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A Circular-Material Hybrid Energy Storage Architecture for Fast-Ramping and Black-Start Support of a 500 MW Coal-Fired Power Plant

Municipal-Waste-Derived Hard-Carbon Sodium-Ion BES Integrated with Fly-Ash Thermal Energy Storage

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Abstract - This paper proposes a multi-timescale energy-storage architecture for retrofitting a 500 MW subcritical coal-fired power plant with a 250 MW/1,000 MWh-class fly-ash thermal energy storage (TES) system and a 30 MW fast-response electrical storage layer. The electrical layer consists of a 5 MW supercapacitor subsystem and a 25 MW sodium-ion battery energy storage system (BESS), with an indicative battery duration of 1–2 h. To reduce dependence on critical imported materials, the proposed sodium-ion cells use municipal-waste-derived hard carbon as the anode, a sodium–iron–manganese cathode family, and qualified secondary aluminium current collectors. Fly-ash-derived silicon is deliberately excluded from the baseline because it adds processing complexity and development risk. The proposed architecture separates electrical fast-response duties from bulk thermal energy shifting: the supercapacitor addresses sub-second transients, the sodium-ion BESS supplies seconds-to-minutes response and black-start support, and the fly-ash TES supplies sustained power for minutes-to-hours. The complete concept is estimated at approximately TRL 4–5, although several constituent technologies are considerably more mature.

Index Terms - sodium-ion battery, hard carbon, municipal solid waste, fly ash, thermal energy storage, black start, fast ramping, supercapacitor, coal power plant.

Accordingly, the paper should claim potential superiority in waste utilization, feedstock availability at the power-plant site, avoidance of virgin-material procurement, and integration with existing ash-handling infrastructure-not an assumed intrinsic heat-capacity advantage. Effective storage capacity must be demonstrated experimentally from measured density, temperature-dependent specific heat, allowable temperature range and thermal losses.

The stronger engineering argument is system-level. Fly ash is already generated, collected and handled at the host thermal plant, whereas suitable sand must be procured, transported and stored. Fly ash can also be immobilized or structured in an alkali-activated/geopolymer matrix, allowing TES geometry, thermal conductivity and mechanical integrity to be engineered. Recent studies report promising high-temperature stability of fly-ash-containing alkali-activated materials for TES applications in approximately the 400–600 °C range [12].

A critical qualification is required when comparing fly ash with sand. Fly ash should not be described as intrinsically having a higher specific heat capacity than sand. Published values for fly ash are commonly around 0.7–0.8 kJ kg^{-1} K^{-1}, while dry quartz sand is approximately 0.83 kJ kg^{-1} K^{-1}; exact values vary with composition, temperature, moisture, particle size and measurement method [10], [11]. Thus, an unsupported claim that raw fly ash has superior gravimetric thermal capacity would weaken the paper.

II. FLY ASH VERSUS SAND AS TES MEDIA

These developments establish the prior-art baseline for the present work: the novelty is not the general concept of storing heat in an inexpensive solid medium. The proposed contribution is the substitution of a coal-power-plant waste stream-fly ash-into a plant-integrated TES architecture and its coordination with a waste-derived sodium-ion BESS and supercapacitor layer.

A related commercial pathway has been demonstrated by Polar Night Energy, whose Sand Battery uses sand or similar solid materials to store electricity as heat and subsequently deliver hot water, steam, or hot air. Its current product information describes systems up to 10 MW heating power and up to 1,000 MWh of thermal capacity, with approximate thermal round-trip efficiencies of 85–90% depending on configuration [8]. Polar Night Energy is also developing power-to-heat-to-power capability [9].

Solid-particle thermal energy storage has been investigated for high-temperature energy storage because inexpensive solid media can tolerate temperatures above those commonly associated with conventional nitrate molten salts. The National Renewable Energy Laboratory (NREL) has published work on

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particle-based TES for concentrating solar power, including designs using inexpensive, thermally stable solid particles as both heat-transfer and storage media. NREL reports particle systems above 800 °C and emphasizes that larger temperature differences can improve storage capacity and enable high-efficiency power cycles [6], [7].

I. BACKGROUND: SOLID-PARTICLE AND SAND-BASED TES

The principal invention proposed in this work is not merely the use of a solid thermal-storage medium. It is the conversion of a large, continuously generated coal-fly-ash waste stream into an engineered thermal-storage asset and its integration with an existing thermal generating fleet to decouple boiler operation from grid-output requirements. The resulting architecture is intended to allow the thermal fleet to operate more flexibly, absorb renewable-energy variability, reduce unnecessary thermal cycling, and provide fast electrical services through a separate electrochemical/supercapacitor layer.

The concept therefore addresses two linked problems: (1) the need to make existing thermal generation more flexible as variable renewable generation increases, and (2) the need to beneficially utilize large quantities of coal-combustion fly ash. The proposed TES transforms fly ash from a disposal liability into an energy-storage infrastructure material, while the sodium-ion BESS and supercapacitor provide services for which thermal storage alone is too slow or operationally inefficient.

I. INTRODUCTION

Coal-fired generating units increasingly require flexibility for fast frequency response, ramping, black start, and renewable-energy balancing. These services occur on different time scales, so a single storage technology need not perform every function. This paper proposes a hybrid architecture in which high-power electrical storage is coupled to a large fly-ash thermal store.

Sodium-ion batteries are increasingly relevant to stationary storage because sodium is abundant and hard carbon is widely regarded as the leading practical anode family for sodium-ion cells [1]. Recent work also emphasizes the importance of hard-carbon microstructure, density, porosity, initial Coulombic efficiency, and rate behavior [1]. Commercial sodium-ion deployment is advancing, although it remains less mature than lithium-ion at global scale [2].

The proposed design focuses on economical deployment in an existing Indian thermal plant. Fly-ash-to-silicon processing is excluded. Municipal waste is instead used as the carbon precursor, while fly ash is reserved primarily for TES. This reduces process complexity and concentrates the material innovation on waste-derived hard carbon.

II. SYSTEM ARCHITECTURE

The reference plant is a 500 MW subcritical coal-fired unit. The proposed flexibility system comprises a 250 MW/1,000 MWh-class fly-ash TES, a 30 MW fast-response electrical layer, and the existing generator and steam cycle.

Layer	Rating	Time scale	Primary duty
Supercapacitor	5 MW; ~0.5–1 MWh	ms–s	Instantaneous response
Na-ion BESS	25 MW; 25–50 MWh	s–min	Fast ramp, black start, frequency response
Fly-ash TES	250 MW; 1,000 MWhth basis	min–h	Sustained thermal flexibility
Coal unit	500 MW	h–days	Long-duration generation

III. PROPOSED SODIUM-ION BESS

The baseline cell uses municipal-waste-derived hard carbon as the anode and a sodium–iron–manganese cathode family selected to minimize nickel and cobalt dependence. Commercially qualified electrolyte and separator systems should initially be used. The research risk is therefore concentrated on the waste-derived carbon.

Municipal solid waste should not be fed directly into electrode production. The proposed chain is segregation of a carbon-rich fraction, removal of metals, glass and mineral contamination, thermal conversion, purification, particle-size control, and electrochemical qualification. The hard carbon should be characterized for ash content, surface area, pore structure, tap density, first-cycle efficiency, reversible capacity and high-rate performance.

Secondary aluminium is proposed for suitable current-collector applications after qualification. Scrap must be sorted, refined/remelted and processed to controlled composition and surface quality. A dedicated aluminium recycling plant is not assumed; qualified recycled foil should preferably be procured from established suppliers.

SiC and fly-ash-derived silicon are excluded from the economic baseline. They may remain future research options, but they are not required for the intended fast-ramp function.

IV. FLY-ASH TES: PRINCIPAL INVENTION AND THERMAL-FLEET FLEXIBILITY

The principal TES innovation is the utilization of plant-generated Class-F coal fly ash as the dominant solid phase in an engineered alkali-activated geopolymer storage matrix. The reference feasibility design uses approximately 8,000 t of fly ash in an approximately 8,500 t storage core, with about 5 wt% expanded graphite as a thermal-conductivity-enhancing additive. The concept uses six parallel storage vaults and thin storage plates to shorten internal conduction distances and increase heat-transfer area. These quantities remain preliminary and require validation using the actual plant ash.

Unlike a conventional battery retrofit, the TES is designed to decouple the boiler/steam-generation process from the timing of electrical dispatch. During charging, a controlled steam extraction or diversion is passed through pressure reduction/desuperheating and a heat exchanger to a closed high-temperature air circuit. The air loop charges the fly-ash geopolymer storage core toward the design temperature. During discharge, hot air passes through a secondary heat-recovery steam generator (HRSG), producing conditioned

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steam for an appropriate turbine-side admission point. The final steam conditions, pressure balance, moisture limits and turbine integration must be established by plant-specific engineering.

The preliminary design basis is 250 MW thermal discharge for four hours, corresponding to 1,000 MWh of nominal thermal storage. A conceptual temperature swing of 650 °C to 250 °C gives an air-flow requirement of approximately 579 kg/s using Cp = 1.08 kJ kg^{-1} K^{-1}. This very large flow is a major feasibility driver and should be treated as a critical design issue, not a finalized equipment specification. Six vaults imply roughly 96–100 kg/s per vault at the nominal point before distribution margins.

The storage core is envisaged as approximately 1 m × 1 m × 35 mm plates with 5–7 mm inter-plate air gaps. The reference concept contains approximately 110,000 plates. Actual plate thickness, graphite fraction, porosity, compressive strength, thermal diffusivity, thermal-cycle stability, manufacturing tolerances and air-side pressure drop must be established experimentally. The enclosure concept uses a high-alumina/fireclay refractory hot face, aluminosilicate ceramic-fibre insulation and a reinforced structural enclosure.

The fleet-flexibility function is central to the invention. Instead of forcing the boiler to follow rapid grid-load changes, the TES can absorb or release thermal energy while the boiler is maintained in a more stable operating region. Potential operating modes include: renewable-energy absorption during periods of surplus generation; peak-period power augmentation; rapid ramp support; reduction of boiler cycling; reduced startup/shutdown stress; minimum-load support; and coordinated dispatch of multiple thermal units. This creates a thermal-fleet flexibility layer rather than a storage device operating independently of the plant.

For a fleet of multiple thermal units, a centralized energy-management system can allocate TES charging and discharging among units according to unit loading, ramp capability, heat rate, maintenance condition and grid requirements. The TES can therefore function as a shared flexibility asset, allowing the fleet to preserve thermal stability while the grid sees a faster effective electrical response. This is potentially more valuable than treating TES only as an arbitrage reservoir.

The prior-art distinction is important. NREL has demonstrated and modeled low-cost solid-particle TES using sand and other solid media at high temperature. NREL work reports particle operation above 800 °C and identifies low-cost particles as a path to long-duration storage. Polar Night Energy has commercialized sand-based thermal storage for heat applications and is developing power-to-heat-to-power capability. The present concept differs by making plant-generated fly ash the principal storage feedstock and by coupling the TES directly to a coal-fired thermal fleet for operational flexibility. The invention claim should therefore focus on this integrated waste-utilization and fleet-flexibility architecture, rather than claiming the generic concept of solid-particle thermal storage.

Fly ash versus sand: raw fly ash should not be claimed to have intrinsically higher specific heat than quartz sand. The stronger technical case is system-level: fly ash is already available at the host plant, avoids virgin-material procurement and transport, can be engineered into a structural geopolymer matrix, and directly addresses ash utilization. The actual storage capacity must be demonstrated from measured density, temperature-dependent specific heat, usable temperature range, thermal conductivity and heat loss. Thus, the proposed superiority is primarily in integrated system economics, waste utilization and plant compatibility-not an assumed superior kJ kg^{-1} K^{-1} value.

IV. FLY-ASH THERMAL ENERGY STORAGE

The TES layer uses Class-F fly ash as the principal storage-material feedstock in an alkali-activated geopolymer system with expanded graphite for thermal conductivity. The preliminary source design uses approximately 8,000 t of fly ash in an approximately 8,500 t storage core, six parallel vaults, refractory protection, insulation, and an air-based high-temperature heat-transfer loop.

The TES is deliberately retained as the bulk energy-storage technology. This avoids purchasing hundreds of megawatt-hours of electrochemical cells solely to provide several hours of sustained output. The TES therefore complements rather than competes with the BESS.

V. BLACK-START AND FAST-RAMP OPERATION

Following a grid disturbance, the grid-forming power-conversion system establishes the electrical reference. The supercapacitor supplies the first high-power transient, followed by the sodium-ion BESS. Essential plant auxiliaries are energized according to the plant-specific black-start sequence. As the thermal system becomes available, the TES supplies sustained thermal input through the heat-recovery system.

The control hierarchy is therefore: supercapacitor response → sodium-ion BESS response → TES thermal response → conventional coal-unit generation. Motor-starting sequence, auxiliary load, minimum BESS energy requirement, turbine rolling requirements, and protection settings require plant-specific dynamic studies.

The separate TES feasibility report estimates a preliminary retrofit-block CAPEX of approximately ₹56.4–78.7 crore, including approximately 8,000 t of fly ash assumed at zero internal transfer cost, approximately 500 t of alkali activators and expanded graphite, refractory, ceramic-fibre insulation, blowers, piping/PRDS/steam interconnections and a secondary HRSG. These figures are planning estimates only and exclude or may exclude contingency, electrical systems, instrumentation, civil works, water treatment, cooling, transformers, switchgear, fire protection, engineering, commissioning, taxes and owner's costs. They must not be presented as bankable CAPEX without vendor quotations and FEED-level design.

Potential value streams include peak/off-peak energy shifting, renewable-energy absorption, capacity and flexibility services where permitted, reduced thermal cycling, reduced startup/shutdown fuel and auxiliary consumption, and ancillary or ramping services. A previous preliminary calculation of ₹146 crore/year gross arbitrage based on a ₹4/kWh spread assumes 1,000 MWh of usable energy, 365 cycles/year and 100% availability; it is therefore an illustrative

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upper-bound calculation rather than a bankable revenue forecast.

VI. ECONOMIC OPTIMIZATION

The principal cost strategy is to size the sodium-ion BESS for power services rather than bulk energy. A preliminary 25 MW/25–50 MWh battery corresponds to approximately 1–2 h nominal duration, while the TES carries longer-duration energy. This reduces cell quantity and associated thermal-management and fire-protection requirements.

Commercial PCS, BMS, EMS, transformers, switchgear, protection, and other balance-of-system equipment should be used. Existing plant switchyard, auxiliary systems, control-room infrastructure, fly-ash handling, and other brownfield assets should be reused wherever technically permissible.

The lowest-risk commercialization route is to demonstrate the plant system initially with qualified commercial sodium-ion cells while developing municipal-waste-derived hard carbon in parallel. Once the waste-derived material meets cell-level performance and life requirements, it can progressively replace purchased hard carbon.

VII. TECHNOLOGY READINESS

Subsystem	Indicative TRL	Main gap
Commercial sodium-ion cells	8–9	Vendor-specific field data
Hard-carbon Na-ion cells	8–9	Chemistry/formulation dependent
MSW-derived hard carbon	4–6	Feedstock consistency and qualification
Secondary Al current collector	8–9	Battery-grade qualification
5 MW supercapacitor	9	Plant integration
25 MW Na-ion BESS architecture	7–8	Project-specific integration
Integrated 30 MW BES	4–5	Full-scale demonstration
250 MW fly-ash TES	3–5	Pilot validation and integration
Complete hybrid system	~4–5	System-level demonstration

The complete system should not inherit the TRL of its most mature component. The overall concept remains approximately TRL 4–5 because the integrated architecture, waste-derived hard-carbon pathway, and plant-scale TES/BESS interaction require demonstration.

VIII. COMPARISON WITH HIGH-TRL ALTERNATIVES

Criterion	LFP	Commercial Na-ion	VRFB	Proposed
Commercial maturity	Very high	High/increasing	Very high	Development
Fast response	Excellent	Excellent	Good	Excellent target
Long-duration role	Excellent	Good	Excellent	TES handles it
Critical-material dependence	Moderate	Lower	Moderate	Potentially low
Waste-material use	Low	Low–moderate	Low	High
Localization potential	Moderate	High	Moderate	Very high potential
Bankability today	Very high	Increasing	High	Low
Innovation	Low	Moderate–high	Moderate	High

The proposed system should not be presented as a present-day replacement for LFP on every metric. Its principal advantage is system-level economics and material circularity: a relatively small high-power BESS is combined with a large low-cost thermal store. Commercial sodium-ion is the appropriate high-TRL benchmark for the cell platform, while LFP remains a benchmark for bankability and mature supply chains.

IX. DEVELOPMENT ROADMAP

1. Characterize the selected municipal-waste carbon fraction and establish a repeatable hard-carbon process.
2. Build laboratory cells and quantify capacity, initial Coulombic efficiency, rate capability, impedance growth, and cycle life.
3. Qualify Na–Fe–Mn cathode formulations and commercial electrolyte/separator combinations.
4. Qualify secondary aluminium current collectors.
5. Demonstrate a pilot sodium-ion module and grid-forming PCS.
6. Validate fly-ash TES through thermal cycling, mechanical testing, and air-side pressure-drop testing.
7. Integrate BESS, supercapacitor and TES controls using digital or hardware-in-the-loop simulation.
8. Conduct a staged plant demonstration before committing to 25 MW BESS and 250 MW TES scale.
9. Obtain vendor guarantees, EPC quotations, safety studies and a lifecycle-cost model.
10. Progress to commercial deployment after performance, safety, durability and economic targets are demonstrated.

X. PRELIMINARY PERFORMANCE TARGETS

Parameter	Target
Combined fast-response electrical layer	30 MW
Supercapacitor	5 MW
Sodium-ion BESS	25 MW
Sodium-ion energy capacity	25–50 MWh
Nominal BESS duration	1–2 h
Round-trip efficiency	$\geq$80% target
Cycle life	$\geq$5,000 equivalent full

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	cycles target
Primary services	Black start, fast ramp, frequency response
Long-duration TES	250 MW / 1,000 MWhth basis

The central contribution should be presented as a flexible thermal-fleet architecture enabled by fly-ash utilization. The fly ash is not merely a low-cost storage medium; it is the enabling waste stream that makes a large, plant-integrated thermal store conceptually attractive. By decoupling boiler heat production from the timing of electrical output, the system can allow existing thermal units to operate with less severe load-following stress while a coordinated storage layer provides rapid and sustained flexibility.

XI. CONCLUSIONS

A cost-optimized hybrid storage architecture is proposed for a 500 MW coal-fired power plant. The design combines a 5 MW supercapacitor, a 25 MW/25–50 MWh sodium-ion BESS and a 250 MW/1,000 MWh-class fly-ash TES. The sodium-ion BESS uses municipal-waste-derived hard carbon, a Na–Fe–Mn cathode family and qualified secondary aluminium current collectors. Fly-ash-derived silicon is excluded from the baseline because it adds processing complexity without being necessary for the required fast-ramp function.

The principal economic advantage is not an assumption that waste-derived cells will immediately be cheaper than commercial LFP. Instead, the architecture minimizes the electrochemical energy inventory and assigns long-duration energy storage to the fly-ash TES. Mature balance-of-system equipment and existing plant infrastructure are retained to reduce risk.

The complete system is approximately TRL 4–5, while individual components range from mature commercial technologies to laboratory-scale waste-derived materials. A staged program can raise system TRL without making the first demonstration entirely dependent on an unvalidated waste-derived cell manufacturing chain.

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