Transforming Energy Distribution in Heavy Industry

Introduction

Heavy industries such as metal and chemical production rank among the largest electricity consumers globally. These sectors often operate facilities with continuous power demands reaching the gigawatt scale, where a non-trivial fraction of energy is lost due to legacy power distribution infrastructure. In particular, transformers, high-current feeders, and repeated conversion stages introduce stepwise losses that compound as facility scale increases. In aluminum smelting operations, for example, studies indicate that approximately 1.8% of total energy is lost in final power delivery alone [1]. At industrial campuses drawing power in the gigawatt range, such losses translate into multiple megawatts of non-productive consumption, increasing operating costs and resulting in thousands of tonnes of avoidable emissions annually.

This paper explores a novel power delivery architecture based on DC distribution, leveraging solid-state converters and superconducting cables to eliminate resistive and distribution losses. The proposed system replaces conventional infrastructure, including multiple transformers and copper or aluminum busbars, with the following components:

- **Solid-state AC to DC rectifiers** at the grid interface, enabling high-efficiency conversion and power factor control
- **High-capacity superconducting cables** that operate with effectively zero resistive loss and minimal cooling overhead
- **Solid-state DC to DC converters** at load points, minimizing the need for long, high-current feeders

By redesigning industrial power distribution at the system level, this work seeks to unlock substantially higher efficiency and capacity. In the sections that follow, we quantify current system-wide losses across several energy-intensive industries and estimate the gains achievable under the proposed DC superconducting architecture. We then examine data centers, aluminum smelters, and inductive steel furnaces, each of which presents distinct operational requirements that the system must satisfy. Finally, we discuss the implications for plant operators and investors, with particular attention to cost savings and climate impact.

Boundary definition: Unless explicitly stated otherwise, all CAPEX and OPEX figures refer to an installed feeder system including conductor, cryostat, terminations, cryoplant, instrumentation, protection, commissioning, and EPC. Civil expansion costs are included only when the baseline requires additional routes and the superconducting alternative avoids them. Reported currents and resistive losses are computed at the stated DC bus voltage and feeder configuration (bipolar vs. monopolar; number of parallel feeders; number of terminations). Cryogenic electrical input is derived from an explicit heat budget divided by stated COP.

Power Use and Losses in Energy Intensive Industries

Before evaluating alternative architectures, it is important to understand the electrical infrastructure used in present-day industrial facilities. In the sub-sections below, we examine typical power consumption profiles and loss mechanisms in several DC-heavy electrochemical and electro-metallurgical process facilities, where high-current buswork represents a primary constraint on efficiency, footprint, and operability.

Aluminum Smelting (Hall-Hérloult Process)

Primary aluminum production is notably energy intensive, with a typical smelter drawing hundreds of megawatts continuously. The Hall-Hérloult process used in these plants operate at low voltages (~4-5 V) but extremely high DC currents (e.g. 300-500kA per potline). Key points on energy use and losses:

- **Busbar and line losses:** Once converted to low-voltage, high-current DC, power is distributed through large aluminum busbars feeding hundreds of electrolytic cells arranged in series. Despite optimization efforts, the extreme current levels result in several megawatts of resistive loss along a single potline. The associated heat generation further necessitates active cooling strategies or specialized physical layouts.
- **Electrical conversion losses:** AC power is converted to DC for the electrolytic cells using large rectifier–transformer assemblies. Although these systems are engineered for high efficiency, they typically incur 1–2% conversion losses, which in a 500 MW facility corresponds to approximately 5 MW of continuous wasted power.
- **Scale of losses:** Consider an aluminum smelter operating at 300 MW. If rectification and distribution together impose a combined loss of roughly 3%, this results in 9 MW of constant dissipation. Over the course of a year, this amounts to approximately 79 GWh of energy lost as heat. At gigawatt-scale facilities, these losses scale proportionally, underscoring the critical importance of distribution efficiency.

Many modern smelters employ high-efficiency rectifiers and optimized busbar designs; however, the fundamental physics and scale of the Hall–Héroult process still result in substantial losses. Given that smelters often operate with dedicated power generation and that electricity accounts for approximately 30–40% of the total cost of aluminum production, even modest improvements in distribution efficiency have an outsized economic impact. A 1% efficiency gain alone can be material. For a representative smelter producing roughly 500,000 tonnes per year and consuming on the order of 7,000 GWh annually, a 1% improvement corresponds to approximately 70 GWh of energy savings per year, equivalent to avoiding roughly 50,000 tonnes of CO_2 emissions if supplied by coal-fired generation.

Chemical Plants (Electrochemical Processes)

Many high–power chemical industries rely on electrochemical reactions or electrically driven heating processes. A prominent example is chlor-alkali production, which uses brine electrolysis cells, as well as electrometallurgical processes for materials such as copper, zinc, and lithium. Several common characteristics are outlined below.

- **Chlor-alkali electrolysis:** Chlor-alkali production typically consumes on the order of 2–3 MWh per tonne of chlorine produced [2,3]. Large-scale facilities in regions such as India and North America can operate at capacities of thousands of tonnes per year, corresponding to electrical loads in the hundreds of megawatts. Similar to aluminum smelters, these plants rely on large rectifier–transformer units and extensive DC bus systems. Losses arising from rectifier inefficiency, resistive heating, and voltage drop directly reduce overall process efficiency. For example, a facility drawing 50 MW incurs 1 MW of continuous loss at just 2% conversion and distribution inefficiency. Given that global chlorine production consumes approximately 150 TWh per year [4], even incremental efficiency improvements have meaningful impact.
- **Electrode and bus losses:** Traditional copper or aluminum busbars and multiple voltage conversion stages introduce additional inefficiencies in electrochemical facilities. These losses can be reduced by streamlining power distribution, such as by employing DC buses that directly feed cells at the required voltage and using localized high-efficiency DC to DC converters rather than centralized transformers. Superconducting feeders could further mitigate these losses by virtually eliminating voltage drop and resistive heating between rectifiers and electrochemical cells.
- **Industrial electrification and heating:** Chemical plants also deploy large electric heaters, pumps, and motors, and in some cases induction heating systems. These systems often achieve only 85–90% end-use efficiency, with the remaining 10–15% lost in coils, conductors, and power electronics.

In summary, chemical processing facilities face a dual challenge: inherently high energy demand and additional avoidable losses associated with electrical power distribution. While thermodynamics impose a lower bound on energy consumption, a substantial portion of electrical losses stems from distribution and conversion inefficiencies, representing a clear opportunity for system-level improvement.

Data Centers (High-Density Computing and AI-Factories)

Large hyperscale data centers, with IT loads ranging from roughly 100 to 1,000 MW, also contend with multi-stage power conversion and distribution losses. In conventional architectures, grid power is first stepped up to medium voltage for campus distribution, then stepped down to low-voltage AC, and finally converted to DC for server loads and on-site energy storage. Each conversion stage incurs an efficiency penalty. In addition, dense copper cabling within data halls continuously dissipates heat due to resistive losses and increasingly acts as a constraint on power density and layout flexibility [5]. As a result, internal distribution and conversion losses can readily approach or exceed 10% in a typical facility.

In response, data center operators are actively evaluating DC distribution and, in some cases, superconducting power links to improve efficiency and unlock additional capacity. Superconducting cables can carry an order of magnitude more current than copper with negligible resistive loss. Demonstration projects, such as large-scale superconducting power links deployed in Europe, have shown the ability to transmit tens of megawatts with minimal losses [6]. Quantitative studies indicate that superconducting cables can incur as little as approximately 1.7% of the losses of traditional AC cable systems [7]. When combined with emerging 800 VDC architectures, these characteristics translate directly into meaningful gains in efficiency and usable power density.

Efficiency Gains with a Superconducting DC System

The proposed system replaces the legacy AC distribution and multiple transforms with a more streamlined DC network. In short, the facility would take power from the existing link, convert to DC, distribute at medium voltage through superconducting cables, and use point-of-load converters for the required voltage. This new architecture targets the losses described above:

- **Transformer losses:** Traditional setups might have two or more transformer stages, with each stage exhibiting ~2-3% losses under load. By using a single high-efficiency rectifier, the intermediate transformer steps can be reduced. We assume a well-designed AC/DC converter can achieve ~97% efficiency, which can see >2% efficiency gains at least.
- **Distribution losses:** Superconducting DC cables essentially eliminate resistive losses in distribution lines. The only penalty is the energy to keep the cable at cryogenic temperatures. Cryogenic OPEX must be computed from a heat budget. While cryostat heat leak scales roughly with length (W/m), termination heat loads scale with current (W/kA) and can dominate at the 25 to 100 kA class. Therefore, refrigeration input power is calculated as:

$$P_{elec} = (Q_{cryostat} + Q_{terminations} + Q_{joints} + W_{pumping})/COP$$

For perspective, a 0.83 kW added load is only 0.0017% of total loss, with the average decreasing over longer distances. In short, the distribution efficiency approaches 100% over campus-scale distances.

- **Conversion at load:** Each major load (furnace, data center, electrolyzer, etc.) would be fed by a solid-state DC/DC converter tuned to its needs. These converts are also highly efficient (often 95-99% depending on voltage levels) which can be leveraged in the proposed system. Additionally, having individual converters per load allows precise voltage control and power flow management, minimizing partial loading cases which further decrease efficiency. It also obviates the need for separate reactive power compensation; The front-end rectifier and DC converters can actively regulate power quality unlike passive AC transformers
- **Reduction of auxiliary losses:** By operating on a common DC bus, some auxiliary systems can be simplified and removed. For instance, the static var compensators used to increase power factor and improve power quality can be completely removed. The solid-state rectifier feeding a DC bus inherently buffers and smooths these fluctuations. This removal can then save megawatts of losses and consumption which they often consume. Furthermore, when the thermal load introduced by busbars are removed, the HVAC requirement greatly decreases, leading to further PUE.

To illustrate the impact, consider a simplified comparison for a representative 100 MW induction furnace campus:

- **Current system:** Suppose the facility has a main substation transformer with 98% efficiency, and various distribution transformers with 97% efficiency, and long cable runs causing ~2% voltage drop loss (due to internal resistance). The overall delivery efficiency might be around ~93%. In other words,~7% of 100 MW is lost (7 MW). In addition, if the process equipment themselves have ~85% efficiency, the net end-to-end efficiency could only be ~79% in this scenario. Of course this last figure depends on the process involved, scale, and age of the system.
- **With superconducting infrastructure:** We replace the dual transformer steps with an AC/DC rectifier at 97% efficiency. The cable itself has 0% resistive loss (see above). The DC/DC converters at loads are ~98% efficient which leads to 95% delivery efficiency. That alone cuts losses roughly in half. For the given plant size, that means ~17.5 GWh energy saved. For carbon intensive regions that can mean tens of thousands of tons of emissions avoided annually.
- **Specific loss elimination:** In an induction furnace, ~5% of losses occur in cabling/busways. This loss can be completely eliminated by superconducting distribution. With an identical ~3% conversion loss, a 23% total loss may become only 18%.

It is evident that a system-level approach can yield material performance improvements. While efficiency gains of a few percentage points may appear modest, for industrial facilities drawing on the order of 100–1,000 MW, each percentage point corresponds to multiple megawatts of continuous savings. These reductions directly improve operating economics, ease demand on the electrical grid, and lower associated emissions, assuming fossil-based generation. In addition to efficiency gains, such architectures deliver ancillary benefits including higher power density, reduced physical footprint, and improved integration of on-site generation and energy storage. By enabling current densities an order of magnitude higher than copper at comparable voltages, superconducting distribution allows substantial simplification of plant power architecture. For example, the AmpaCity project in Essen demonstrated that a single 10 kV superconducting cable could replace an entire conventional 110 kV feeder.

Finally, the DC nature of the system enables straightforward integration of renewable energy sources and energy storage. Renewable integration represents a significant advantage, as large solar arrays or battery installations can connect directly to the DC bus through DC to DC converters with minimal additional conversion overhead. This allows operators to reduce reliance on the grid, preferentially utilize low-carbon energy sources, and strategically time grid imports during periods of favorable availability, such as when hydro, solar, or wind generation is abundant. Similar benefits apply across industrial campuses. While many heavy processes require stable baseload power, solar generation can supplement daytime demand and battery systems can provide peak shaving, particularly for variable loads such as induction furnaces or data centers. This added flexibility supports a more rapid transition toward cleaner energy sources in energy-intensive industries.

Enabling Greener Solutions and Capacity Expansion

Beyond efficiency, a major upside of switching applicable heavy industry to a modern DC superconducting system is the facilitation of greener operations. While many are already under pressure to cut emissions, steel and aluminum smelters and data centers are especially subject. Steel companies are eyeing direct reduction of iron with hydrogen and then melting in induction furnaces, while aluminum producers invest in renewable power and cell innovations. Data Center operators and chip designers are demanding larger and larger power requirements while stepping up efficiency metrics. Our system aligns perfectly with these trends:

- It reduces the baseline electrical losses: less power needs to be generated for the same output. If that power comes from fossil fuels, emissions drop. If it comes from renewables, those renewables can stretch further to supply more industrial output. It essentially improves the energy return on investment of clean power in industry.
- It increases reliability and power quality, making it easier to integrate renewable generation. For instance, a plant could incorporate on-site solar or wind and feed it into the DC bus. Since most applicable heavy industries can't tolerate power interruptions, historically, they haven't directly used renewables without big buffers. With a DC system and optionally on-site battery, renewables can be buffered and supply a portion of the load. In further development, the superconducting cable itself could act as a magnetic energy storage device. This opens pathways to use solar in daytime to offset grid draw, or to store cheap/off-peak or surplus renewable energy and release it during high demand, thereby lowering the plant's carbon footprint.

- In data centers, a known benefit of such architecture was easier addition of solar and achieving sustainability targets [8]. We anticipate similar benefits in all campuses where we deploy.
- Capacity increase: Using superconducting cables can raise the power throughput without the need to upgrade to higher voltages or parallel feeders. A notable constraint in expanding industrial capacity is often grid limit, substation limit, or space restrictions (particularly in data centers). By replacing traditional copper/aluminum feeders with superconducting cables, one can push more current at the same voltage. This means a plant couple potentially expands to more furnaces, cells, racks without a complete overhaul of its grid connection. In other words, an internal architecture change can mean massive deferred capital expenses.

Techno-Economic Feasibility

Superconducting DC distribution is economically credible in industrial campuses that combine (i) very high continuous electrical throughput, (ii) high-current DC backbones or large rectified loads, and (iii) material Joule heating losses and size constraints in buswork that scale superlinearly with current. The strongest near-term commercial wedge is primarily aluminum producing and recycling, where the system routinely operates at hundreds of kA DC and is already supported by published techno-economic cases and global site mapping. A second attractive wedge is chlor-alkali electrolysis, where electricity intensity is structurally high and sites are numerous. Induction-furnace steel melting is viable primarily as a multi-furnace campus power backbone opportunity, but is less universally compelled unless the deployment measurably addresses dominant loss and power-quality constraints rather than only line losses.

Aluminum Production Segment Breakdown

Some key figures:

- Global coverage and scale are well established with 249 aluminum smelters representing over 98% of global primary production.
- China dominates the commercial opportunity, with 60% of global output [10].
- Electrical scale is extreme, with new smelters consuming up to 2.4 GW of energy [11].
- Published busbar reports show material loss reduction and multi-year payback for high current runs, driven by avoided busbar losses net of cryogenic power.

Lead to the primary levers:

- **Avoided Joule heating losses** in busbars at hundreds of kA
- **Thermal constraint relief** (uprating current or de-bottlenecking)
- **Reliability** (reduced heating degradation)
- **Decarbonization** optionality (savings scale directly with grid/carbon intensity)

Combining these points gives a simple metric for determining break-even requirements. A project is economically viable when the net electrical savings monetized over operating hours exceeds annualized CAPEX + incremental OPEX:

$$(\Delta P_{loss} - P_{cryo}) \times hours\ per\ year\ \times electricity\ price\ \geq (installed\ CAPEX\ \times Capital\ Recovery\ Factor)\ +\ Incremental\ Service$$

Where ΔP_{loss} is the avoided electrical losses (kW) relative to the baseline conductor and P_{cryo} is the refrigeration electrical overhead (kW). From this equation, we come to the conclusion that two packages can be offered. In the first package, a cable/busbar retrofit can capture the highest-value loss corridor without requiring a full conversion-system replacement. In other words, the smallest change which solves the largest issue. In the second package, a cable + rectification system adds value through power-quality and controllability in addition to the benefits of package one.

Chlor-alkali Electrolysis Segment Breakdown

Some key figures:

- The World Chlorine Council cites over 650 sites with ~58 Mt/year chlorine [12]
- Electricity intensity is high and well documented; DOE materials cite diaphragm methodologies at 2,900 kWh/t chlorine and membrane methodologies at 2,500 kWh/t chlorine [13]

Lead to the primary levers:

- **Conversion + distribution loss reduction** around rectifier halls, DC feeders, and buswork to electrolyzer banks
- **Power quality and harmonic loss reduction** i.e. reducing heating/derating and improving plant-wide electrical efficiency
- **Uptime/reliability** where electrolyzer trains monetize availability; electrical faults impose high indirect costs
- **Renewables integration** electrolysis is a candidate load for cleaner power strategies where a DC backbone reduces integration backlash

Given the above, our break-even requirement is as follows. Given energy intensity, even a small net site electrical reduction is monetizable at scale. The same annualized break-even inequality from the aluminum case applies; feasibility is maximized where (i) electrolyzer capacity is large, (ii) DC buswork runs are long/thermally constrained, and (iii) plant tariffs penalize poor power quality. As with the aluminum case, two packaging options are available depending on CAPEX sensitivity and adoption risks. In short, Chlor-alkali is a strong second wedge where multiple sites, continuous duty, and clear electrification/decarbonization narratives exist supported by authoritative energy-intensity benchmarks.

Induction-Furnace Segment Breakdown

Some key figures:

- India is unusually induction-heavy in electric steel production; IEEFA notes that 56% of India's steel output was from electric furnaces, with the majority attributed to induction furnaces [14]
- Reports indicate over 1,128 induction furnaces operating in India alone. [15]

Lead to the primary levers:

- **Campus backbone loss and constraint relief** in multi-furnace shops (shared feeders, hot bus corridors, distribution limitation)
- **Power-quality-driven efficiency and derating mitigation,** especially where multiple furnaces run concurrently
- **Capacity enablement** (more throughput without a full grid interconnect upgrade)
- **Operational reliability** in harsh environments (electrical faults, hot joints, busbar maintenance)

Given the above, our break-even requirements are as follows. Economic feasibility is strongest when the deployment addresses a meaningful fraction of total electrical losses and/or unlocks capacity. Where furnace losses are dominated by thermal/process factors, a cable-only retrofit captures a smaller share of the value pool. The annualized break-even inequality still governs, but the numerator often relies on capacity and reliability monetization in addition to kWh savings. Unlike the two previous examples, the primary offer would be as follows: A DC backbone + power conversion architecture that improves power quality and distribution constraints across many furnaces. In conclusion, IF steel is most viable at large multi-furnace campuses where electrical infrastructure is capacity-limited or power-quality constrained.

Direct Comparison with Existing Technology

While extensive existing research shows that superconducting systems may be a winner in many heavy industries, it is important to create direct comparisons between the different systems. Pre-existing work within the aluminum smelting sector allows for a clear comparison between the two [16]. Note that comparisons reflect an installed feeder system (cable assembly; terminations; cryoplant; controls/protection).

	Aluminum	Superconductor	
Conductor current density	0.06	50	kA/cm²
Nominal total current	400		kA
Cable cross section	6,667.00	12.62	cm²
Mass per meter	1,800.0	45	kg/m
Overall length	415		m
Total electrical resistance	0.022		mΩ

Temperature rise above ambient	40		K
Cable temperature at nominal current	355	65	K
Voltage drop at nominal current	8.9		V
Electrical power for cooling		1,030.4	kW
CAPEX	7.06	16.6	$MM
Operating energy (losses + machinery)	3,557	1,030.4	kW
Electricity price	40		$/MWh
OPEX annualized	1.29	0.361	$MM
Relative Payback Period	Base	9.88	Years

Table 1: A comparison of aluminum and superconducting implementations in a 400 kA class aluminum smelter power collection system. Cooling power is computed from the heat budget and COP assumptions [Appendix I]

	Aluminum	Superconductor	
Conductor current density	0.06	50	kA/cm^2
Nominal total current	50		kA
Cable cross section	833	12.62	cm^2
Mass per meter	1,800.0	16	kg/m
Overall length	415		m
Total electrical resistance	0.429		mΩ
Temperature rise above ambient	40		K
Cable temperature at nominal current	353	65	K
Voltage drop at nominal current	21.4		V
Electrical power for cooling		130.4	kW
CAPEX	2.27	6.6	$MM
Operating energy (losses + machinery)	1,071	130.4	kW
Electricity price	40		$/MWh
OPEX annualized	0.375	0.046	$MM
Relative Payback Period	Base	13.2	Years

Table 2: A comparison of aluminum and superconducting implementations in a 400 kA class aluminum smelter inter-connection. Cooling power is computed from the heat budget and COP assumptions [Appendix II]

	Copper	Superconductor	
Configuration and voltage	AC 110	DC 1.25	kV
Conductor current density	0.1	50	kA/cm²
Nominal total current	2.1	160	kA
Cable cross section	21	12.62	cm²
Overall length		1,500	m
Transformer efficiency	99.6%		
Power loss of transformers	3,200		kW
Line power loss	3,340		kW
Total electrical resistance	15.5		mΩ
Electrical power for cooling		413.2	kW
CAPEX	25.3	23.2	$MM
Operating energy (losses + machinery)	6,630	413.2	kW
Electricity price		40	$/MWh
OPEX annualized	2.323	0.145	$MM
Relative Payback Period	Base	**CAPEX lower**	Years

Table 3: A comparison of copper AC and superconducting DC implementations in a 400 kA class aluminum smelter standard transmission. Cooling power is computed from the heat budget and COP assumptions [Appendix III]

Market Sizing: TAM, SAM, SOM

To break down our estimated market capture, we utilize some base definitions:

- **TAM:** global annual spend on qualified projects (retrofits + expansions) where superconducting DC distribution and associated conversion systems are technically and economically applicable (see above).
- **SAM:** subset of TAM that is commercially reachable with early product configurations (standardized HTS DC backbone modules, industrial cryogenics, etc.) and does not require deep process redesign.
- **SOM:** project-based capture defined as the number of projects that can be executed annually at reference quality through a constrained deployment capacity (manufacturing + EPC + commissioning).
- **Primary aluminum:** 249 smelters provide a bounded global account list.
- **Chlor-alkali:** over 650 sites globally provides a bounded global account list.
- **IF steel:** 1,103 induction furnace plants in India alone provides a minimum global installed base and supports a project-led rollout in dense geographies.

Starting with TAM, we utilize common annual project cadence for retrofit/upgrades to estimate projects per year:

- Aluminum: $249/6\ years\ =\ 41.5\ projects/year$
- Chlor-alkali: $650/8\ years\ =\ 81.25\ projects/year$
- IF steel: $826/12\ years\ =\ 68.8\ projects/year$
    - While there are more sites, not all meet our baseline requirements

To form a concrete value, we must estimate pricing per site-level project (installed scope varies by line length, kA, redundancy, and system type).

Vertical	ASP
Aluminum production	$28M
Chlor-alkali	$10M
IF steel (large sites)	$6M

Table 4: Pricing figures for verticals with project variants

The figures listed in the table above are anchored in publicly available data for pricing superconducting systems within an aluminum smelter [16] with our specific pricing figures for different system variants. In addition to the publicly available base prices, a 40% budget to cover owner's engineering + EPC, civil work, training/commissioning, and contingency was applied. Note that the aluminum production case was reduced to a single midpoint value. To expand to the other verticals, a linear approach was taken to scale the project to the different distances, ampacities, etc. While this does require projecting, there are sources for estimating Chlor-alkali CAPEX and verifying our linearity assumptions [1]. To fit the new vertical, an assumed retrofit of high-current DC buswork with superconducting busway segments, current leads, cryogenic plants, and commissioning was used. The $10M seen in the Chlor-alkali figure was chosen as a midpoint value between "short, single corridor projects" and "multi-corridor" retrofits that require budgeting well over $10M for civil complexity. The IF steel ASP had the least anchoring available and were derived from scope-based budgeting heuristics. In this vertical, the cable only case was set at $6M based on the cabling requirements for the high-current secondary feeders, constraints in routing/derating, and reliability for IF steel.

Based on these results, we can estimate Annual TAM bookings: **$2.39B/yr**

- Aluminum: $1.26B/yr
- Chlor-alkali: $0.18B/yr
- IF steel $0.41B/yr

SAM applies an "in-scope" factor for constraints that commonly gate retrofits (minimum continuous power, layout tractability, downtime windows, and near-term willingness to execute a non-standard upgrade):

- Aluminum: **0.80**
  - Most primary aluminum smelters are structurally similar: DC rectification + very high current buswork + continuous duty. That means a large fraction will have at least one corridor where superconducting replacement is technically and economically meaningful. Pair this with successful pilots and the figure of 0.80 makes sense. The 20% exclusion represents sites that were recently rebuilt (no near-term retrofit window), very low electricity costs, layout constraints that make first deployment unattractive, or high operational risk.
- Chlor-alkali: **0.70**
  - Like aluminum, Chlor-alkali is DC-heavy, but the installed base is more heterogeneous than aluminum. In other words, there is a wide range of plant sizes, different electrolyzer technologies, or varying current levels. The 30% exclusion represents sites that are: smaller, well-optimized, unable to handle retrofit downtime, or have requirements for building rectifier modernization but no near-term option.
- IF steel: **0.35**
  - Induction steel is the most fragmented. The global count includes many small/medium foundries and batch operations where power distribution losses are non-dominant, run far less than 24/7, or don't have a need for this sort of upgrade. The 65% exclusion then represents sites that are too small, have a problem scope that isn't meaningful, have limited CAPEX cycles, or have duty cycles that minimize annual MWh savings.

Leads to annual SAM bookings of **$1.28B/year.**

A projects/year SOM is chosen rather than a percentage basis because procurement is lumpy and reference-driven. Using a metric of 10 projects per year steady state:

- Aluminum: 3
- Chlor-Alkali: 4
- IF steel: 3

Has a resultant SOM booking of **$142M/year.**

Conclusion and Outlook

Transitioning applicable heavy industries to a superconducting DC architecture offers a compelling argument; significant energy savings and capacity gains for operators, and substantial emissions reductions for society. By cutting out inefficient transformers and distribution lines, plants can reduce electrical losses by several megawatts each. The systems-level energy flow becomes far more streamlined and controllable, enhancing reliability and flexibility.

Crucially, these efficiency gains enable and accelerate decarbonization. With easier integration of renewables and electrification technologies operating at peak performance, industries can lower their carbon footprint without sacrificing productivity. For a steel mill converting from coal to electric,. The proposed system not only makes that switch more energy-efficient but also helps overcome some infrastructure hurdles. It creates an environment where green production is more viable because every bit of clean power is used optimally.

From an investor's viewpoint, implementing such cutting-edge power systems in heavy industry is the kind of high-impact innovation that many funds seek. It targets one of the largest emission producers with a solution that is a breakthrough and practical. Existing advances in cabling and power electronics have been proven in their contexts. The potential ROI comes not only from energy cost savings but also the enabling of companies to meet ESG goals. Early adopters could also enjoy efficiency premiums and positive publicity. For instance, a recycling facility in India using our system may market itself as producing low-carbon steel from scrap, leveraging both renewable energy and ultra-efficiency power distribution without the added price premium.

In conclusion, the path forward for applicable heavy industries involves embracing electric, digital, and superconducting technologies to overhaul legacy systems. The upside is clear: lower operating costs, greater process efficiency, and reduced emissions, along with added resilience and capacity for growth. The solution in this paper positions industrial players to not only save energy but also integrate with the clean energy future.

Appendix

I-III. The dominant cold-load term is termination heat, not distributed cryostat heat leak; our electrical input figures assume four terminations (bipolar, both ends).

I.

Cable heat leak	0.3	W/m
Termination efficiency	45	W/kA
Thermal load	72.1	kW
COP at operating temperature	0.07	W/W
Electrical input for deployment	1,030	kW

II.

Cable heat leak	0.3	W/m
Termination efficiency	45	W/kA
Thermal load	9.1	kW
COP at operating temperature	0.07	W/W
Electrical input for deployment	130.4	kW

III.

Cable heat leak	0.3	W/m
Termination efficiency	45	W/kA
Thermal load	28.9	kW
COP at operating temperature	0.07	W/W
Electrical input for deployment	413.2	kW

References

(1) Reiser, Wolfgang & Räch, Carsten & Kreuter, Daniel. (2021). Superconductor Busbars—High Benefits for Aluminium Plants. 10.1007/978-3-030-65396-5_52.

(2) Isabel Garcia-Herrero, María Margallo, Raquel Onandía, Rubén Aldaco, Angel Irabien,
Environmental challenges of the chlor-alkali production: Seeking answers from a life cycle approach,
Science of The Total Environment,
Volume 580,
2017,
Pages 147-157,
ISSN 0048-9697,
https://doi.org/10.1016/j.scitotenv.2016.10.202.
(https://www.sciencedirect.com/science/article/pii/S0048969716323932)

(3) Kermeli, K., & Worrell, E. (n.d.). *Energy efficiency and cost-saving opportunities for the chlor-alkali industry: An ENERGY STAR® guide for energy and plant managers*. U.S. Environmental Protection Agency.

(4) Emerson Electric Co. (2021). *Drive your chlor-alkali units to maximum capability with real-time, non-intrusive corrosion monitoring* [PDF]. Emerson Automation Solutions.

https://www.emerson.com/documents/automation/flyer-drive-your-chlor-alkali-units-to-maximum-capability-real-time-non-intrusive-corrosion-monitoring-en-7835712.pdf

(5) Nexans. (n.d.). *Revolutionizing Data Centre Power*. Nexans. Retrieved December 26, 2025, from https://www.nexans.co.uk/en/business/power-transmission-distribution/superconductivity/revolutionizing-data-centre-power.html

(6) Karlsruhe Institute of Technology. (2014, April 30). *Operation of longest superconducting cable worldwide started*. Retrieved December 26, 2025, from https://www.kit.edu/kit/english/pi_2014_15058.php

(7) Xiaoyuan Chen, Shan Jiang, Yu Chen, Zhice Zou, Boyang Shen, Yi Lei, Donghui Zhang, Mingshun Zhang, Huayu Gou,
Energy-saving superconducting power delivery from renewable energy source to a 100-MW-class data center,
Applied Energy,
Volume 310,
2022,
118602,
ISSN 0306-2619,
https://doi.org/10.1016/j.apenergy.2022.118602.
(https://www.sciencedirect.com/science/article/pii/S0306261922000794)

(8) Nexans. (n.d.). *Revolutionizing data centre power*. Retrieved December 26, 2025, from https://www.nexans.co.uk/en/business/power-transmission-distribution/superconductivity/revolutionizing-data-centre-power.html

(9) Steel on the Net. (2025). *Global steel cost trends: Producer margins per tonne*. Retrieved December 26, 2025, from https://www.steelonthenet.com/advisory/trends/economics.html

(10) Home, A. (2025, April 25). *As China nears peak aluminium production, what next?* Reuters. https://www.reuters.com/markets/commodities/china-nears-peak-aluminium-production-what-next-andy-home-2025-04-24/

(11) Wiestner, M. (n.d.). *Power quality results in energy efficient aluminium smelter operation* (ABB BU Minerals). ABB Switzerland. https://abblibrary.s3.amazonaws.com/public/87aea01a2a4f90fac12577e3003a631b/Power%20quality%20ABB%20BU%20minerals_lr.pdf

(12) World Chlorine Council. (n.d.). *Sustainable progress* (PDF). https://worldchlorine.org/wp-content/themes/brickthemewp/pdfs/sustainablefuture.pdf

(13) U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy. (n.d.). *Advanced chlor-alkali technology* (DOE Industrial Technologies Program). https://www1.eere.energy.gov/manufacturing/industries_technologies/imf/pdfs/1797_advanced_chlor-alkali.pdf

(14) Basirat, S., & Nicholas, S. (2022, February 14). *India's technology path key to global steel decarbonisation*. Institute for Energy Economics and Financial Analysis. https://ieefa.org/resources/ieefa-indias-technology-path-key-global-steel-decarbonisation

(15) Shanmugam, S. P., Nurni, V. N., Manjini, S., Chandra, S., & Holappa, L. E. K. (2021). *Challenges and outlines of steelmaking toward the year 2030 and beyond—Indian perspective. Metals*, *11*(10), Article 1654. https://doi.org/10.3390/met11101654

(16) Reiser, W., Reek, T., Räch, C., & Kreuter, D. (2021). *Superconductor busbars—High benefits for aluminium plants* (Technical paper). Vision Electric Super Conductors & University of Applied Sciences. https://www.vesc-superbar.de/wp-content/uploads/2021/03/Superconductor-Busbars-High-Benefits-for-Aluminium-Plants.pdf

(17) ABB Ltd. (n.d.). *High power rectifiers* (Power Electronics). https://new.abb.com/power-electronics/high-power-rectifiers?utm_source=chatgpt.com

Prepared by: Aether Transmission Systems
Contributors: Nathan Groth, Ishaan Panda