White Paper

Grid Efficiency: The Core Challenge

Using steel core to optimize the efficiency of your overhead conductors

Bekaert

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Optimizing grid efficiency is the core challenge for today

The needs of power markets are rapidly changing. Today, operating the grid is all about integrating renewable and conventional sources and delivering reliable electricity to consumers at a favorable cost. This means **optimizing grid efficiency** by selecting overhead conductors with the optimal material, size, and design.

Adding a steel core increases the breaking strength of an aluminum conductor by a factor of 2 to 3. Conductors with a steel core are more resistant to thermal sag and sag caused by various load conditions such as heavy winds and ice loading. Moreover, the cores reduce horizontal blowout distances and, as a consequence, the probability of horizontal clearance violations.

Stranded steel wire cores have been used to reinforce aluminum, bare overhead conductors since the early 1900's. This was when **Aluminum Conductor Steel Reinforced (ACSR)** conductors allowed the use of longer span lengths and higher safety factors at high mechanical and electrical loads. In the last 40 years, the most widely used high-temperature conductor is **Aluminum Conductor Steel Supported (ACSS)**. Its annealed aluminum strands allow lines to operate at conductor temperatures as high as 250°C with zinc-aluminum alloy coated steel wire.

This century, **composite core conductors** have provided an alternative solution, based on advantages such as reduced weight, low coefficient of thermal expansion, high tensile strength, and corrosion resistance.

But which offers the best efficiency at optimal cost: steel cores or composite cores?

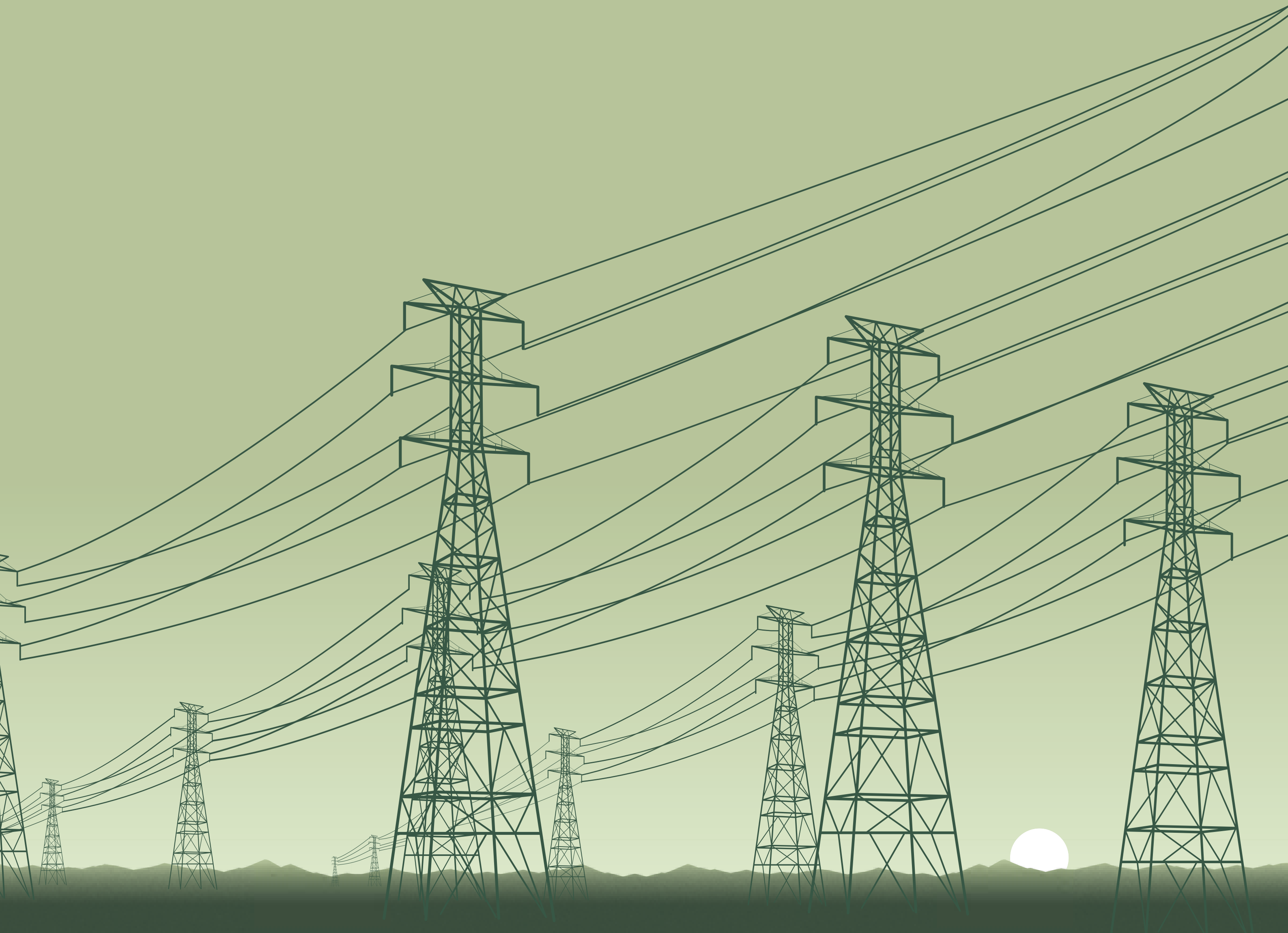
The drive to improve grid efficiency

Improving the efficiency of the electrical grid is one of many actions to address climate change and rising energy costs. Conservative temperature limits for the earliest overhead lines made them efficient. By the mid-1970s, load growth, combined with the financial and political cost of new lines, led to thermal uprating of existing line. The downside is a corresponding increase in the line losses.

For the purpose of this paper, we define conductor efficiency as the point-to-point power delivery efficiency for each line section: the energy delivered at the load divided by the energy provided at the source. Grid efficiency is more difficult to define, but is a multi-factor weighted average of the efficiency of each point-to-point line section.

Many transmission lines are extremely efficient due to operation at low average capacity factor. Bundled EHV and UHV lines are typically highly efficient because bundling needed to suppress corona results in these lines operating at a small fraction of their thermal capacity. The suggestion has been made that replacing all ACSR with advanced conductors will make the grid more efficient.

The US government is likely at some point to impose requirements designed to improve the efficiency of the grid. If this happens regulatory agencies will be funded and tasked with writing regulations to limit energy loss, including losses in overhead lines. That will inevitably drive purchasing decisions towards larger and more efficient conductors. What is the best use of money for improved grid efficiency? The smart grid (sensors for situational awareness, decision tools, control devices) has its place. However, conductors dominate the loss. Therefore, larger (lower resistance) conductors and the associated structure changes will also receive careful attention.



The economic value of a 1% conductor efficiency improvement

Power loss in a conductor is easily computed as the line current squared, multiplied by the AC or DC resistance of the conductor. Line current is highly variable over different seasons and times-of-day. It is therefore necessary to estimate an average annual current load to determine the annual loss. Once the engineers compute the energy loss in kWh, the economists place a dollar value on the line loss during the service life of the conductor. A more efficient conductor is justified by the value today for savings expected to accumulate over decades into the future.

Reference 1 in the Bibliography presents the rigorous and daunting method for computing the value of line losses. In addition to the cost of energy, the method addresses the utility-specific owning costs for generation and transmission assets, demand charges, and other direct and indirect costs. A simple shortcut is to assume electricity is priced correctly and use the average selling price of electricity as the cost. A present value computation of the annual savings is used to justify an investment today that pays back over decades into the future.

Using 795 kcmil ACSR “Drake” conductor as the reference, and assuming a 200 A, annual average line load (~20% of capacity), 25 ˚C average annual temperature, and 2 ft/s (0.61 m/s) average annual wind speed, the IEEE 738 method computes an average conductor temperature of 35.6 ˚C. The computation for a 1% efficiency improvement follows:

AC resistance		Average annual load		Convert		365 days		Energy cost		Annual cost
0.1215 Ω /mi	X	(200 A)^2	/	1,000 w/kW	X	8,760 hr/yr	X	$0.20/kWh	=	$8,515/mi/yr
0.0755 Ω /km										$5,289/km/yr

1% decreased resistance		Inflation		Service life		Net present value		Conductor cost		Efficiency vs conductor cost
$85.15/mi/yr	@	3.5%	@	40 years	=	$ 1,795.96/mi	@	$2/ft ($10,560mi)	=	17%
$52.89/km/yr						$ 1,115.50/km		$6.56/m ($6,560/km)		

The bottom line is that assuming the conductor cost is USD 2/ft (USD 6.56/m), this justifies a 17% cost increase for each 1% efficiency improvement.

Improve efficiency through design and manufacturing

Numerous options exist for increasing the conductor efficiency at low to moderate cost. Options that effect interoperability within the existing system should be pursued only if all other options fail to meet the goal.

For an example of interoperability, utilities maintain a supply of spare conductor and fittings for system restoration after storms and other events. It is unworkable to keep spares for special conductors needing special fittings. The fittings suppliers have a role in qualifying their special fittings to serve as storm spares for both legacy conductors and high-efficiency conductor. Similarly, the high-efficiency conductors should be suitable as storm reserves for similar legacy conductors in service.

In approximate order of cost-effectiveness, these are some easily available options you might like to consider:

Design/Manufacturing Option	Efficiency Improvement	Cost[1]
ACSS Annealed Aluminum instead of ACSR Hard-drawn Aluminum	1% to 1.5%	<1% - 10%
Larger conductor	0.1% - 10%	0.1% - 10%
Higher strength materials for the core to reduce core area and increase aluminum area	3%	10% to 200%[2]

[1] not including effect on structure cost
[2] cost depends on steel vs composite core

The economic optimization of conductor size

It is well-understood that conductor characteristics, especially the sag, impact the structure cost, and that conductor cost should therefore not be considered independent of its effect on the structure cost. In this paper there is no attempt to quantify the structure cost implications, which, depending on the line design, can be a deciding factor. As a basic principle, the conductor and structure combined cost increases linearly with the conductor size.

Figure 1 shows a graphical presentation of Kelvin's law for conductor size optimization. The blue line shows the linear relationship between the conductor size and the conductor cost. The brown line is an exponential curve, showing that the cost of losses increases exponentially as the conductor becomes too small. The benefit of increasing the conductor size reaches the point of diminishing returns, where it becomes uneconomical to further increase the conductor size. The green curve is total cost, which is the sum of the conductor/structure cost and cost of line loss. The size for the minimum total cost is the optimum size, located at the dashed black line. Note that the green total cost curve is relatively flat near the optimum. This means that picking a conductor one or two sizes above the optimum has a very small impact on the cost, if losses are considered.

Kelvin's Law for Optimizing Conductor Size

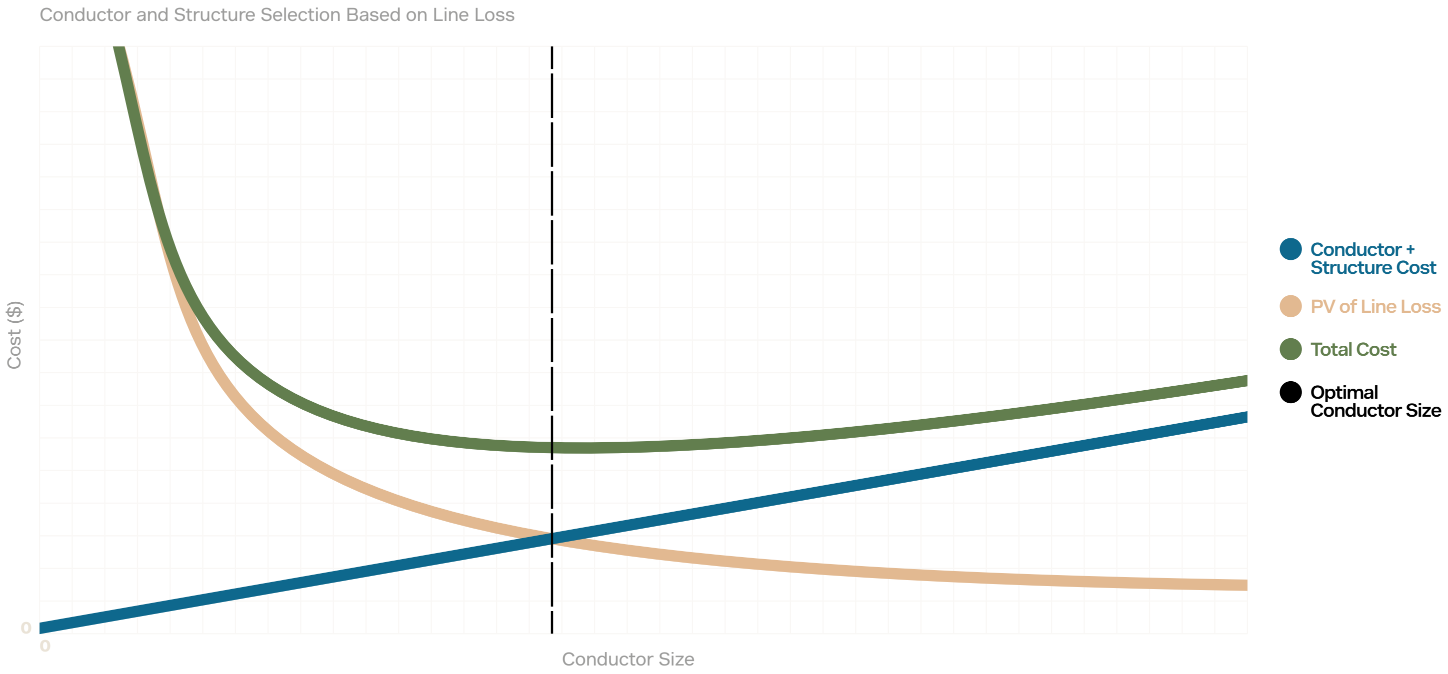


Figure 1: Kelvin's Law for Optimizing Conductor Size

Selecting the right conductor classification for optimal efficiency

1. Diameter

Equal diameter, which is a requirement for reconductor options when existing structure limitations require a conductor no larger than the conductor being replaced

2. Efficiency

Equal efficiency, where the size and cost impacts are compared for any given efficiency target

3. Cost

Equal cost, where the size and efficiency are compared on an equal-cost basis

All conductor options considered in this paper use annealed aluminum, which offers lower resistance compared to hard-drawn aluminum used in ACSR and numerous other conductor designs. The proposed alternatives also use compact trapezoidal wire (TW) aluminum strands to increase the aluminum area or to reduce the conductor diameter for the same aluminum area. Annealed aluminum used in ACSS conductors also offers a large capacity increase due to higher thermal limits compared to ACSR conductors.

Open-source data and industry-standard software were used to compute the temperature and corresponding AC resistance for conductors representing the three classification options. For simplicity, data for the alternate conductors are normalized by dividing the engineering value by the value for the “Drake” ACSR conductor. “Drake, accordingly, has a normalized value of one (1). The AC resistance values for the ACSS/TW Bezinal® core options assume the efficiency benefit of the annealed aluminum.

An average line load of 500 A (50% of “Drake” capacity”) is assumed to keep the comparisons on an equal basis. The larger conductors will run cooler at 500 A, resulting in an efficiency benefit from both lower resistance and lower operating temperature (aluminum resistance increases with increasing temperature at a rate of 0.4%/˚C).

1) Conductors of equal diameter

Figure 2 shows two leading equal-diameter conductor choices for efficiency and cost. In this comparison, the leading “Drake” replacement candidates are equal-diameter 959.6 kcmil (486.7 sq mm) ACSS/TW “Suwannee” with a steel/Bezinal® core, and a proprietary equal-diameter 1026 kcmil (523.9 sq mm) conductor with a composite core.

The ACSS/TW conductor offers 24.9% greater efficiency at a 40% greater cost versus “Drake” ACSR. The composite core option has a smaller core allowing an increase in the aluminum area to 1026 kcmil. This increases the efficiency by 31.8%, at a 200% greater cost versus “Drake” ACSR. Higher strength cores would close the competitive disadvantage for steel in the same-diameter reconductor niche.

Not reflected in the chart is the capacity increase from the reconductor: 100% for the ACSS option, and 70% for the composite core option.

Drake Reconductor Options, Equal Diameter, 500 A Load

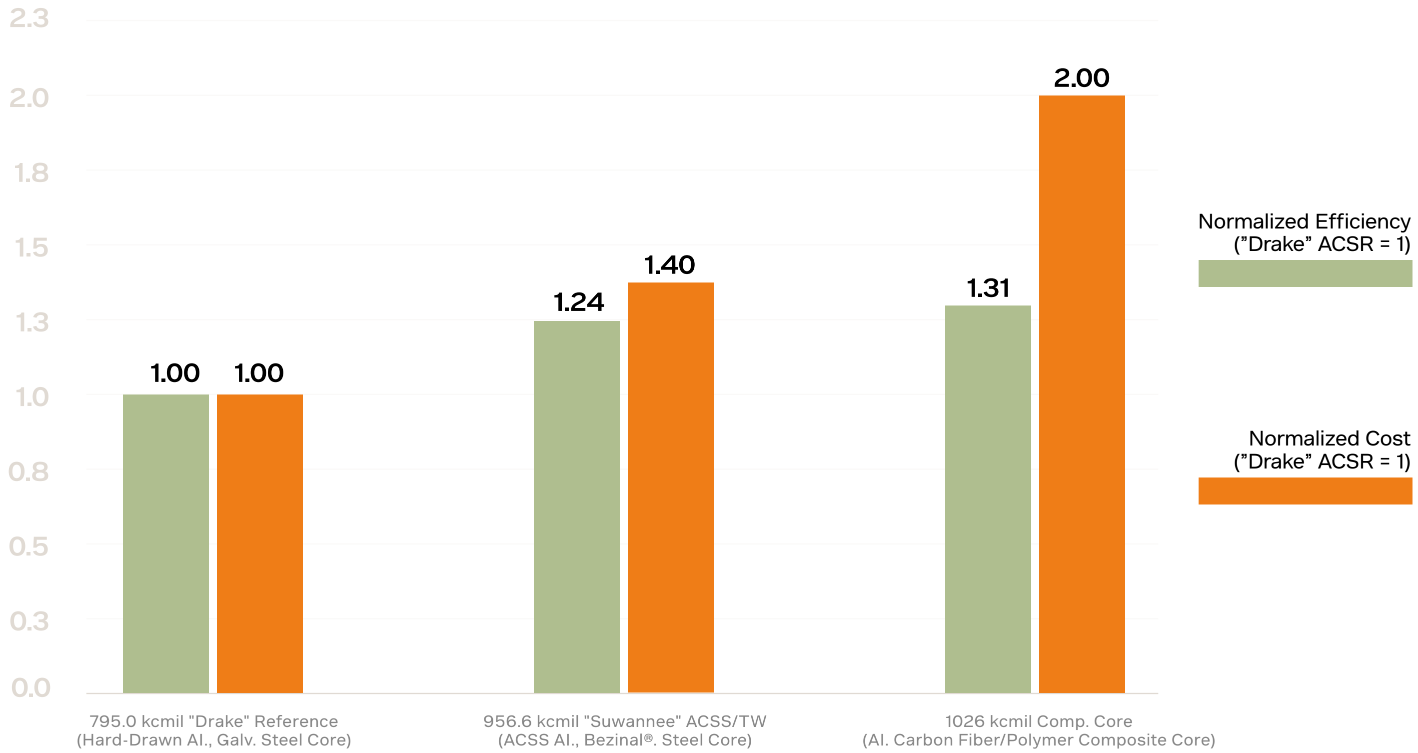


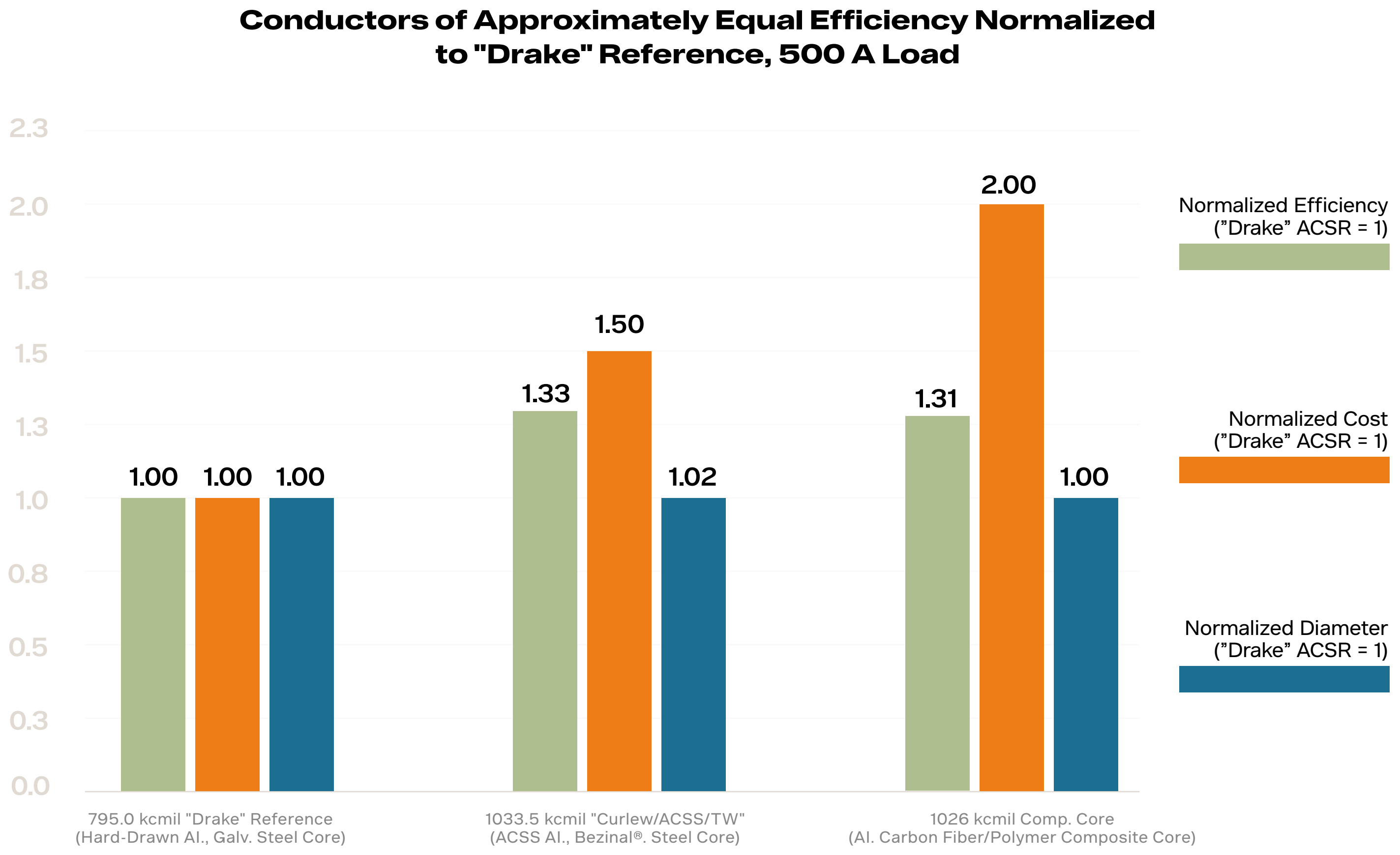
Figure 2: Two Equal-Diameter Reconductor Options, Values Compared to Same Values for Drake Acsr

2) Conductors of equal efficiency

Figure 3 compares two conductors of approximately equal efficiency, where equal-diameter is not the deciding factor. The gray bar is added to the chart to show the normalized diameter.

The ACSS option has a 2% larger diameter and 30% greater aluminum area, compared to the reference “Drake” ACSR.

Figure 3 shows that for a 2% diameter increase, the 1033.5 kcmil ACSS/TW option offers a 33.7% efficiency increase compared to “Drake” ACSR, and a 1.4% efficiency increase compared to the composite core option. In this comparison, the ACSS/TW option is both lower cost and higher efficiency.



Conductors of Approximately Equal Efficiency Normalized to "Drake" Reference, 500 A Load

Figure 3: Conductors of Approximately Equal Efficiency Normalized to "Drake" Reference, 500 A Load

3) Conductors of equal cost

The final comparison is the case of a fixed conductor budget, and a goal to increase the efficiency to the maximum for a given budget.

Two options of approximately equal cost are illustrated in Figure 4. In this comparison, the 1622 kcmil (821.9 sq mm) ACSS/TW “Pecos” conductor offers a 104% increase in aluminum area compared to the “Drake” reference conductor.

The “Pecos” diameter penalty is 28.2% compared to “Drake” and the same-diameter composite core conductor. The payoff is a 103.5% efficiency increase, compared to the “Drake” reference, and a 71.4% efficiency increase compared to the same-cost composite-core conductor.

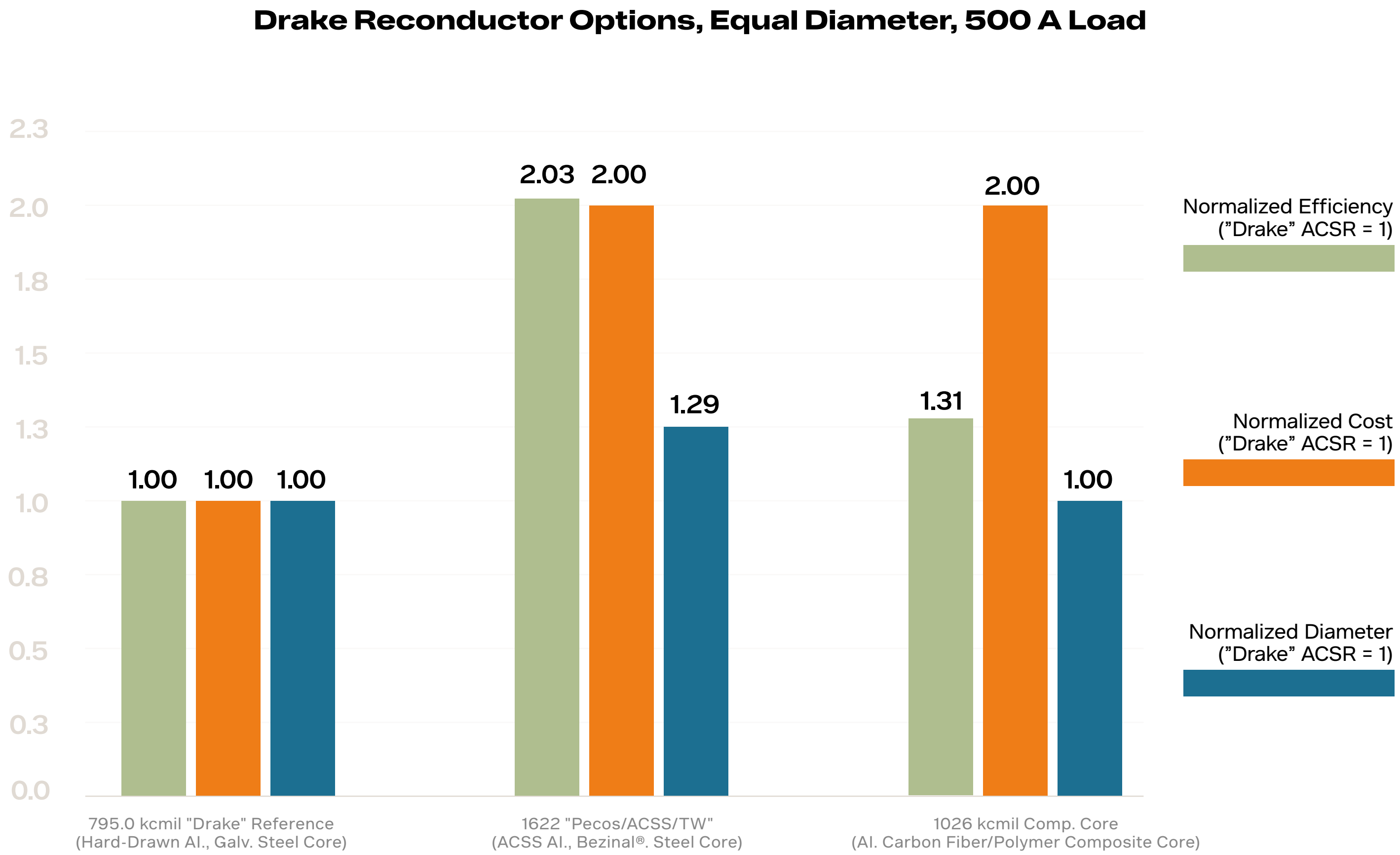

Drake Reconductor Options, Equal Diameter, 500 A Load

Figure 4: Drake Reconductor Options, Equal Diameter, 500 A Load

Conclusions

The grid of the future will have higher efficiency due to increasing energy costs, public pressure, and policy directives that very likely will include a requirement to account for the cost of line losses in the line design. **Steel cores meet this challenge head-on thanks to their excellent combination of low cost and high efficiency.** Composite cores fill a niche where the premium for a composite core is outweighed by structure costs.

In this analysis, an ACSS conductor is shown to be **71.4% more efficient than the same-cost composite core conductor**. An ACSS conductor with 1.4% greater efficiency than a composite core conductor is shown to **cost 25% less**. It is important that the policy makers and decision makers set rules that enable the selection of the most cost-effective and efficient conductor options. In most cases, the optimum conductor will have a steel core.

Contributors

Dan Berkowitz

Dan Berkowitz currently leads the North American Energy marketing & strategy department for Bekaert, focused on driving the Power Transmissions ACSS/ACSR Conductor growth. Dan has held many product management roles throughout his career related to the Energy Industry. His aspirations are to deliver the most efficient and economical solution that brings our electric grid into the future.

David Berta

David Berta is the quality manager at Bekaert's Van Buren, Arkansas facility which manufactures steel cores for the United States and North American conductors. David has a background in material science from the Georgia Institute of Technology, black belt training in Lean and Six Sigma, and holds American Society for Quality certifications in Quality Engineering and Quality Management. His has been hands on with the design and manufacture of electrical conductors and their components for over 15 years.

Bibliography

Reference 1: Aluminum Association Publication 54:

"The evaluation of losses in conductors", Second Edition, 1998.

Reference 2: US Senate Bill S2659:

Advanced Energy Technologies and Grid Efficiency Act of 2021

Reference 3: US House Bill HR 4972 (identical to Senate bill):

Advanced Energy Technologies and Grid Efficiency Act of 2021

Reference 4: Conductivity, Capacity, and Temperature Calculations:

These parameters are determined using industry-standard methodologies outlined in IEEE 738. This approach is widely adopted by manufacturers and line designers for conducting these computations.

Reference 5: ACSR Cost Estimation:

The cost estimation for ACSR (Aluminum Conductor Steel Reinforced) is based on a reasonably accurate calculation. It comprises the LME landed metal costs for aluminum, steel, and zinc, augmented by an additional 30% to cover conversion costs, overheads, and profit margins.

Reference 6: Conductor Technical Data:

The technical data for conductors is sourced from reputable manufacturer websites and adheres to the specifications outlined by ASTM standards.

Reference 7: Sag and Tension Analysis:

For sag and tension analysis, the following software tools are employed: PLS-CADD Software, and other conductor manufacturers online software.

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