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Aluminum-Air Generator for Data Centers

Zero-Emission Long-Duration Backup Power

Technology and Deployment Perspectives

Prepared by Phinergy, in collaboration with Rosendin Electric

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Audience & Scope

This white paper is intended for data center operators, power and infrastructure architects, and sustainability and technology leaders evaluating power resilience alternatives and architectures for their facilities. It is also relevant for utilities, regulators, and AHJs seeking to understand next-generation backup technologies and their integration into data center environments. Engineering teams, system integrators, and decision makers focused on resilient, low carbon digital infrastructure will find value in the technical and architectural perspectives presented.

At a Glance

Data centers face increasing pressure to maintain uninterrupted power, while reducing emissions, footprint, and total cost of ownership. Traditional diesel generators introduce permitting complexity, maintenance overhead, and environmental constraints, while many alternative clean technologies struggle to meet the combined requirements of long duration, scalability, and cost effectiveness.

An Aluminum-Air Generator (AAG) is an energy on demand generation system that uses aluminum as fuel by converting aluminum into electricity through an electrochemical reaction between aluminum and oxygen drawn from the surrounding air. It takes advantage of aluminum's high energy density, with ~4kWh/kg net capacity, similar to the net energy of the same amount of diesel[1].

Phinergy's Aluminum Air Generator (AAG) is a zero emission, cost-effective, long duration backup power solution designed to meet the operational and architectural requirements of next generation data centers.

The AAG delivers multi day continuous backup power with ability to sustain full load for extended outage events, while remaining chemically inert during standby with no self discharge. Its DC native design enables efficient integration with advanced emerging data centers power architecture. With its low footprint, non flammable operation, and minimal maintenance, the AAG provides a resilient and scalable alternative to conventional backup technologies.

This zero emission characteristic enables shorter, more predictable permitting processes, eliminates air quality approvals, reducing project risk and accelerating deployment timelines for data center developments. Combined with modular system design, flexible AC or DC integration, and low maintenance requirements, the AAG is well suited for Hyperscale to Edge, AI centric, and mission critical facilities seeking resilient backup power without compromising sustainability, safety, or economic performance.

From Product to Deployment

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The Phinergy-Rosendin collaboration

Phinergy is collaborating with strategic partners such as Rosendin Electric to roll out AAG solutions, combining aluminum-air generation technology with a proven electrical EPC delivery platform. Leveraging Rosendin's experience delivering complex, MW to GW, mission-critical systems, the collaboration provides a clear path from pilot deployments to fleet-scale rollout, reducing adoption risk for data center operators. The partnership addresses key limitations of diesel backup systems, including emissions, permitting complexity, fuel logistics, and long lead times, while supporting the reliability, scalability, and schedule requirements of hyperscale and AI-driven facilities.

How Aluminum-Air Energy Works

An Aluminum-Air Generator (AAG) is an energy on demand generation system that converts aluminum into electricity by reacting with oxygen drawn from the surrounding air.

Similar to conventional generators, the aluminum inside the system is gradually consumed, as energy is produced, and when it is depleted, fresh aluminum is loaded into the system to refuel it.

At the core of the AAG is Phinergy's aluminum-air technology which includes aluminum-air cells with air electrodes (cathodes) and aluminum plates (anodes), an electrolyte circulation system, a thermal management system, for dissipating excessive heat, and an energy management system[2].

The system level architecture - including the electrolyte tank, cells, thermal management components, and control unit - is depicted in *Figure 1* below.

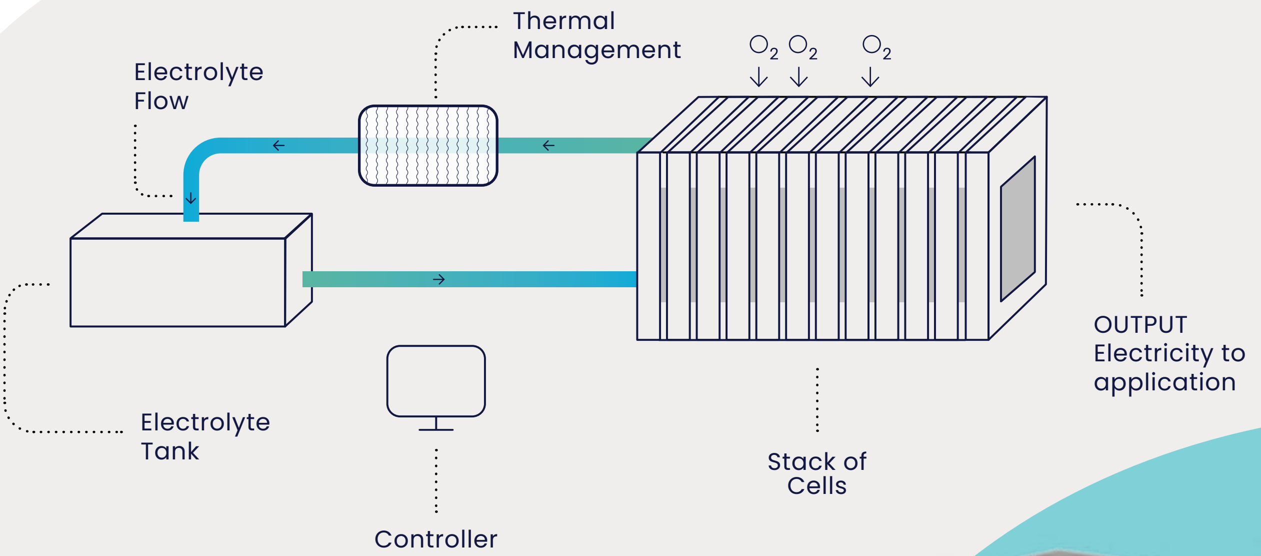


Figure 1:
Aluminum Air System Layout.

Electrolyte is used to activate and deactivate the cells and for thermal management.

When the generator is activated, electrolyte flows through stacks of cells, instantly activating them. Oxygen enters through the air electrodes that serve as a cathode, forming reactive ions (OH-) that travel through the electrolyte and oxidize the aluminum, thus consuming the aluminum "fuel".

This controlled electrochemical process releases electrical power while the spent aluminum dissolves into the electrolyte. Phinergy's cell and system technology ensures uniform, efficient and predictable consumption of the aluminum plates, as shown in Figure 2.

When the generator is deactivated, the electrolyte drains out of the cells and the energy generation and aluminum consumption are stopped. This gives the AAG a unique operational advantage: during standby, as the cells remain completely dry, with the electrolyte stored separately in a tank, no chemical reactions occur in them. In this state, the system experiences no self discharge, allowing essentially unlimited standby time. Neither the aluminum plates nor the liquid electrolyte are subject to aging, thus allowing infinite storage without additional processes such as fuel polishing.

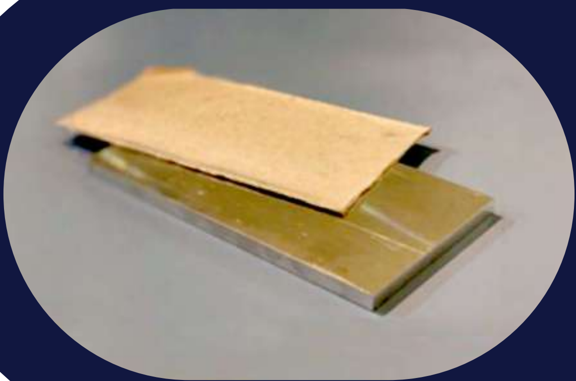


***Figure 2*:**
A fresh aluminum plate (lower) vs. a nearly depleted one (upper).

The difference in plate gauge is correlated to the consumed energy. Flatness of the faces and edges of the consumed anode indicates an efficient, controlled and balanced consumption of the anode, which then translates into a stable, efficient and predicted operation of the complete system.

This approach combines the benefits of a battery-like electrochemical system, generator-like start-stop operation, and superior standby performance.

In Phinergy's AAGs, the air electrodes provide high oxygen reduction activity and CO_2 resistant performance, while the proprietary aluminum alloy ensures uniform consumption and high energy efficiency. Together with system level thermal and operational controls, the AAG delivers reliable, scalable, and predictable energy output for applications where long duration, on-demand power, combined with long standby times are essential.

Aluminum-Air Generator (AAG™) for Data Centers

Key AAG™ features

The AAG is a multi-day, zero emission backup power system engineered to replace diesel gensets or other backup power assets for Cloud and AI data center facilities.

Zero emissions

The AAG releases zero NOx, SOx or CO_2 making it a clean source of energy with no environmental impact. As a result, it does not require air permitting, unlike diesel generators, which, shortens development timelines and avoids expansion constraints on existing sites.

Unlimited standby time

Unlike conventional batteries, AAG cells remain chemically inert when dry, capable of infinite standby without self discharge and avoiding fuel-related maintenance procedures such as fuel polishing. Periodic test cycles of the AAG are performed automatically and do not consume aluminum fuel.

No air permitting required

With zero on site emissions, the AAG eliminates the need for air permitting, unlike diesel generators, thereby shortening development timelines and easing site expansion.

Silent

The AAG operates with very low noise and vibration levels, enabling deployment in dense urban environments and sites with strict acoustic or vibration constraints.

Extended backup time

The AAG can deliver 100% of its rated power continuously for 48 hours on a single energy load of aluminum with the ability to extend runtime via aluminum and electrolyte reloads during operation, as with a diesel generator.

Low footprint

AAG footprint is on par with diesel generators and is smaller than many clean alternatives by an order of magnitude.

Fast response

The system achieves response times comparable to diesel generators (typically 10–30 seconds), with system buffering ensuring continuity during ramp-up.

Cost-efficient

The AAG offers competitive TCO vs. diesel generators, and a significantly lower TCO than alternative clean, non-polluting solutions for long-duration backup such as hydrogen fuel cells and Li-ion batteries.

AAG system layout

Phinergy addresses AAG deployment in data center environments through modular architecture, using a 1 MVA / 40 MWh containerized AAG unit (the AAG Power Unit) as the fundamental building block. In a like for like replacement scenario, a standard 3 MVA diesel generator can be substituted with three AAG Power Units, providing equivalent power with long duration autonomy. AAG Power Units scale linearly to dozens and hundreds of megawatt configurations for large campuses, following the same modular expansion principles commonly applied to diesel generators. The technical specifications of the AAG Power Unit are summarized in *Table 1*.

Parameter	Value
Continuous Power	800kW (1 MVA)
Capacity per load of aluminum	40MWh
Output voltage	480Y/277VAC, 3 PH 4W; Optional to 800 VDC
Frequency	50/60Hz
Footprint	13’x40’
Ambient temperature	15°F -113°F (-10°C -45°C) -4°F–122°F (-20°C -50°C) with dedicated kits
Humidity:	< 95%
Altitude:	< 5100 ft (1554 m)
UL Compliance	UL9540, UL508A, UL60950, UL1973 IEC 62933, IEC 60204-1, IEC 62368-1, IEC 62485
NFPA Compliance	NFPA 1, NFPA 2, NFPA 67, NFPA 70, NFPA 101, NFPA 110, NFPA 111, NFPA 400, NFPA 497, NFPA 855

Table 1:
Specification of Phinergy’s AAG containerized unit configuration

The AAG is coupled with a fast-response buffer system (such as existing onsite batteries) that provides transient support, smoothing power delivery and managing start/stop dynamics. This layer functions as a resource management platform that abstracts system behavior from the operator.

For extended events beyond 48 hours, the architecture supports on the fly aluminum and electrolyte reload that keep generation online while consumables are reloaded. During this time the buffer is used to partially support the load, compensating for the power of the specific module that is being reloaded.

Site-level storage includes aluminum warehousing and electrolyte storage. Aluminum is stored in plates on standard warehouse pallets. Being inert, the aluminum does not require any specific conditioning or safety measures when stored. Electrolyte storage can be configured as distributed tanks (adjacent to each container) or in a centralized reservoir feeding multiple containers. Site designer can choose based on site topology, functional zoning strategy and service logistics.

Integration into data center power architectures

The AAG supports both AC- and DC-coupled integration and is therefore suitable for existing data center architecture as well as next-generation DC-based ones:

AC coupled

As direct diesel generator replacement: connect to the 400–480 VAC, 3 phase, 50/60 Hz bus conversion stages. Manage power quality and fault coordination within the existing AC backbone.

DC coupled

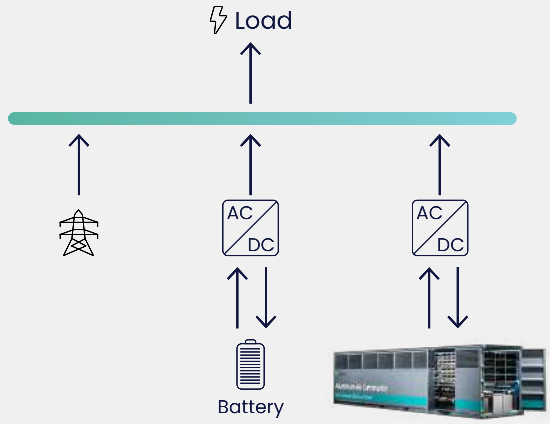
As part of DC-to-the-rack architecture: feed 800–1500 VDC distribution via a high efficiency DC DC interface, reducing conversion stages in DC designs and aligning with current high voltage DC architecture roadmaps of data centers.

Other integration alternatives

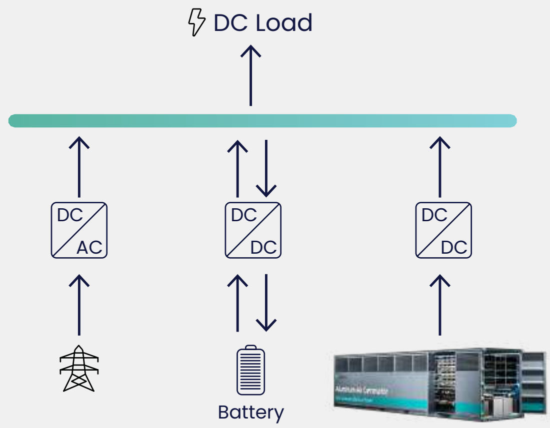
The buffer capacity may be located according to the site's requirements. For example, the AAG can be integrated with a BESS that is used for storage of renewable energy that is connected to the AC backbone, or a UPS battery that is connected to a DC bus.

The architectures shown are examples only and do not represent the full range of possible configurations.

A **AC Coupled Integration**



B **DC Coupled Integration**



C **Integration with Energy Storage**

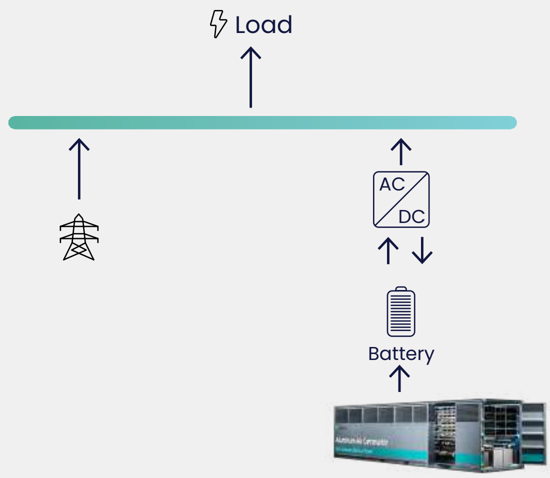


Figure 3

AAG integration with a datacenter backbone.

A: AC coupling into AC backbone, seamlessly replacing a diesel generator[3].

B: DC coupling into site's DC bus[4].

C: DC coupling with existing DC devices such as a BESS, UPS, etc.

Deployment & operational considerations

Architectural options discussed here reflect design patterns currently evaluated by data center owners and EPCs for next-generation facilities.

Resilience model

Usage of an AAG for backup in a data center offers additional flexibility in the data center's resilience model. AAGs, similar to battery backup systems, are intrinsically built in a modular fashion. An AAG Power Unit is built using multiple internal modules and multiple AAG Power Units are aggregated to reach site power requirement. Therefore, a failure in an internal module inside the AAG Power Unit results in partial output power rather than a complete shutdown of this unit, as it would be the case with a diesel generator. It is therefore possible to optimize the resilience model of the site based on this attribute and rely on partial power of units rather than add units to the site (e.g. N+x diesel generators).

Reloading and logistics

The AAG supports continuous operation while reloading aluminum. Designers should provision onsite aluminum and electrolyte storage sufficient for the required multi-day autonomy. Aluminum is inert and non-flammable, allowing it to be safely stored in large quantities using standard warehousing practices. This enables data center operators to maintain extended backup energy onsite, enhancing resilience while avoiding additional permitting, safety concerns, or operational complexity, and reduces dependence on external fuel deliveries during prolonged grid outages. Storing aluminum and electrolyte at the site is low-cost compared to alternative long-duration energy storage or fuel infrastructure.

Siting & footprint

AAG Power Units can be stacked vertically to maintain a footprint of a single 40-foot container. The electrolyte can be stored either next to the AAG or in a centralized reservoir which saves footprint next to the white space and simplifies reloading of liquid to a single point.

Permitting & safety

With zero onsite NOx, SOx and CO_2 emissions and its non flammable chemistry, AAG does not require air permit. Beyond eliminating air-related permitting, its safe clean operation simplifies the boarder permitting process, enabling shorter deployment timelines and reduced project risk compared to diesel systems.

Operations & maintenance

The inert standby of the AAG cells reduce maintenance efforts and eliminate fuel burn testing. Instead, an automatic self test procedure checks regularly all system components without producing electricity in the cells. Combined with remote monitoring, active preventive maintenance is reduced to scheduled visual inspections of the system.

Aluminum is a Renewable Fuel

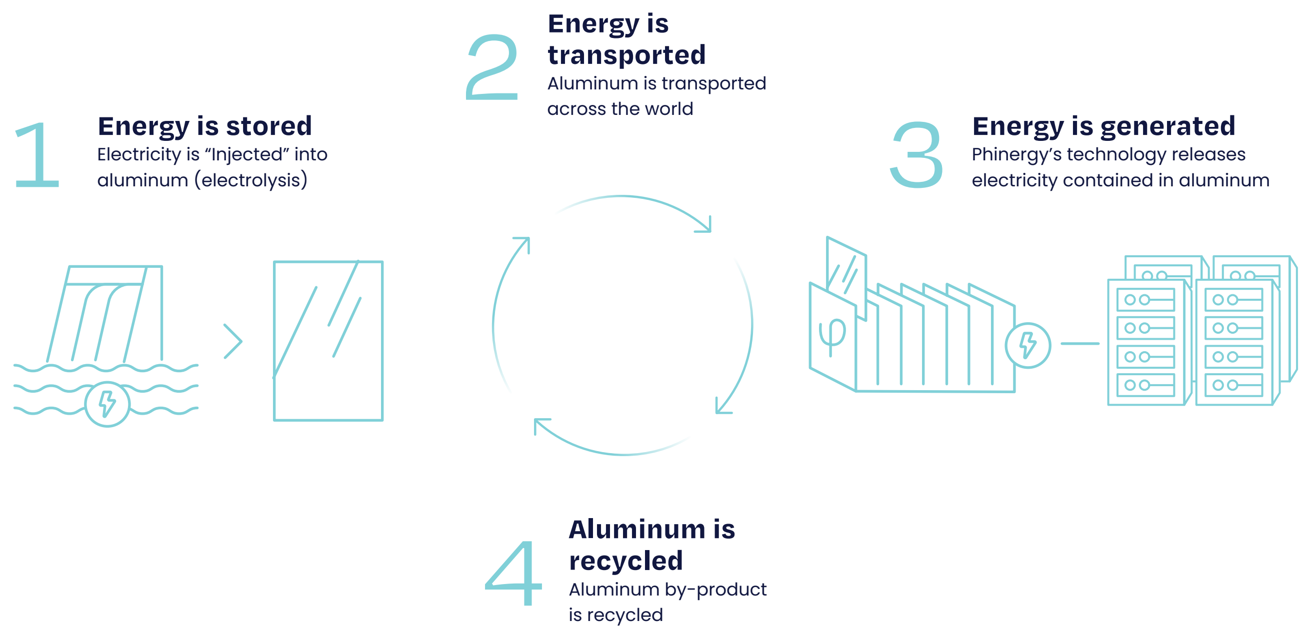
The energy carrier

Aluminum is the most abundant metal in the Earth's crust, comprising approximately 8% of the crust by mass[5], and is produced at industrial scale worldwide. Primary aluminum production begins with bauxite mining, followed by refining into alumina and electrochemical reduction through the Hall–Héroult process, in which electricity is used to remove oxygen from alumina and produce metallic aluminum. This process embeds a significant amount of electrical energy into the aluminum metal itself. In parallel, large volumes of secondary (recycled) aluminum are produced globally from post consumer and industrial scrap (e.g., beverage cans), requiring only a fraction of the energy needed for primary production and relying on mature, global recycling and logistics infrastructure.

Aluminum Air technology enables the controlled discharge of this energy stored within the aluminum metal. Through an electrochemical reaction with oxygen from air, the aluminum is oxidized, releasing its stored energy as usable electricity without combustion.

As a result, aluminum effectively functions as an energy carrier—one that is already produced, traded, transported, and stored safely at massive scale using existing industrial infrastructure. Both primary and secondary aluminum can be utilized, allowing the AAG to tap into an established global supply chain rather than requiring new fuel production or distribution systems.

This capability enables a circular economy model: aluminum is "charged" with energy during its production process; aluminum is "discharged" while producing electricity in Aluminum Air Generators; and the "discharged" aluminum (aluminum hydroxide) is then collected and sent back to the aluminum production process .



The energy reload process

The AAG uses aluminum as its energy carrier. During operation, the aluminum plates are gradually oxidized, and the resulting aluminum hydroxide is washed into the electrolyte. Once the electrolyte reaches saturation with aluminum hydroxide, it is drained out from the system and replaced with fresh electrolyte to restore operating capacity. Off-board the AAG, the aluminum oxides can be separated from the electrolyte, which can be reused in the AAG. The aluminum oxides (either separated or still within the electrolyte solution) can be reused across a range of chemical and industrial applications, including recycling back into aluminum.

Stacks of cells with depleted aluminum plates are designed for hot swap reloading, allowing fresh aluminum plates to be inserted while the AAG remains in continuous operation. Reload operations are performed using mechanical or automated handling systems, enabling aluminum replacement without interrupting power delivery. Depending on site configuration and operational preferences, depleted stacks can be reloaded with aluminum either on site or exchanged and serviced at centralized facilities.

Global availability and supply

Aluminum plates

The AAG aluminum plates are produced by conventional aluminum manufacturers using standard industrial alloying and semi finished product fabrication processes. The AAG employs an aluminum alloy specifically engineered for use as its anode material. This alloy is optimized to enhance electrochemical performance and thereby improve the overall energy utilization of the aluminum "fuel".

Global aluminum production capacity is well established and continues to expand in line with industrial demand. Worldwide primary aluminum output reached approximately 73–74 million[6] metric tons in 2024–2025, with installed operating capacity exceeding 77 million metric tons[7], supported by smelter expansions and restarts globally.

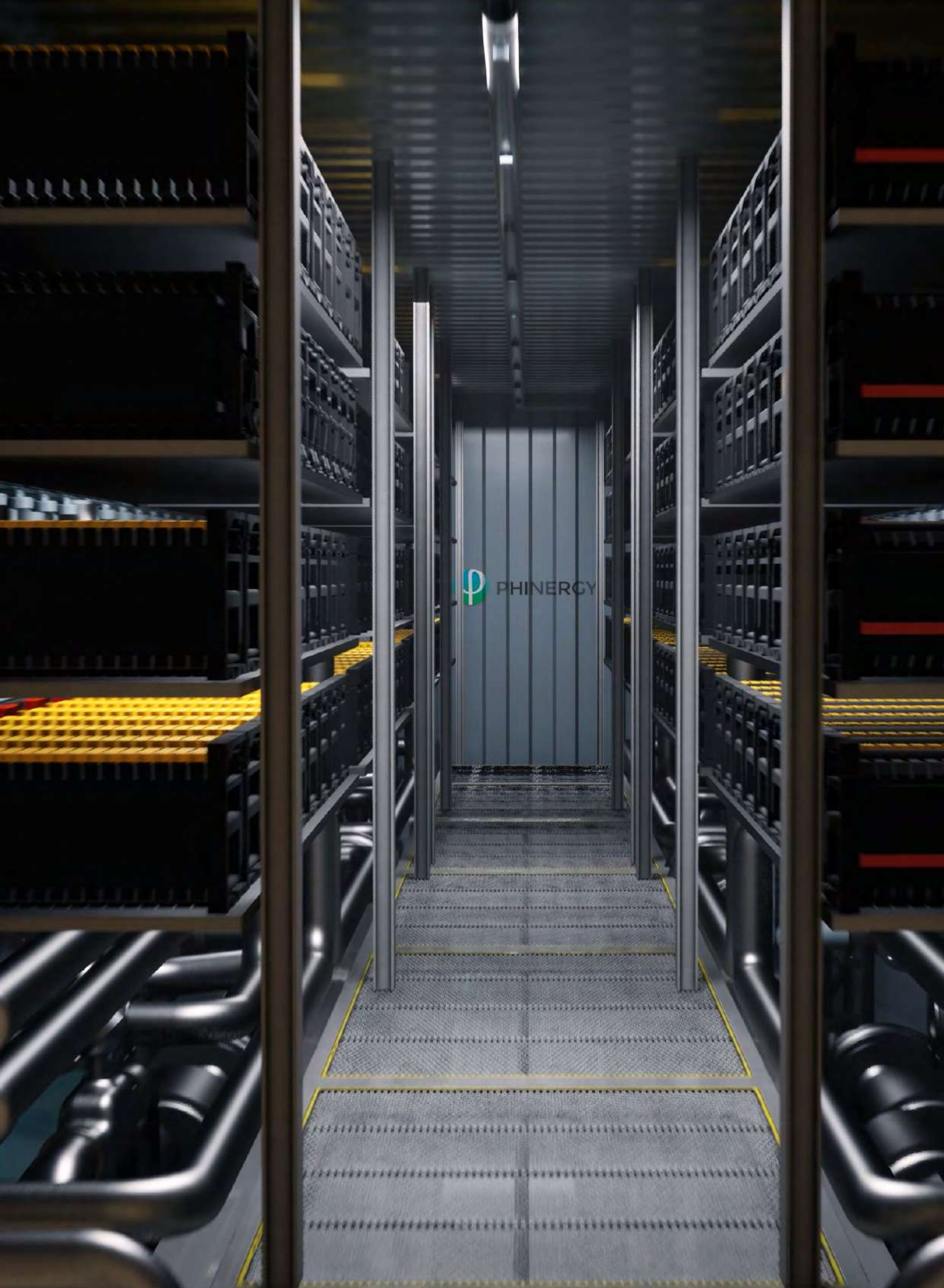
In North America and Europe, more than 90%[8] of primary aluminum is produced using low carbon electricity, primarily through hydropower based smelting in regions such as Canada, Norway, and Iceland.

In parallel, the secondary (recycled) aluminum sector represents a large and mature global industry, producing on the order of 30–35 million metric tons[9] annually from post consumer and industrial scrap, supported by well established collection, remelting, and refining infrastructure worldwide. Together, primary and secondary aluminum supply chains provide a scalable, globally available, and circular material base suitable for long term deployment of aluminum air energy systems.

As an illustrative example, supplying 100% of the global data center fleet (based on ~82 GW of installed capacity in 2025[10]) with aluminum air backup for 20 hours per year would consume approximately 410 thousand metric tons of aluminum annually—less than 0.4% of global aluminum production, a negligible portion of the existing primary and secondary supply capacity.

Electrolyte

The electrolyte is an aqueous alkaline solution. It is a standard and widely produced chemical product which constituents are readily sourced locally in most regions worldwide, minimizing supply-chain dependencies and logistics complexity. The electrolyte is non -flammable, and remains chemically stable during storage, over a wide operating temperature range, remaining liquid and functional below -30°C (-86 °F). When stored in a standby state, it does not degrade over time, due to its non biological nature, enabling essentially unlimited shelf life without conditioning or maintenance.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Conclusion

Phinergy's AAG represents a fundamentally different approach to data center backup power, combining the functional role of a conventional generator with the efficiency, cleanliness, and controllability of an electrochemical system. From a deployment perspective, the AAG is designed as a direct, one to one replacement for diesel generators, delivering equivalent power ratings, multi day runtime, and generator class operating behavior, while eliminating the key pain points associated with diesel, including onsite emissions, flammable fuels, fuel degradation, and complex air permitting requirements. Critically, this substitution can be achieved without requiring major changes to established backup power architectures or operating models, enabling straightforward adoption within existing data center designs.

Beyond direct replacement, the characteristics of the AAG enable new architectural and operational possibilities that are difficult or impractical with combustion based systems. Its modular design, inert standby state, and DC native electrochemical operation support more flexible resilience strategies, alternative redundancy models, and tighter integration with both current AC and emerging DC power topologies. The use of aluminum as an energy carrier, supported by global primary and secondary aluminum supply chains, and locally sourced electrolyte, strengthens supply chain resilience while enabling circular material flows consistent with long term decarbonization objectives.

As data center operators increasingly prioritize sustainability, reliability, and total lifecycle cost, the AAG offers a practical, scalable, and future ready alternative to diesel generators and other clean backup technologies, positioning it as a core enabler of resilient, low carbon digital infrastructure.

Next in the Series

Subsequent papers will address the practical integration of AAG into data centers, a range of of usecases, and key operational considerations for deployment.

Together, these topics will provide a framework for translating aluminum air technology into deployable, site specific backup power designs.

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Authors and Contributors

This paper was prepared by Phinergy in collaboration with Rosendin Electric, combining aluminum-air energy technology expertise with deep experience in the design and delivery of mission-critical electrical infrastructure for large-scale data centers and industrial facilities.

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