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Grid-Scale and Renewable-Firming Storage with the Hydrogen-Aluminum Energy Cell

Utilities and grid operators need stationary storage that can sit charged for months, cycle daily for decades, and survive a fault without burning down a substation, all while shifting megawatt-hours of solar and wind into the hours the grid actually needs them. This application describes how that storage profile is served by the Hydrogen-Aluminum Energy Cell, disclosed in U.S. Provisional Application No. 64/055,649, whose bulk-equipotential architecture and surface-bonded hydrogen chemistry are matched to the load-shifting and renewable-integration duty of behind-substation deployment. The domain framing here is external context; the device behaviors trace to the disclosed architecture.

What This Application Specifies

This application describes a stationary, grid-connected energy storage installation, the kind sited behind a distribution or transmission substation, inside a renewable generation plant, or at an industrial point of interconnection, built from the Hydrogen-Aluminum Energy Cell disclosed in U.S. Provisional Application No. 64/055,649. The disclosed cell is a sealed electrochemical storage cell whose interior is a single continuous volume of dual-domain proton-conducting carbon gel holding a population of hydrogen-activated metal nanoflakes, with no internal separator between its two carbon current collectors. Energy is stored as electron-stabilized metal-hydrogen surface bonds on the nanoflakes and dispatched when an external circuit closes.

In the grid-scale embodiment, the building block is a large-format cell. The disclosed enclosure admits an aluminum equipotential inner layer in the thicker part of its range (the disclosure recites roughly 50 micrometers to 5 millimeters, with thicker layers contemplated for large stationary cells), so a utility-format cell uses heavier case construction than a portable one. Because the disclosed single-cell operating voltage is bounded (the disclosure recites an upper bound in the range of approximately 2.5 to 3.0 volts per cell, above which carbon-framework oxidation becomes irreversible), high-voltage grid blocks are built by series-stacking many cells, exactly as the disclosure contemplates: arbitrarily high system voltage through cells added in series, with inter-cell electrical isolation, mechanical support, thermal management, and per-cell state-of-health monitoring. Series strings are paralleled into racks, racks into containers, and containers into a substation-scale plant interfaced to the grid through conventional power-conversion equipment. The storage medium is the disclosed cell; the racking, enclosure, inverters, and controls around it are ordinary balance-of-plant.

Why It Matters

Grid storage has two duty profiles that pull in opposite directions, and conventional chemistries serve each one imperfectly. The first is load-shifting and renewable firming: charge on midday solar or overnight wind, discharge into the evening ramp, every day, for the twenty-year life of the plant. That duty punishes cycle life. The second is reserve and resilience: a plant that may sit near full charge for weeks or months, holding capacity against an outage, a wildfire shutoff, or a capacity-market obligation. That duty punishes calendar life, because conventional cells lose roughly one to five percent of capacity per year at rest regardless of whether they are cycled, through the spontaneous internal degradation the disclosure catalogs (electrolyte decomposition, solid-electrolyte-interphase growth, transition-metal dissolution).

The disclosed architecture addresses both pressures through structure rather than through a better separator or electrolyte additive. Self-discharge at rest is governed by the bulk-equipotential charge retention principle: in the charged state with no load connected, every nanoflake sits at the same electrochemical potential, so there is no internal driving force for charge to redistribute, and charge is held by saturation rather than by an insulating barrier that can be breached. The disclosure projects calendar self-discharge well below one percent per year on this basis (a projection from the disclosed mechanism, not a measured figure), and identifies long-duration grid storage, emergency backup, and infrastructure resilience as the natural fit for its long-term storage mode. On the cycling side, the disclosure describes mechanochemical self-healing, in which mobile carbon migrates to mechanically strained sites during cycling and repairs fatigue damage, and a projected use-positive aging regime in which cumulative cycling does not produce monotonic capacity loss until the auxiliary carbon reservoir nears exhaustion. A storage asset that does not punish daily cycling and does not bleed capacity while idle is matched to a plant that must do both.

How It Composes With the Domain

A renewable-firming installation maps cleanly onto the disclosed operating modes. During a charge window (excess midday photovoltaic output, off-peak wind), the power-conversion system applies charging bias across each series string. The disclosed charging mechanism is proton-coupled electron transfer at the flake surfaces: an applied bias drives protons into a high-energy transit state that crosses the hydrophobic gating region and bonds atomic hydrogen to surface metal atoms. During the evening discharge ramp, the plant controller closes the external circuit into the grid interconnection; load-driven electron drain withdraws the bonding electrons, the metal-hydrogen bonds release their hydrogen as protons into the hydrophilic channel network, and the cell discharges only as fast as the load admits. The disclosed asymmetry between charge ingress and discharge egress (charging crosses the hydrophobic gate, discharging exits directly into the hydrophilic channels) is what lets the same cell accept a slow midday charge and deliver a controlled evening dispatch.

Several disclosed properties are load-bearing for the economics of the deployment. The absence of an internal separator gives the gel high combined electronic and ionic conductivity, which the disclosure ties to a high-rate capability suitable for grid-frequency response; the same plant that does daily energy arbitrage can therefore also bid into fast frequency-regulation markets without a separate asset. The bulk-equipotential architecture means charge can be drawn from any region of the cell rather than from a localized electrode, which the disclosure relates to more uniform thermal management and stress distribution across the flake population, a relevant property when thousands of large cells share a container. For diurnal firming the healing-optimized cycling mode is apt: the disclosure recites moderate depth-of-discharge (approximately 50 to 80 percent) and moderate rates (approximately C/3 to 1C) as the regime that maximizes use-positive aging, which is close to the natural duty of a solar-shifting plant. For a reserve plant that mostly waits, the long-term storage mode holds state of charge with the low projected self-discharge described above.

The active metal in the preferred embodiment is aluminum, which the disclosure selects for low cost and abundance, with no recited dependence on cobalt, nickel, or lithium supply chains, a material posture that matters when an installation is measured in megawatt-hours and procured against commodity-grade feedstock rather than constrained cathode metals. Embodiments span a configuration range the disclosure makes explicit: lower nanoflake loading for high-cycle-life duty, higher loading for higher energy density, and higher fractal-generation-count flakes for greater accessible surface area, letting an integrator tune cells toward a firming plant's cycle-heavy profile or a reserve plant's capacity-heavy profile.

What This Enables

Treating storage behaviors as architectural rather than incidental opens deployment patterns that a conventional chemistry makes awkward.

A firming plant can be sized for cycle count instead of for calendar-derating headroom. Because the disclosure separates calendar stability at rest (a bulk-equipotential property) from cycle endurance (a mechanochemical-healing property), an operator is not forced to overbuild capacity to offset the few-percent-per-year rest fade that conventional cells impose; a reserve obligation and a daily-arbitrage obligation can be carried by the same nameplate.

Fault behavior at the substation changes character. The disclosure describes a heat-triggered programmable discharge stall: at elevated cell temperatures (a tunable range cited around 60 to 90 degrees Celsius and above) controlled carbon-framework failure outpaces healing, internal resistance climbs, and discharge current falls to negligible levels, a stall the disclosure recites as reversible on cooling and as distinct from the irreversible thermal-runaway mode of conventional lithium-ion cells. It further describes a mechanical-breach response in which atmospheric oxygen entering a punctured cell drives stored energy into benign gaseous products (aluminum oxide, water vapor, carbon dioxide) rather than flammable organic-solvent vapor. For a containerized installation near distribution infrastructure or in a wildfire-prone service territory, intrinsic over-temperature stall and a non-flammable breach signature are directly relevant to siting, fire code, and insurability, which are legitimate domain concerns the cell architecture engages.

End-of-life is handled by centralized remanufacturing rather than field service. The disclosed cell is hermetically sealed with no field-service ports; the disclosure routes material recovery through full cell remanufacturing at a centralized facility and frames it as a cradle-to-cradle recovery path, which fits utility asset-management practice of returning racks to a depot at end of contract.

Across these, the through-line is that the duty a grid asset must perform (sit charged, cycle daily, fail safe, be recovered) is met by behaviors the disclosed architecture composes, not by behaviors invented for this article.

Boundary Conditions

The honest limits matter most at grid scale, where capital is large and dispatch obligations are contractual. The underlying materials science here is prior art: metal-hydrogen surface chemisorption, proton-conducting carbon gels, electrochemical exfoliation of metal nanoparticles, and mechanochemical effects at strained interfaces are all established and characterized in published research. Nothing in this application claims a newly discovered material, bond, or physical effect. The novelty the home filing asserts is the combination and architecture (the separator-free bulk-equipotential cell integrating surface-bonded hydrogen storage, electrostatic flake isolation, asymmetric charge and discharge paths, hydrogen-gated flake expansion, mechanochemical healing, and boron-doping precision), and the new cell category that combination defines.

This is a provisional disclosure of that architecture. The cell has not been built, benchmarked, or validated at grid scale, and this application states no energy density, round-trip efficiency, cycle-life count, calendar-life figure, or cost per kilowatt-hour. Performance-shaped statements in the disclosure (self-discharge well below one percent per year, use-positive aging, projected cycle counts) are recited as projections from the disclosed mechanisms and are expressly to be determined empirically through long-duration and prototype testing. Practical questions that decide any real grid deployment, including round-trip efficiency under daily cycling, large-format manufacturing yield, the behavior of long series strings under cell-to-cell variation, and degradation under continuous frequency-regulation duty, are exactly the things a provisional does not yet answer. Some recited long-term degradation modes (aluminum-cation migration into the boron-carbon pairing) are estimated to act on multi-decade timescales, but those estimates are order-of-magnitude, not measured. A utility integrator should read this as an architecture matched to grid duty, not as a qualified product.

Disclosure Scope

The technology described here is the Hydrogen-Aluminum Energy Cell, disclosed in U.S. Provisional Application No. 64/055,649, and every statement about what the cell does (bulk-equipotential charge retention, surface-bonded hydrogen storage, asymmetric charge and discharge paths, mechanochemical self-healing, heat-triggered discharge stall, oxygen-driven breach response, series stacking, and centralized remanufacturing) traces to that disclosure. The grid-scale and renewable-firming framing, including load-shifting and frequency-response duty, behind-substation siting, utility and ISO asset-management practice, and fire-code, wildfire-shutoff, and insurability considerations, is external domain context provided to show an enabling deployment of the disclosed architecture; it is not part of the patent claims and should not be read as such. References to grid operators, interconnection practice, and renewable integration describe the application environment, not asserted device performance. No energy-density, efficiency, cycle-life, or cost figure is claimed, and the underlying materials science is acknowledged as pre-existing prior art whose novel contribution here is its disclosed combination, configuration, and resulting category.

Hydrogen-Aluminum Energy Cell (/h-al-battery)

All 40 steps → (/inventive-steps)

Sealed electrochemical cell storing energy as reversible covalent hydrogen bonds on carbon electrodes.

Provisional application

PRIMARY TECHNICAL DISCLOSURE

- A Hydrogen-Aluminum Surface-Bond Storage Cell with Bulk-Equipotential Charge Retention (/articles/a-hydrogen-aluminum-surface-bond-storage-cell-with-bulk-equipotential-charge-retention)

SECONDARY TECHNICAL

- Charge Retention by Bulk-Equipotential Saturation Without an Internal Separator (/articles/h-al-battery/bulk-equipotential-charge-retention)
- Storing Energy as Electron-Stabilized Metal-Hydrogen Surface Bonds Formed by Proton-Coupled Electron Transfer (/articles/h-al-battery/hydrogen-metal-surface-bond-storage)
- Electron-Mediated Bond Stability: The Kinetically Trapped Idle State Behind Indefinite Calendar Life (/articles/h-al-battery/electron-mediated-bond-stability)
- Hot-Proton Charging Versus Cold-Proton Discharge: The Bias-Gated Asymmetry That Blocks Self-Charge and Self-Discharge (/articles/h-al-battery/hot-cold-proton-asymmetry)
- Asymmetric Dual-Domain Proton Paths: Separate Ingress and Egress Routes in a Hydrogen-Aluminum Storage Gel (/articles/h-al-battery/asymmetric-dual-domain-paths)
- Hydrophobic Gating: Rejecting Neutral and Molecular Hydrogen While Admitting Only Biased Protons (/articles/h-al-battery/hydrophobic-gating)
- The Storage Gel as a Polarized Electrochemical Switch: Coherent Alignment, Equipotential Locking, and Load-Proportional Discharge (/articles/h-al-battery/gel-polarized-switch)
- Flake-Flake Electrostatic Isolation: DLVO Repulsion as a Self-Discharge Barrier in a Separator-Free Hydrogen-Aluminum Cell (/articles/h-al-battery/flake-electrostatic-isolation)
- Dynamic Flake Expansion: Carbon-Intercalation Wedging to Expose Buried Metal Surface Under Bias (/articles/h-al-battery/dynamic-flake-expansion)
- Hydrogen-Locked Expanded State: Surface-Energy Inversion as a Positive-Feedback Capacity Mechanism (/articles/h-al-battery/hydrogen-locked-expanded-state)
- Secondary Carbon-Hydrogen Storage on Transmuted Intercalated Carbon (/articles/h-al-battery/secondary-carbon-hydrogen-storage)
- Mechanochemical Strain Self-Healing and Use-Positive Aging in a Bulk-Equipotential Hydrogen-Aluminum Cell (/articles/h-al-battery/mechanochemical-self-healing)
- Boron Doping of the Carbon Framework as a Multi-Function Precision Multiplier (/articles/h-al-battery/boron-doping-precision-multiplier)
- The Floating Aluminum Equipotential Extension Layer: A Multifunctional Inner Case for the Bulk-Equipotential Cell (/articles/h-al-battery/aluminum-equipotential-extension-layer)

APPLICATIONS · GENERAL

- **Grid-Scale and Renewable-Firming Storage with the Hydrogen-Aluminum Energy Cell (/articles/h-al-battery/grid-scale-storage)**
- Building-Integrated and Behind-the-Meter Storage: Putting Energy Cells Inside the Structure With the Hydrogen-Aluminum Energy Cell (/articles/h-al-battery/building-integrated-storage)
- Stationary Backup and UPS Reserve Power for Data Centers, Hospitals, and Telecom (/articles/h-al-battery/backup-and-ups)
- Storage for Microgrids, Islands, and Off-Grid Sites: A Stationary Cell Built From Abundant Materials (/articles/h-al-battery/microgrid-and-off-grid)
- Electric Mobility and Transport: How a Hydrogen-Aluminum Cell Architecture Maps to Vehicle Constraints, and Where It Does Not (/articles/h-al-battery/ev-and-mobility)
- Marine and Rail Energy Storage: A Bulk-Equipotential Hydrogen-Aluminum Cell for Mass-Tolerant Heavy Transport (/articles/h-al-battery/marine-and-rail)
- Supply-Chain-Resilient Field Power: An Abundant-Material Energy Cell for Defense and Expeditionary Operations (/articles/h-al-battery/defense-and-field-power)

Hydrogen-Aluminum Energy Cell overview → (/h-al-battery)