WhitePaper

# Connecting Renewable Energy with Giga-Strength Steel

## The Benefits of Giga-Strength Steel for Reconductor and Greenfield Projects

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# Steel Core Background

The design of overhead lines must be customized to address issues such as the route, terrain, climate, and power delivery requirements. The overhead line design also needs to consider intangibles related to existing infrastructure and the preferences of the numerous stakeholders. Given these factors, determining optimal conductor technology without project-specific criteria is impossible.

Integrating renewable energy into the US grid is now a matter of urgency. Giga-strength advanced steel cores provide a solution to the challenges of renewable energy integration.

In the white paper "Accelerating Transmission Expansion by Using Advanced Conductors in Existing Right-of-Way" published by the UC Berkeley Energy Institute at Haas in 2024, the authors argue that advanced conductors can increase capacity and support renewable energy integration in the US. The paper posits that integration is critical and there is no time for new construction. Reconductoring of the existing grid is the best option.

The Haas paper focuses on the low thermal sag characteristic of conductors with carbon fiber composite (CFC) core.

Reconductoring is not a "one size fits all" situation, as there are equally important conductor characteristics where steel core conductors outperform CFC core conductors in important aspects of reconductoring projects.

Conductors with steel cores are suitable for both greenfield and reconductor applications. Steel core has several desirable characteristics that are lacking in CFC core. Steel core is low-cost, durable, and has high elastic modulus (resistance to stretching). The elastic modulus of CFC is approximately half that of steel. When the conductor is subject to ice and wind loads, steel cores outperform CFC core because of this difference.

**In this White Paper, we make the case that steel core is the best solution for increasing capacity and reducing energy loss in the transmission system.**

**Giga-strength steel core provides ACSS/TW conductor options with the lowest achievable line loss and a considerable advantage in capacity.** Additionally, further downsizing a CFC core is limited by performance issues related to its relatively low elastic modulus.

# Configuring a Realistic Reconductor Scenario

**This paper sets realistic basic criteria for real-world reconductor projects:**

- The existing line is a 795 kcmil 26/7 “Drake” ACSR rated to carry 1000 amp at its 100 ˚C maximum operating temperature (MOT).
- A minimum of 70% capacity increase is required.
- The line is located in the NESC “Heavy” loading district, which is approximately 30% of the United States, designs must withstand ½” of radial ice combined with a 4 lb/sq ft wind force perpendicular to the line at a temperature of 0 ˚F (-17.8 ˚C).
- Time constraints, permits, and environmental concerns make modifications to the existing structures impractical. With this in mind:
  - The new conductor may not sag more than the currently installed “Drake” ACSR at its MOT.
  - Structure loads may not increase relative to “Drake” design loads from the original line design.
- Load from one (1) inch of radial ice at 32 ˚F (0 ˚C) is also considered but is not required to meet sag or tension limits.
- Line loss will be calculated assuming a 500 A average annual load. The net present value (NPV) of the next 30 years of line loss shall become part of the cost/benefit evaluation.

# Determining the Optimum Conductor Candidates

To avoid increased structure loads during ice and wind conditions, the conductor diameter cannot exceed the “Drake” diameter of 1.108 in (28.1 mm).

Two commercial conductors and one pre-commercial ACSS/TW conductor with an advanced steel core are evaluated and listed in order of increasing aluminum area. The ACCR (Aluminum Conductor Composite Reinforced) conductor is not considered because this application is a poor match for its special characteristics. All reconductor candidates considered in this discussion use the same grade of fully annealed aluminum for the conductive component. All also employ trapezoidal wire (TW) aluminum strands as a strategy to increase performance by increasing the aluminum area compared to round aluminum strands:

- **959.6 kcmil ACSS/TW/MA5 “Suwannee/MA5”:** MA5 designates an Ultra-High-strength steel core with a high-temperature corrosion-resistant coating (Bezinal®).

- **1025.6 kcmil ACCC® “Drake”**: ACCC® is constructed using a carbon fiber composite (CFC) core.

- **1031.7 kcmil ACSS/TW/MA8 “Mississippi”**: A 7 x 0.1221” Giga-strength core (an ACSR “Nuthatch” size) is specified for compatibility with existing connectors, tools, and die systems. Aluminum content is increased compared to all other options, because a smaller Giga-strength steel core delivers the necessary performance while allowing for greater aluminum area within the diameter limitation.

Conductor properties for the commercially available options are from open-source references. Industry-standard practices and software were used to model properties for 1031.7 kcmil ACSS/TW/MA8 “Mississippi”.

Table 1 shows the important properties for evaluating a reconductor candidate. PLS-CADD wir files and SAG10 charts are available for each conductor listed.

**Table 1: Properties of "Drake" ACSR and Reconductor Candidates**

| Conductor Size & Designation | Rated Breaking Strength (lb) | Weight (lb/1000 ft) | Core Size | 60 Hz AC Resistance* @ Temp (ohm/mi) | | Maximum Operating Temperature (MOT) (°C) |
|---|---|---|---|---|---|---|
| 795.0 kcmil ACSR “Drake” | 31,500 | 1093 | 7 x 0.1360 | 0.1166 @ 25°C | 0.1503 @ 100°C | 100 |
| 959.6 kcmil ACSS/TW/MA5 “Suwannee” | 38,600 | 1317 | 7 x 0.1493 | 0.0941 @ 25°C | 0.1517 @ 180°C | 250 |
| 1025.6 kcmil ACCC “Drake” | 41,299 | 1052 | 1 x 0.3750 | 0.0903 @ 25°C | 0.1454 @ 180°C | 180 |
| 1031.7 kcmil ACSS/TW/MA8 “Mississippi” | 31,900 | 1246 | 7 x 0.1221 | 0.0888 @ 25°C | 0.1426 @ 180°C | 250 |

*AC Resistance computed using SWRate Pro software

# Ensuring Accurate Conductor Performance Modeling

Models for 795 ACSR “Drake” and 959.6 ACSS/TW/MA5 “Suwannee” are available in libraries embedded in industry-standard software SAG10® and SWRate Pro®.

1026 ACCC® “Drake” is modeled by creating a custom conductor using ACCC® published specifications and the manufacturer-provided “wir” file data for stress-strain and creep coefficients.

# Evaluating the Results

## Conductor Capacity

The reconductor criteria includes a minimum of 70% capacity increase relative to “Drake” ACSR at its 100 °C MOT. The 1025.6 kcmil ACCC® “Drake” conductor meets the 70% capacity increase by a combination of a higher (180 °C) temperature limit and increased aluminum area compared to ACSR “Drake”. Using compact trapezoidal wire (TW) the outer diameter will be the same while having more aluminum area compared to the round strands used in ACSR "Drake".

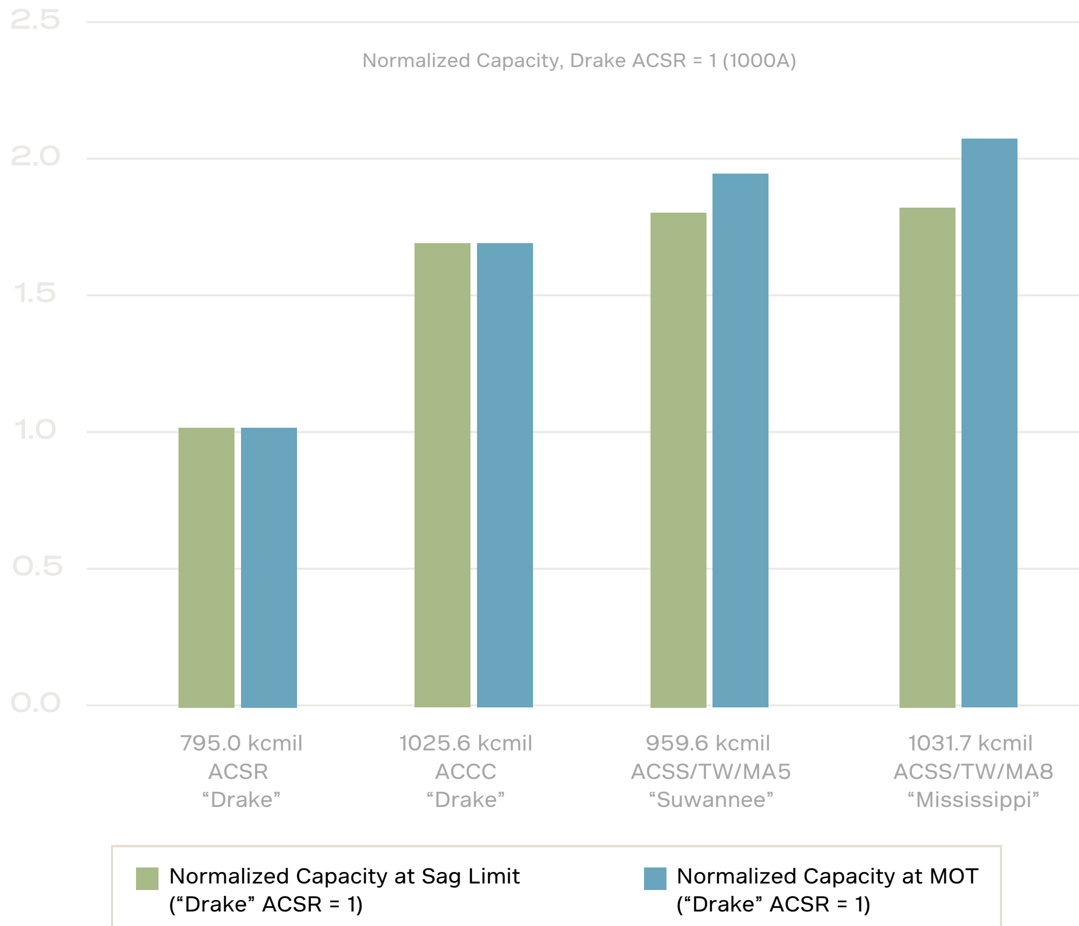
Both the 959.6 kcmil ACSS/TW/MA5 “Suwannee” and 1031.7 kcmil ACSS/TW/MA8 “Mississippi” also use compact trapezoidal wire (TW) aluminum strands, and have a thermal operating limit of 250 °C.

All of the reconductor candidates meet the capacity criterion. ACCC® meets the reconductor requirement at its thermal limit (180 °C). **Both ACSS/TW candidates exceed the capacity requirement** with approximately a one-foot margin to the sag limit. Extra capacity above the required 70% increase is available until the sag limit is exceeded.

Figure 1 shows the conductors’ capacities normalized to show the capacity increase above the 1000 A capacity of the existing “Drake” ACSR. The maximum operating temperature limit for ACSR is a thermal/metallurgical limit based on annealing (softening) of the hard-drawn aluminum conducting component. **The maximum operating temperature limit for ACCC® is governed by thermal degradation of the polymer matrix in the CFC core.** The capacity limit for both ACSS/TW options is governed by the sag limit set in the ground rules for reconductor candidates.

The blue bars in Figure 1 show the conductors’ capacities at their maximum operating temperature: 100 °C for ACSR, 180 °C for ACCC®, and 250 °C for ACSS/TW/MA5 and ACSS/TW/MA8 options. The green bars show the more limiting operating limit, which can be thermal, and can be a sag limit from the reconductor scenario (see page 1).

**Figure 1: Normalized Capacity for "Drake" and Reconductor Alternatives**




- Capacity computed per IEEE 738, assuming: 40 C ambient, 2 t/s perpendicular wind, full sun, & 46°N Latitude

Key: "Drake", "Suwannee", and "Mississippi" are industry designators for three conductor designs. "kcmil" is the industry unit for the conductor's aluminum area. ACSR was introduced in 1909, designates Aluminum Conductor Steel Reinforced. ACSS was introduced in 1973, designates Aluminum Conductor Steel Supported

## Conductor Line Loss

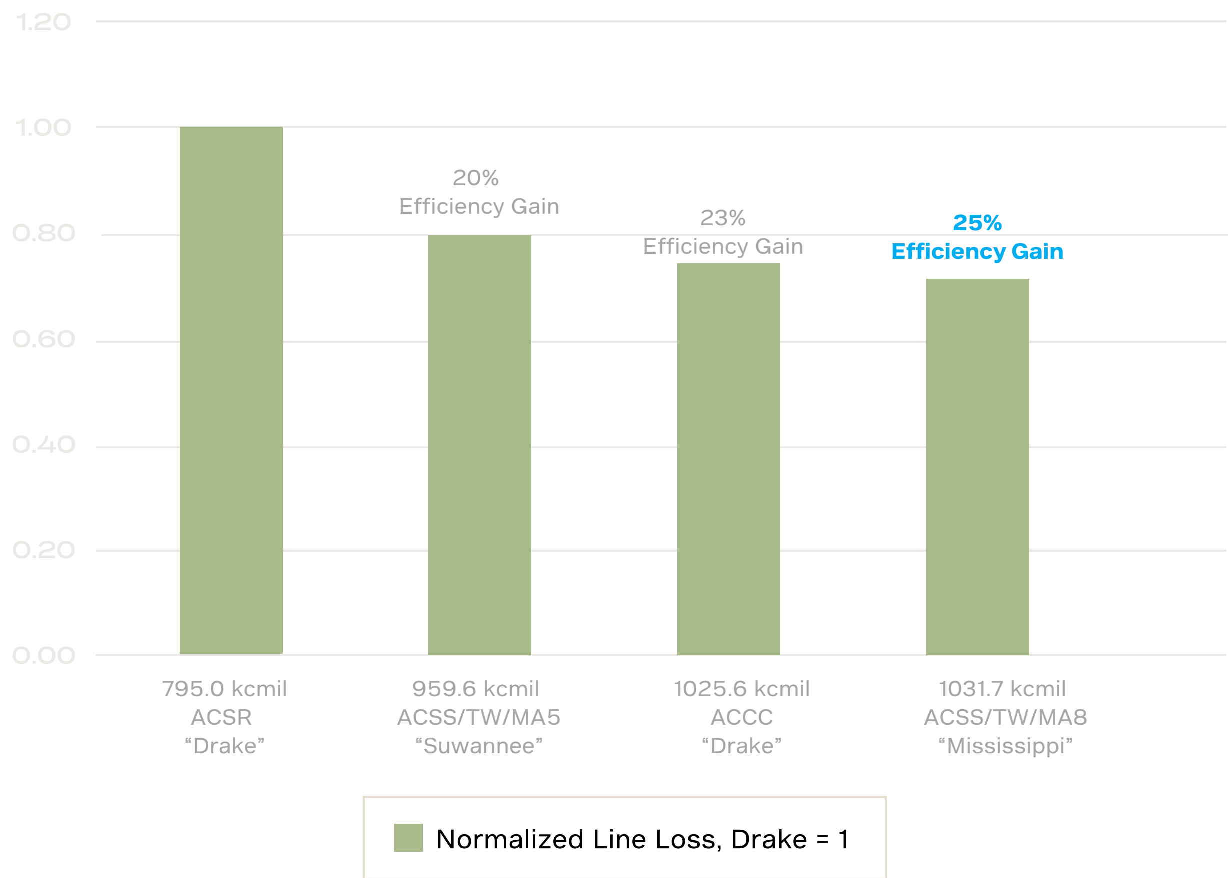
In North America, the value of future line loss is usually not considered during conductor selection. However, this practice is changing. Renewable energy now sells at a premium and is often metered at the destination. Avoided line losses can be captured as revenue at the meter.

It is difficult to accurately calculate line loss since line loads can vary considerably depending on the season and time of day. A shortcut to a valid relative ranking of line loss is to compute the loss assuming an average annual line load. For this paper, we have assumed a line load of 500 A. Different assumptions for average line load would result in the same relative rankings.

Similar to the capacity chart, the engineering values are normalized by reference to the "Drake" ACSR conductor.

At 795 kcmil of aluminum area, "Drake" has the highest line loss designated as loss = 1.0. The value of 0.8 for the 959.6 kcmil ACSS/TW/MA5 "Suwannee" option indicates the line loss is 80% of the line loss (20% efficiency gain) for the 795 kcmil "Drake" ACSR at the same 500 A line load. The highest aluminum content conductor is the 1031.7 kcmil ACSS/TW/MA8 "Mississippi". The Giga-strength steel allows for a smaller core, and correspondingly greater aluminum area for line loss that is 75% of the line loss (25% efficiency gain) of the "Drake" line being reconductored. The ACCC® conductor also benefits from greater aluminum content than "Drake" and has a normalized line loss that is 77% of the line loss (23% efficiency gain) in the "Drake" ACSR conductor. Figure 2 shows these values in bar graph format:

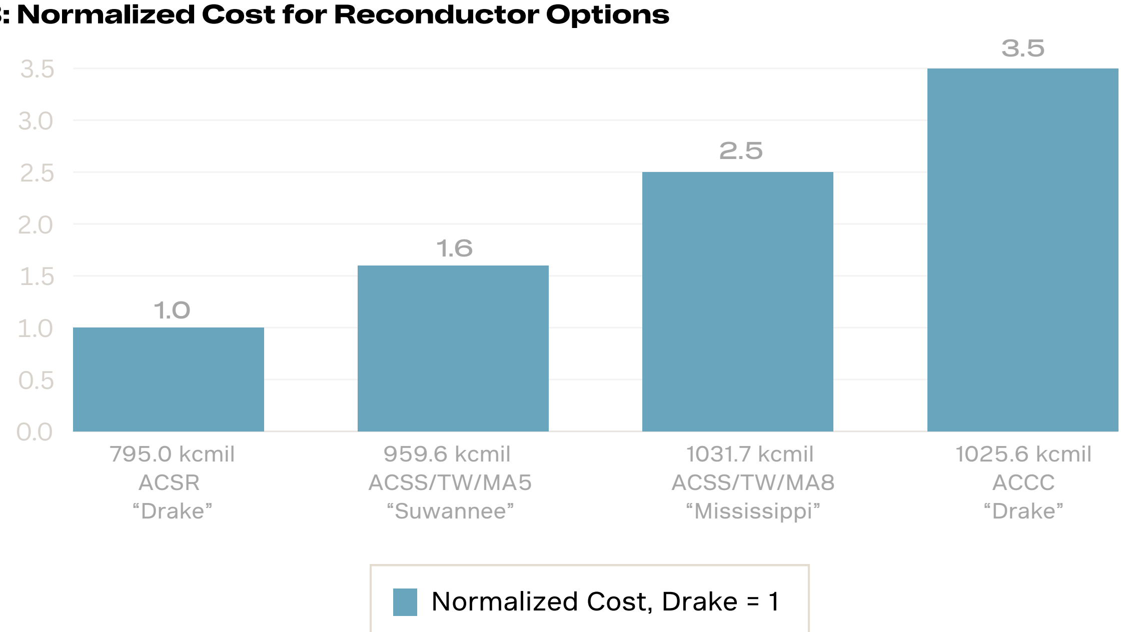
**Figure 2: Comparison of Line Loss at 500 A Average Annual Load**




## Conductor Cost

In most projects, the conductor cost is approximately 20% of the total cost. Conductor performance impacts the cost of structures, right-of-way, and cost of losses. The cost of line loss can be significant when it is considered as part of the project cost. (Line loss is addressed in the prior section). The estimated first cost for a conductor is summarized in Figure 3.

**Figure 3: Normalized Cost for Reconductor Options**



# Advanced Conductor High-Temperature Sag

## Sag at Maximum Capacity per the Reconductor Criteria

The ACCC® meets the 70% capacity increase requirement at its 1695 amp thermal limit. The ACCC® option meets the high-temperature sag target with 10 ft to spare.

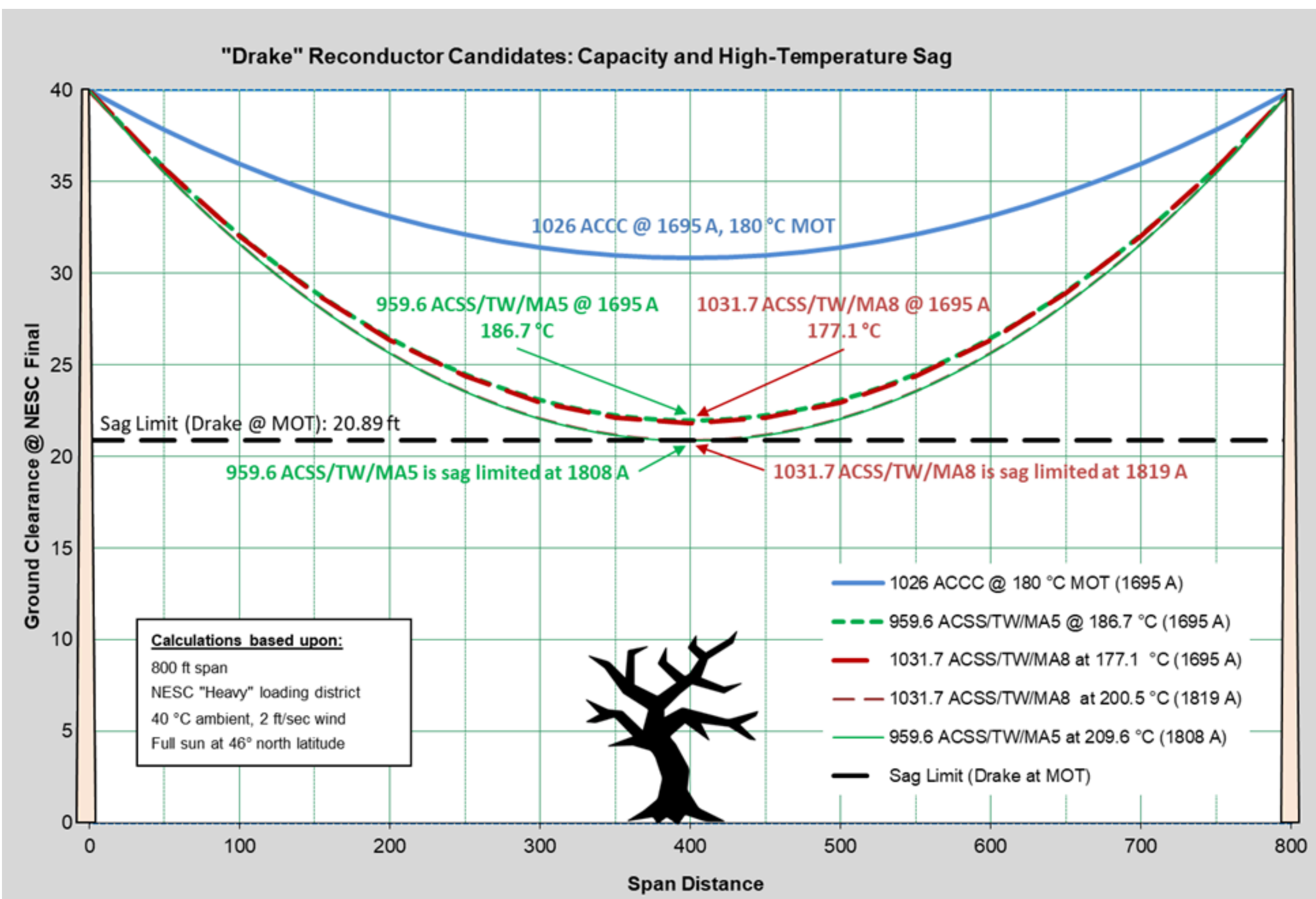
The two ACSS/TW options have higher thermal limits, but capacity is limited by conductor sag at high temperature. At the same capacity gain as the ACCC®, the ACSS/TW conductors safely meet the sag requirement with one (1) foot of margin (shown in Figure 4 below).

It should be noted that it is not uncommon for a transmission line's capacity to be limited by the sag limit.

In the case of 959.6 ACSS/TW/MA5, the sag limit is reached at a temperature of 209.6 °C. This corresponds to a capacity of 1808 amp which is an **80.8% increase over the capacity of ACSR "Drake".**

The slightly larger 1031.7 ACSS/TW/MA8 reaches the sag limit at 200.5 °C, corresponding to a capacity of 1819 amp. **This is an increase of 81.9% compared to ACSR "Drake".** Figure 4 shows the conductor sags computed for the maximum capacity per the reconductor criteria.

**Figure 4: Sag Performance at Maximum Capacity per the Reconductor Criteria**



## Conductor Sag and Capacity at MOT

The nominal reconductor criteria does not permit structure enhancements to accommodate greater capacity. However, capacity is valuable, and transmission organizations loath to leave "money on the table" by failing to achieve rated capacity for their conductor investment. They typically find that most or all the existing structures have some height margin, or that low-cost "nips and tucks" are available to increase the clearance at a small number of problem areas.

An investment in structures is generally justified to allow the conductors to operate safely at maximum capacity.

Table 2 shows the capacity and sag implications for ACSR "Drake" and reconductor options.

**Table 2: Capacity and Sag Implications for "Drake" and Reconductor Options**

| Conductor Size & Designation | Maximum Capacity per Limiting Criterion (A) | Capacity Increase Over ACSR "Drake" (%) | Capacity at MOT (A) | Capacity Increase Over ACSR "Drake" at MOT (%) | Sag Remediation Required at MOT (ft) |
|---|---|---|---|---|---|
| 795.0 kcmil ACSR "Drake" | 1000* | - | 1000 | - | 0 |
| 959.6 kcmil ACSS/TW/MA5 "Suwannee" | 1808** | 81** | 1990 | 99 | 1.9 |
| 1025.6 kcmil ACCC "Drake" | 1695* | 70* | 1695 | 70 | 0 |
| 1031.7 kcmil ACSS/TW/MA8 "Mississippi" | 1819** | 82** | 2052 | 105 | 2.0 |

*@ thermal limit
**@ sag limit

## Conductor Loaded (Ice and Wind) Sag

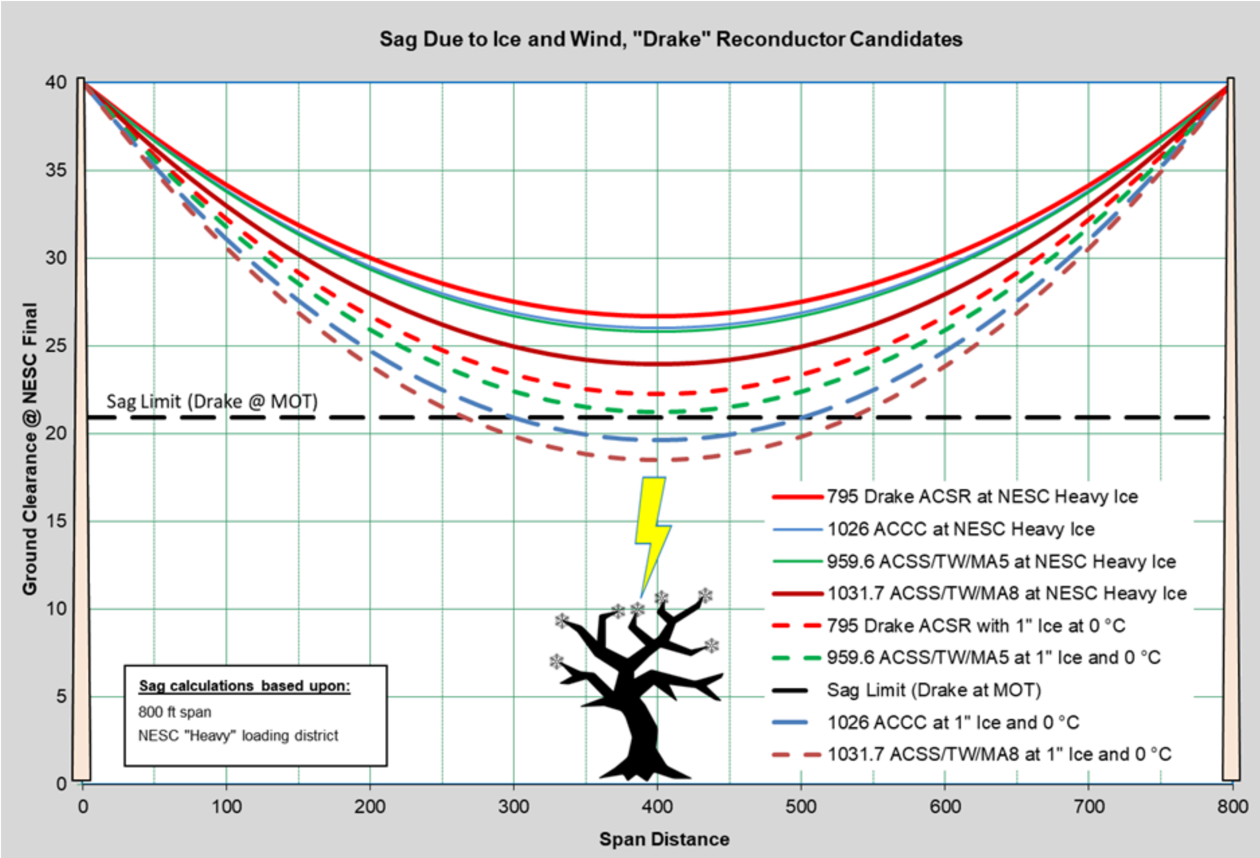
Per the reconductor criteria, the sag was computed under the NESC "Heavy" loading criteria of 1/2" ice combined with 4 lb/sq ft wind force at 0 ˚F (-17.8 ˚C). Sag for this condition is shown as solid lines in the figure below. Sag is also computed for one inch of radial ice at 32 ˚F (0 ˚C). Sag for this condition is shown as dashed lines in the figure.

In Figure 5, we can see that all the proposed reconductor candidates comfortably meet the sag target for NESC "Heavy" loading. The ACCC® conductor no longer has a sag advantage as it sags almost identical to 959.6 ACSS/TW/MA5 under NESC "Heavy" loads, and sags below the nominal sag criterion with a one-inch ice load.

The significant sag increase of the CFC relative to the steel core conductors is due to the relatively low CFC elastic modulus, which is approximately half the elastic modulus of steel. ACCC® is offered in variants that improve performance under weather loads, but at higher cost and with reduced performance in capacity and line loss.

Similarly, the 1031.7 ACSS/TW/MA8 conductor sags below the criterion at a one-inch ice load because the steel core is undersized for such an extreme load. A different conductor would be needed to address one-inch ice loads.

**Figure 5: Sag Performance for Loaded Conditions**




## Conductor Resiliency

Resiliency measures the conductor's ability to survive extreme events including wildfires, weather events, and hostile acts. Resiliency also considers the speed of recovery following damage or destruction.

ACSR has the structural redundancy of a strong aluminum outer shell combined with a tough steel core containing multiple strands. In most use cases, each component alone is strong enough to keep the conductor in the air, albeit with a sag increase. Accordingly, ACSR ranks highest in the ability to survive extreme events. With a 100-year usage history and 80% historical market share, ACSR also has the best time-to-repair ranking.

A conductor with a steel core will survive a wildfire event up to the 660 °C melting point of aluminum. A CFC core will degrade rapidly and is likely to fail if the core temperature exceeds 250 °C.

The ACSS/TW options do not have the structural redundancy of a strong aluminum outer shell, but they do have the same advantages as ACSR for the redundancy of a stranded core and an established repair infrastructure.

ACCC® ranks below the ACSS/TW options for resiliency. The CFC core has less than half the fracture toughness of a steel core and has no redundancy due to the single-strand design. It is more vulnerable to wildfire and has less developed repair infrastructure.

## Conductor Sustainability

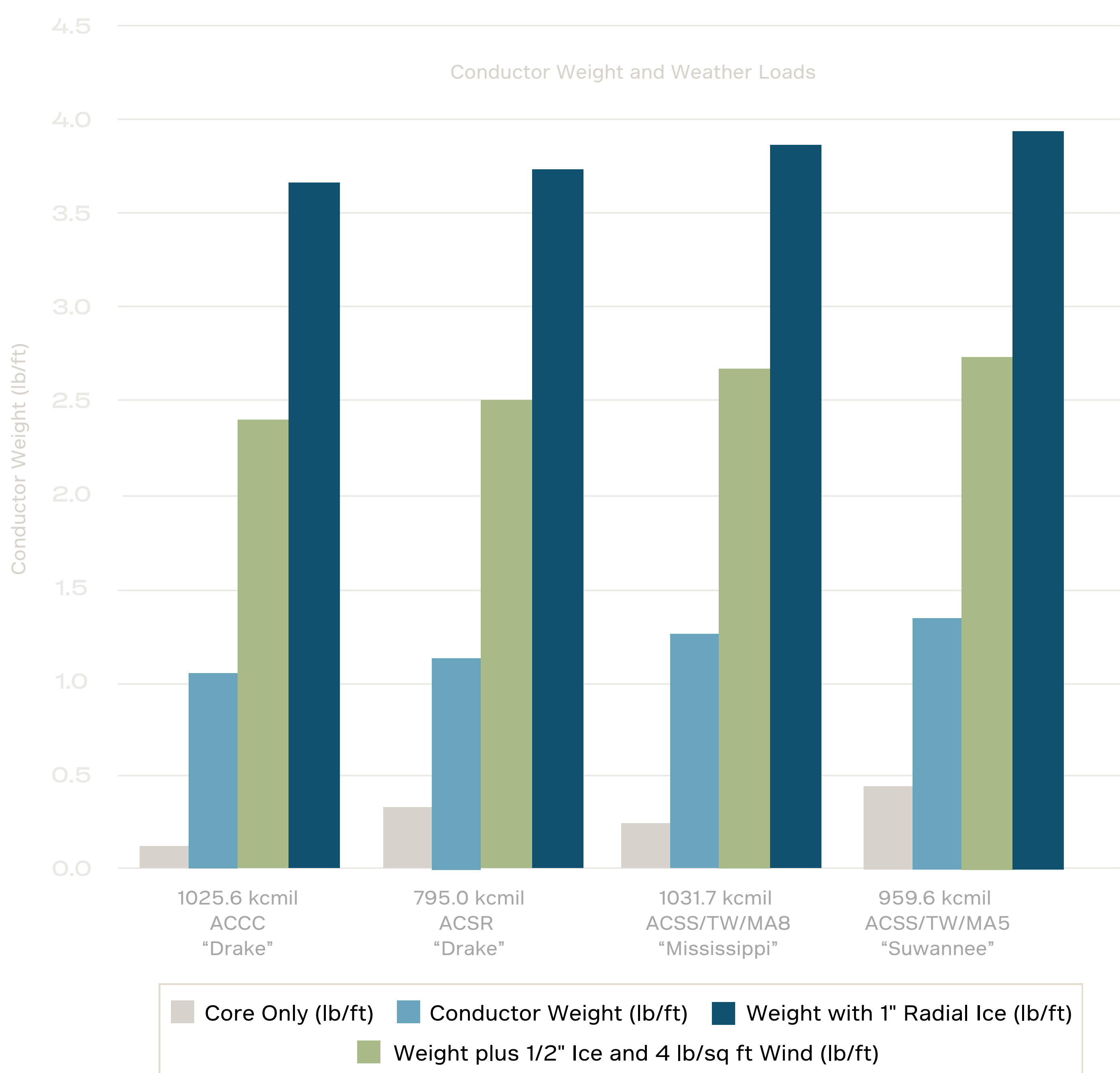
ACSR and ACSS have a long service life and are less expensive and use less resources to produce. They also have an established value in the recycle stream. A retired conductor can be chopped into short lengths and the steel component is easily separated using magnets. Both steel and aluminum have high value in the recycle stream making them 100% recyclable. Bekaert steel cores use more than 90% recycled steel.

CFC conductors, like fiberglass, the matrix polymer is cross-linked by an irreversible process which makes recycling problematic. Due to this process, composite cores can only be disposed of in landfills or by incineration.

# Advanced Conductor Weight

Lower weight is often claimed as a major advantage for polymer composites. This claim is valid for aerospace and motorsports applications. However, in overhead line applications, weight is lead by the aluminum component and the design ice and wind loads. Figure 6 summarizes the core and conductor weights under different service conditions. Line designers focus on the loaded weight (dark teal and green bars in the figure below).

**Figure 6: Weight of Core, Conductor, and Conductor with Weather Loads**



# How the Reconductor Candidates Rank

Table 3 shows the rankings of the conductors against the important criteria. All the reconductor candidates meet the basic criteria. Ultimately, the final selection will be governed by cost and any weighting factors applied by stakeholders.

It is clear from this analysis that the market is making informed decisions when ACSS/TW conductors are selected. The Giga-strength core provides a compelling ACSS/TW reconductor option for minimizing line loss and maximizing capacity. Ranking 1 indicates the highest performance, whereas 4 denotes the lowest.

**Table 3: Ranking of Conductor Candidates by Criterion**

| | 1031.7 kcmil ACSS/TW/MA8 "Mississippi" | 959.6 kcmil ACSS/TW/MA5 "Suwannee" | 795.0 kcmil ACSR* "Drake" | 1025.6 kcmil ACCC "Drake" |
|---|---|---|---|---|
| High Capacity | 1 | 2 | 4 | 3 |
| Low Line Loss | 1 | 3 | 4 | 2 |
| Low Sag | 4 | 2 | 3 | 1 |
| Low Cost | 3 | 2 | 1 | 4 |
| Resiliency | 2 | 2 | 1 | 4 |
| **Total Score** | **11** | **11** | **13** | **14** |
| **Ranking** | **1** | **1** | **3** | **4** |

*ACSR is unsuitable for most reconductor applications due to low capacity

# Conclusions

All the proposed reconductor candidates meet the necessary criteria to replace an ACSR without requiring structural modifications. The 1025.6 kcmil ACCC® "Drake" conductor leads in the high-temperature sag comparison and is oversized for the reconductor application while being 3.5 times the cost. It is a compelling choice for the rare cases when the high-temperature sag of the steel core options cannot be accommodated at moderate cost.

ACCC® also has a slightly higher aluminum area than any same diameter commercially available ACSS/TW options. Although it is bested by the ACSS/TW/MA8 conductor in aluminum area. However, ACCC® has a large sag increase under loaded conditions and fails the sag criterion if a one-inch ice load is considered.

959.6 ACSS/TW "Suwannee" is commercially available in two different steel grades: MA3/High-strength and MA5/Ultra-High-strength. "Suwannee" is a compelling reconductor candidate as it has the **highest capacity, and lowest cost**. It has acceptable sag characteristics and acceptable line loss. "Suwannee" is the **only reconductor candidate that meets the sag criterion under a one-inch ice load.**

Giga-strength steel allows for a smaller core diameter with a corresponding increase in aluminum area for **highest capacity and lowest line loss** of any option considered. The high-temperature sag is comparable to the "Suwannee" ACSS/TW/MA5 sag. However, due to the downsized core, 1031.7 ACSS/TW/MA8 does not meet the sag criterion for a one-inch ice load.

**Greater capacity and lower line loss are clear advantages for Giga-strength steel core**. CFC core has lower temperature limits and therefore cannot equal the capacity of steel core conductors. Giga-strength steel allows for an even smaller core with acceptable sag characteristics. The **smaller steel core allows the aluminum area to increase above the ACCC® area.** This results in **lowest line loss and highest capacity in addition to its other advantages.**

Creating a sustainable energy grid for the North American market requires the uptake of new technologies. As this paper has shown, Giga-strength advanced steel cores provide the market with a viable option when compared to existing conductors.

# Reference

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