projects

Year	Project Name	Project Type	Conductor Used	Voltage Level	Line Length	Project Purpose
2009	Populus Terminal	New construction	ACCC	345 kV	20 miles	Capacity
2020	Aeolus Shirley Basin	New construction	ACSS/TW	230 kV	12 miles	Capacity

PNM & TNMP

(ACSS, ACCC/E3X)

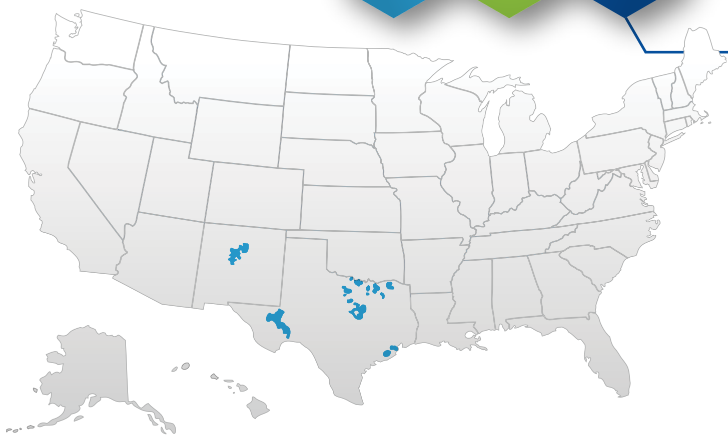

Figure A-83. PNM and TNMP coverage map.

Utility Profile

Public Service Company of New Mexico (PNM) provides Electric in the Northern part of New Mexico, from Belen to Santa Fe. The transmission system covered for this region is illustrated in Figure A-83.

Texas-New Mexico Power Company (TNMP) provides electricity to more than 270,000 homes and businesses throughout Texas. They are a subsidiary of PNM.

Conductor Application Successes

Figure A-84. ACSR/ACSS.

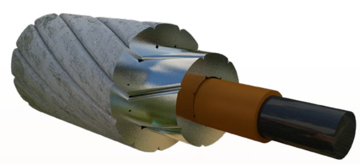

Figure A-85. ACCC.

PNM and TNMP both use ACSR or ACSS (Figure A-84) as their preferred conductors for new or rebuilt 115 kV and 230 kV. With the high load growth areas of their service territory, they have started using ACSS for the higher capacity. TNMP has gradually been replacing all older wooden structures with new steel structures, which will give sufficient clearance and the ability to switch to a composite core conductor if needed. TNMP is currently reconductoring an ACSR line using ACCC with E3X coating (Figure A-85). Some tower modifications are necessary as the tension required for the larger ACCC conductor used is higher than the previous ACSR. The dead-end structures are being replaced to accommodate the higher tension while the more numerous tangent structures are being reused. The E3X coating was needed to increase the capacity of the ACCC conductor to achieve the 3000-amp rating required without a complete rebuild. The ACCC conductor being used is equipped with Infocore fiber optics so the conductor can be tested for damage during production, shipping, and installation.

Exemplary Projects

Year	Project Name	Project Type	Conductor Used	Voltage Level	Line Length	Project Purpose
2023	Wink-Fishhook	Reconductor	ACCC Infocore with E3X	115 kV	10 miles	Industrial load growth

Portland General Electric

(ACSS)

Utility Profile

Portland General Electric (PGE) provides power to approximately 900,000 customers in seven counties and 51 cities. PGE provides roughly 75% of the state's commercial and industrial power. The transmission system covered for this region is illustrated in Figure A-86.

Conductor Application Successes

PGE has used ACSS conductor for multiple reconductoring projects and plans to use ACSS for future reconductoring projects (Figure A-87).

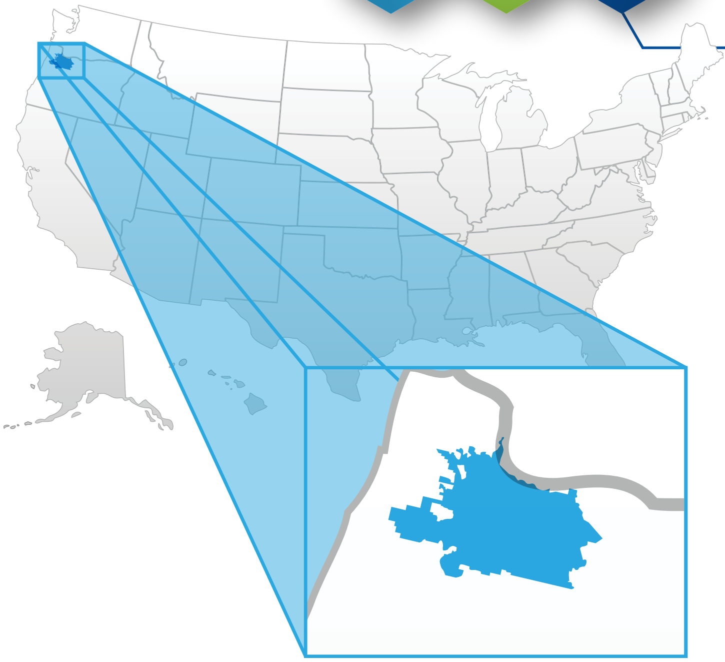

Figure A-86. PGE coverage.

Figure A-87. ACSR/ACSS.

Exemplary Projects						
Year	**Project Name**	**Project Type**	**Conductor Used**	**Voltage Level**	**Line Length**	**Project Purpose**
2019	Orenco-Sunset	Reconductor	ACSS	115 kV	3 miles	Thermal overloads

PPL Electric Corporation

(ACSS/TW)

Utility Profile

PPL Electric Corporation provides power to customers in 29 counties in Pennsylvania. The transmission system covered for this region is illustrated in Figure A-88.

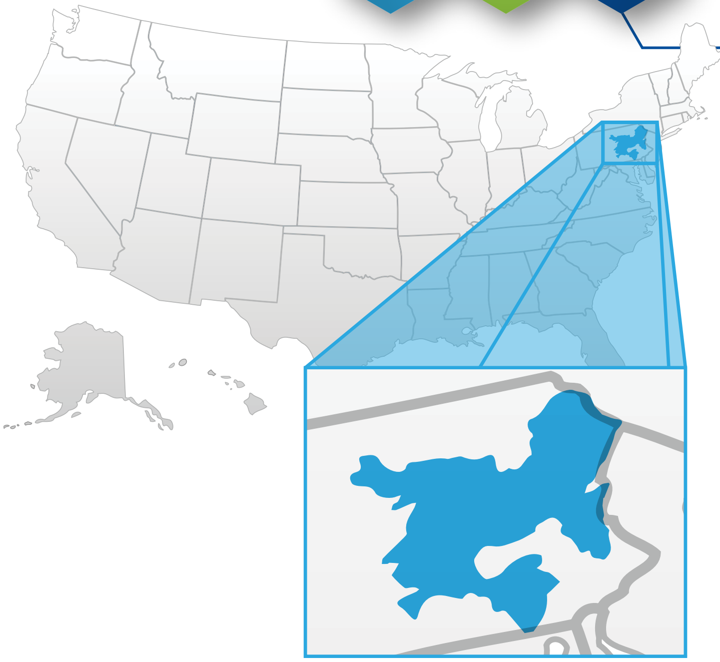

Figure A-88. PPL coverage.

Conductor Application Successes

PPL has proposed using ACSS (Figure A-89) for a reconductoring project in the PJM Interconnection. During the work they have proposed to replace the existing porcelain insulators with new glass strings of insulators, presumably because of age or deterioration of the existing insulators. Only one structure would need to be replaced out of 75 existing structures, although others would need to be reinforced. The existing shield wire will remain in place. The ACSS proposed incorporates HS285 steel (Southwire tradename), which is designated as MA5 by ASTM. Ultra-high-strength steel allows for tighter tensioning of conductors and reduced sag.

Figure A-89. ACSR/ACSS.

Exemplary Projects

Year	Project Name	Project Type	Conductor Used	Voltage Level	Line Length	Project Purpose
2023	Juniata - Cumberland	Reconductor	ACSS/TW	230 kV	14.2 miles	Unknown

Public Service Enterprise Group

(ACSS)

Utility Profile

Public Service Enterprise Group (PSE&G) covers much of New Jersey residents and businesses. The transmission system covered for this region is illustrated in (Figure A-90).

Conductor Application Successes

PSE&G has used ACSS for reconductoring projects (Figure A-91).

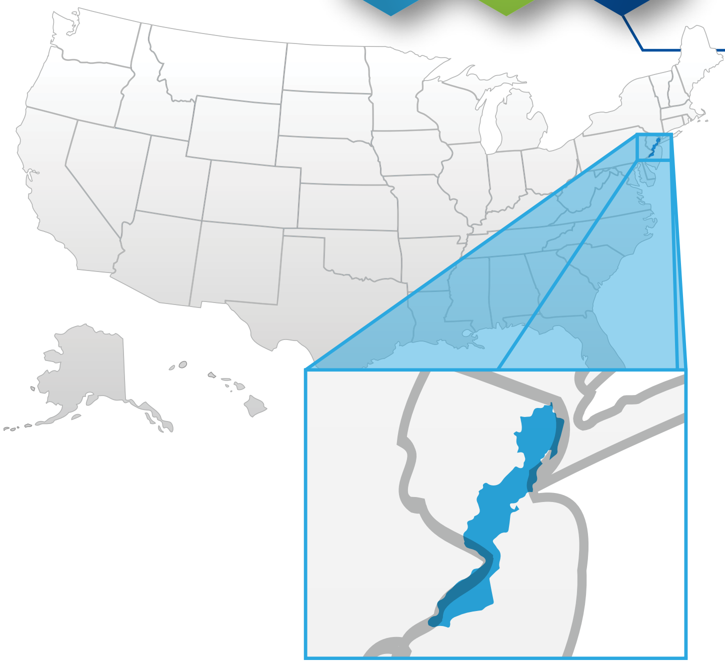

Figure A-90. PSE&G coverage area.

Figure A-91. ACSR/ACSS.

Exemplary Projects

Year	Project Name	Project Type	Conductor Used	Voltage Level	Line Length	Project Purpose
2007	Kittatinny-Newtown	Reconductor	ACSS	230 kV	Unknown	Unknown

San Diego Gas & Electric Company

(ZTACIR, ACSS)

Utility Profile

San Diego Gas and Electric (SDG&E) has a relatively small service area (Figure A-92), covering the southern-most parts of Orange County and spanning south to the Southern California border with Mexico. They currently serve 3.7 million customers spanning over 4,100 miles[2].

Figure A-92. San Diego Gas and Electric service region.

Conductor Application Successes

SDG&E has done several reconductoring projects. The conductors used include ACSS and ZTACIR. The projects include 607 miles of new conductor running through the Cleveland National Forest, and several smaller projects (less than 10 miles each) running around and through the cities of San Diego, La Jolla, San Clemente, and others. SDG&E is the only known utility user of ZTCIR in the U.S.. ZTCIR is known as a "heat resistant aluminum alloy conductor invar reinforced" conductor and is similar to ACSR, but uses aluminum zirconium alloy as the conductive metal and uses aluminum cladinvar steel core wire, which exhibits a low-thermal coefficient of expansion; therefore, it has low sag at high temperatures.

Exemplary Projects

Year	Project Name	Project Type	Conductor Used	Voltage Level	Line Length	Project Purpose
2016	Artesian and Bernardo	Reconductor	ZTACIR	69 kV	2.2 miles	Capacity increase
2018	Meadowlark Junction to Escondido	Reconductor	ACSS	69 kV	7.4 miles	Reliability and clearance improvement

Southern California Edison

(ACCC, ACCR, ACSS/TW)

Utility Profile

Southern California Edison (SCE) serves approximately 15 million people in southern California (Figure A-93). The utility owns its transmission infrastructure, but it has sold many of its generating assets. The company has a strong dedication to the development of green energy and embracing technologies that will secure the net zero future. From the Tehachapi Pass Wind Farm to solar contracts and solar generation development and EV rate programs, SCE is constantly searching for new technologies to improve the environment and their value for southern California.

Figure A-93. Southern California Edison service area.

Conductor Application Successes

SCE has about 300 circuit miles of lines on at least 15 projects that have been reconductored with composite core ACCC conductor (Figure A-94). They are significantly invested in CTC Global technology for reconductoring purposes. SCE also regularly use ACSS conductors (Figure A-95) for new builds and rebuilds and has also raised existing towers to increase line clearance to ground.

SCE used ACCR (Figure A-96) to reconductor a 3-mile section of a 500-kV line. Reconductoring and transmission line work has been done both to increase transmission capacity and to remediate approximately 11,000 safety clearance violations identified with surveys using LiDAR technology.

SCE has adopted ACCC and the ACSS technology and are replacing lines as they either age out or become points of congestion. Other technologies have been deployed to reduce congestion, such as the smart wires smart valves. The ecosystem of technologies provides a rich range of options that allow utilities to tailor the lowest cost solution to each unique problem.

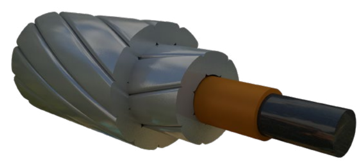

Figure A-94. ACCC conductor.

Figure A-95. ACSS conductor.

Figure A-96. ACCR conductor.

Exemplary Projects

Year	Project Name	Project Type	Conductor Used	Voltage Level	Line Length	Project Purpose
2018	Springville-Magunden	Reconductor	ACSS/TW	230 kV	50 miles	Unknown
2018	Victor-Aqueduct-Phelan	Reconductor	ACCC	115 kV	34 miles	Unknown
2018	TLRR project	Reconductor	ACCR	500 kV	3 miles	Unknown

Southern Company

(ACCR, ACSS)

Utility Profile

Southern Company is a parent company of several power companies covering large areas of the Southern United States (Figure A-97). Currently, they are the parent company of three electric utilities, five natural gas utilities, and five other power and telecom companies. They are currently responsible for more than 27,000 miles of transmission lines, 3,700 substations, and 300,000 acres of right of way.

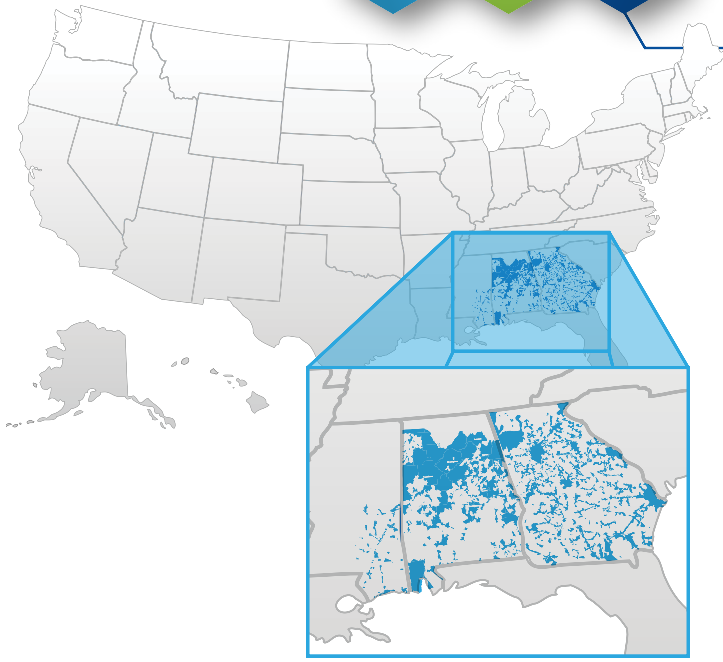

Figure A-97. Southern Company service territory.

Conductor Application Successes

Southern Company states they are the largest utility user of ACCR Conductor from 3M, having installed over 300 circuit miles on many reconductoring projects. Southern Company also uses ACSR and ACSS for projects. Between 2010 and 2020, Southern Company partnered with Dalton Utilities, Power South Energy Cooperative, South Mississippi Electric, Georgia Transmission, and Municipal Electric Authority of Georgia to construct nine new ACSR transmission lines, three new ACSS transmission lines, and one replacement of an existing line with ACSS.

Exemplary Projects

Year	Project Name	Project Type	Conductor Used	Voltage Level	Line Length	Project Purpose
2013	Kraft to McIntosh	Reconductor	ACCR	230 kV	16.7 miles	Avoiding construction in wetlands

Tennessee Valley Authority

(ACSS/TW, ACCR, TS)

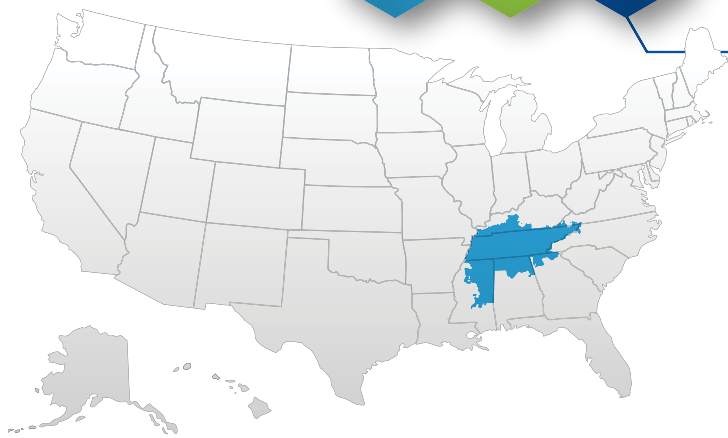

Figure A-98. TVA region.

Utility Profile

The Tennessee Valley Authority (TVA) works in partnership with local power companies to keep reliable public power flowing to residential and commercial electricity users throughout the seven-state Tennessee Valley region. Both municipal utilities and regional cooperatives purchase power from TVA and distribute it to consumers within their designated service areas, which are illustrated in Figure A-98.

Conductor Application Successes

TVA has installed ACSS, ACCR, and TS conductors (Figur A-99, Figure A-100, Figure A-101) in their infrastructure, noting in particular ACCR in 2014 and more recently TS conductors. ACSS is a standard conductor for use within their infrastructure for application alongside ACSR, addressing the need for a higher capacity conductor in certain installations.

TVA has been progressive in the application of transmission technologies and advanced conductors in their infrastructure. TVA installed the world's first 500-kV transmission line in 1965 and has been using ACSS conductor since the early 1970s. TVA completed a line reconductor using ACCR on a 500-kV line in 2013, which was the world's first application of ACCR on a three-bundle 500-kV configuration. TVA is now investigating TS Conductor as a cost-effective method to upgrade existing lines without performing tower modifications.

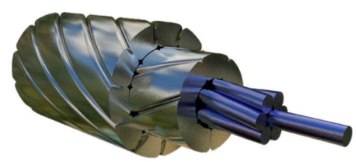

Figure A-99. ACSS conductor.

Figure A-100. ACCR conductor.

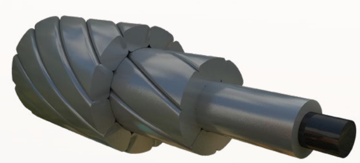

Figure A-101. TS conductor.

Exemplary Projects

Year	Project Name	Project Type	Conductor Used	Voltage Level	Line Length	Project Purpose
2013	Pinhook-Wilson	Reconductor	ACCC	500 kV	Unknown	Increased capacity
2023	Unknown	Reconductor	TS conductor	Unknown	Unknown	Increased capacity
Since 1973	Various	New and reconductor	ACSS	Various	Unknown	Various

Tucson Electric Power Company

(ACSS)

Utility Profile

Tucson Electric Power (TEP) has a relatively small service area (Figure A-102), covering the city of Tucson and surrounding areas. They own over 2,600 miles of transmission lines ranging from 46 to 500 kV. They currently serve over 442,000 customers.

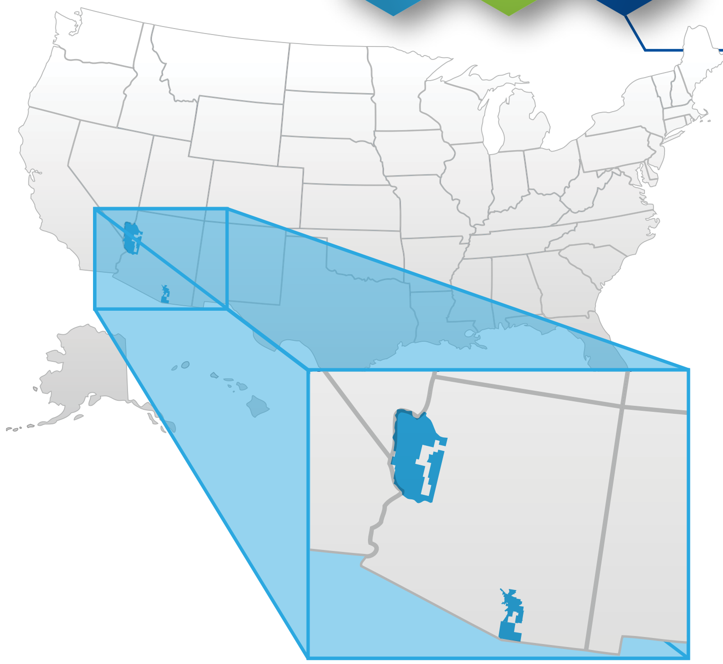

Figure A-102. Tucson Electric service region.

Conductor Application Successes

TEP uses 954-kcmil ACSS (Figure A-103) 45/7 Rail as a standard for 138-kV lines, which is rated at 2265 amps and is used for both new construction and for reconductoring. TEP used 1590-kcmil ACSR for a 500-kV new line construction that connects the Pinal Central and Tortolita substations. The total distance of the line is 40 miles and consists of a single circuit.

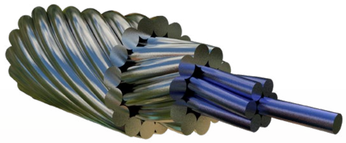

Figure A-103. ACSS conductor.

Exemplary Projects

Year	Project Name	Project Type	Conductor Used	Voltage Level	Line Length	Project Purpose
2020	Irvington-Vail	Reconductor	ACSS	137 kV	11.1 miles	Capacity
2015	Pinal Central-Tortolita	New construction	ACSR	500 kV	40 miles	Various

Western Area Power Administration

(ACSS/TW MA5, ACCR, ACCC)

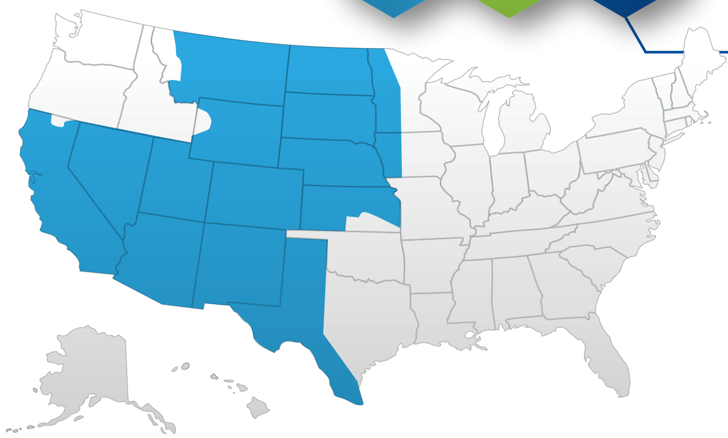

Figure A-104. WAPA region.

Utility Profile

The Western Area Power Administration (WAPA) is Federal Power Marketing Agency, serving as a wholesale power provider for 15 western and central states shown in Figure A-104.

Conductor Application Successes

WAPA installed 1.5 thousand miles of ACSS conductor (Figure A-105) in 2008, needing to increase capacity while changing an aged ACSR line. The reconductoring performed had minimal tower modifications. A number of reconductoring and installation projects using ACSS has been noted to the current day.

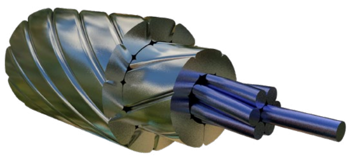

Figure A-105. ACSS/TW conductor.

ACCR (Figure A-106) has also been applied in 2006 and in other applications to boost power capacity. This included power from the Boulder Dam to increase capacity in the region and replace an aged line with minimal tower rebuilding.

Figure A-106. ACCR conductor.

ACCC (Figure A-107) was tested in 2006 in Arizona to evaluate performance against wind and other conditions.

WAPA recognized the benefits of reconductoring using the latest ACSS/TW after performing a tradeoff study of the costs with just ACSR replacement. The reduced costs of the reconductoring with ACSS with the added benefit of increased capacity, which was desired, was a driving motivation. WAPA continues this strategy.

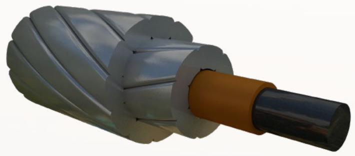

Figure A-107. ACCC conductor.

Exemplary Projects

Year	Project Name	Project Type	Conductor Used	Voltage Level	Line Length	Project Purpose
2007	Davis Mead	Reconductor	ACSS/HS285	230 kV	61 miles	Capacity
2005	Liberty-Parker #2	Reconductor	ACCC	230 kV	2 miles	Capacity
2002	Jamestown to Fargo	Reconductor	ACCR	230 kV	1 mile	Capacity

Xcel Energy Electric Company

(ACSS, ACSS/TW, ACCC, ACCR)

Utility Profile

Xcel Energy has a service area that spans across parts of seven different states (Figure A-108). They currently serve more than 3.7 million customers and have 20,000 miles of transmission lines.

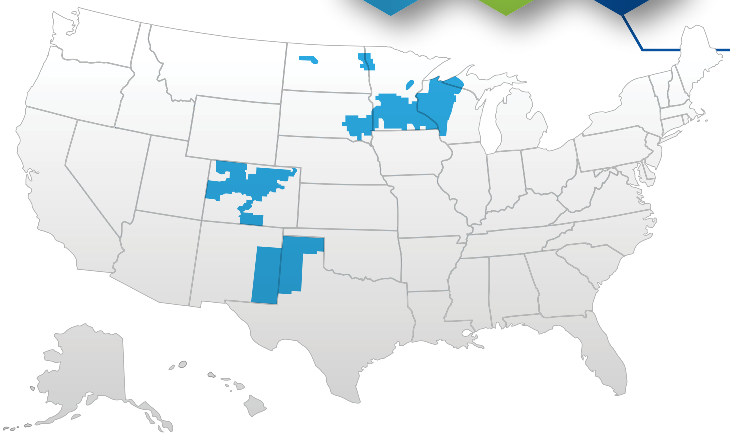

Figure A-108. Xcel Energy service region.

Conductor Application Successes

Xcel Energy uses a variety of conductor types in their transmission lines. ACSR is one of the standard types of conductors used in their transmission including twisted pair ACSR in areas prone to galloping. They currently use ACSS (Figure A-109) in approximately 20% of their new construction projects. Xcel installed the world's first commercial project for ACCR (Figure A-110) on the Black Dog-Blue Lake project as a good alternative to provide higher ampacity and less sag without rebuilding the line. Xcel was a partner along with 10 other utilities in the CapX 2020 project, which was the largest transmission project completed in the upper Midwest since the 1970s. Xcel utilized ACSS/TW on their portion of the project. During construction, the line experienced a significant problem with galloping conductors, which had to retrofit with 25-foot spacers to keep the phases separated and to inhibit the vibrations. Four of these 200-pound spacers were installed per span to mitigate the problem.

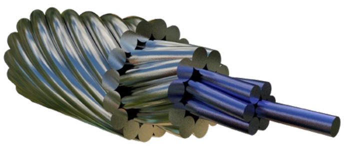

Figure A-109. ACSS conductor.

Figure A-110. ACCR conductor.

Exemplary Projects

Year	Project Name	Project Type	Conductor Used	Voltage Level	Line Length	Project Purpose
2005	Black Dog-Blue Lake	Reconductor	ACCR	115kV	10 miles	Capacity increase
2017	CapX 2020	New construction	ACSS/TW	345 kV	156 miles	Renewable energy capacity

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