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Emerging Trends in Hybrid Energy Storage for Low-Inertia Islanded Microgrids: Technologies, Applications and Research Directions

Conference theme: Innovations for Sustainable Development and Resilient Infrastructure

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Presentation roadmap

1. The challenge

Renewable variability and low physical inertia make islanded microgrids more sensitive to disturbances.

2. Storage options

Compare battery–supercapacitor, battery–flywheel, battery–hydrogen and emerging options.

3. Applications

Frequency support, renewable smoothing, energy balancing, voltage regulation and resilience.

4. Emerging trends

Multi-timescale control, multi-service scheduling, integrated converters and uncertainty-aware operation.

5. Research priorities

Standardized benchmarking, stronger experimental evidence, service coordination and lifecycle assessment.

Central message: there is no universally best HESS—the right design depends on the service, operating conditions and quality of evidence.

Why low-inertia islanded microgrids are challenging

- Solar PV and wind reduce reliance on diesel and extend access to underserved regions.
- Their output varies with weather, while inverter-based resources generally do not provide the same physical rotating inertia as synchronous machines.
- In islanded operation, there is little or no support from a larger grid when generation and demand become unbalanced.
- Frequency can change rapidly after a disturbance; fast response and coordinated energy management become critical.

Low physical inertia

Faster frequency response to sudden generation or load changes.

Renewable variability

Short-term fluctuations can stress control and storage resources.

Limited backup

Islanded systems must balance their own generation and demand.

Virtual/synthetic inertia can support frequency response, but it is not the same as restoring physical synchronous inertia.

Aim and research questions

Aim

Synthesize emerging HESS technologies, integration architectures, applications and evidence-based research priorities for low-inertia islanded microgrids.

RQ1

Which technologies, hybrid combinations and topologies have been investigated?

RQ2

Which applications justify different HESS combinations, and what trade-offs are evidenced?

RQ3

What emerging research themes and methodological changes can be identified?

RQ4

What gaps remain, and what should research and funding prioritize?

Review methodology and evidence handling

1	**Search**	HESS, battery–supercapacitor, battery–flywheel, microgrid, islanded, isolated, low inertia
2	**Screen**	Remove duplicates; screen titles/abstracts; assess full texts against inclusion criteria
3	**Extract**	Technology, topology, application, operating mode, performance metrics and limitations
4	**Classify evidence**	Analytical, simulation, laboratory, hardware-in-the-loop (HIL) or field-based
5	**Synthesize**	Compare themes cautiously; avoid treating unlike operating conditions as equivalent

Important: the write-up describes the intended search and screening approach; a final review should report actual search dates and record counts.

HESS: matching storage to timescale

Hybrid energy storage systems combine technologies with complementary power and energy characteristics.

Milliseconds–seconds

Very fast response

Supercapacitors / flywheels

Seconds–minutes

Frequency recovery & smoothing

Batteries + fast storage

Minutes–hours

Energy balancing / peak demand

Batteries

Hours–days

Long-duration energy

Hydrogen-based storage

Illustrative mapping only: actual roles depend on system ratings, state of charge, converter limits, control strategy and operating conditions.

Main HESS technology combinations

Battery + supercapacitor

Strength: rapid transient response plus sustained energy.

Use: frequency support and renewable smoothing.

Trade-off: extra cost, controls and limited supercapacitor energy.

Battery + flywheel

Strength: rapid power exchange and repeated cycling.

Use: short-duration, high-cycle support.

Trade-off: rotor containment, parasitic losses, complexity and capital cost.

Battery + hydrogen

Strength: batteries handle short-term needs; hydrogen can support longer deficits.

Use: extended-duration storage.

Trade-off: electrolysis/fuel-cell losses, infrastructure and safety.

Emerging battery chemistries

Sodium-ion and all-solid-state sodium are research options; maturity and deployment evidence must be checked.

Multi-technology HESS

Potential to allocate services to complementary devices, but more interfaces and supervisory coordination are needed.

HESS architectures and coupling choices

Passive

Shared converter; simpler and potentially lower cost, but limited independent power allocation.

Semi-active

One storage device has independent converter control; intermediate flexibility and complexity.

Fully active

Independent converters improve power-flow flexibility but add hardware, losses and control complexity.

Network coupling

DC-coupled

Can reduce conversion stages where sources and storage share a DC bus; efficiency depends on design.

AC-coupled

Can flexibly interface AC sources and devices; converter coordination and voltage/frequency control matter.

No architecture is universally superior. Selection depends on application, protection, power flow, reliability, efficiency and lifecycle cost.

Applications of HESS in islanded microgrids

Frequency support

Fast power injection/absorption

Measures: RoCoF, frequency nadir, recovery time

Renewable smoothing

Reduce short-term PV/wind variability

Measures: Ramp-rate reduction, variability, curtailment

Energy balancing

Meet demand, shave peaks, preserve reserves

Measures: Peak demand, energy not served, SOC

Voltage / power quality

Regulate voltage and manage power exchange

Measures: Voltage deviation, settling time, reactive power

Resilience / restoration

Reserve energy for critical loads and recovery

Measures: Autonomy, critical-load supply, restoration success

Multi-service operation

Coordinate services competing for power and energy

Measures: Service performance, reserve headroom, degradation

Frequency support and renewable smoothing

Frequency support

- Respond quickly to generation–load imbalance
- Fast storage can take the transient; batteries sustain response
- Compare RoCoF, frequency nadir, recovery time and peak storage power

Renewable-power smoothing

- Absorb or supply power during PV/wind fluctuations
- Assess ramp-rate reduction and power variability
- Track curtailed energy, renewable utilisation and battery throughput

Evidence caution

Simulation supports a control concept, but does not by itself establish field performance. A cited frequency study with a 38 GW model should not be assumed to represent a typical small community microgrid.

Simulation | Real-time HIL | Laboratory | Field

Energy management, power quality and resilience

Load management

Fast frequency response is power-intensive and brief; peak shaving requires sustained energy. Sizing must consider power, energy, load profile and SOC.

Voltage regulation

Converter control and reactive-power capability can support AC voltage or DC-link regulation. Results depend on network impedance and system limits.

Resilience

Stored energy can protect critical loads and support emergency operation. Black start also needs grid-forming control, protection coordination and sequenced restoration.

Multi-service trade-off

Services share finite converter power, stored energy and state-of-charge headroom. Energy used for one event may not be available for a later renewable deficit or outage.

The objective is not to add as many services as possible; it is to coordinate them without compromising stability, energy adequacy or resilience.

Emerging research trends

1	**Multi-timescale coordination**	Day-ahead planning, intra-day balancing and fast response are coordinated across different time horizons.
2	**Multi-service scheduling**	Controllers allocate limited power and energy among frequency support, smoothing, peak shaving and reserves.
3	**Integrated power conversion**	Multiport converters may simplify interfaces, but can increase control coupling and fault-isolation complexity.
4	**Technology diversification**	Sodium-ion, hydrogen and other options broaden design choices; maturity and safety require assessment.
5	**Uncertainty-aware operation**	Deterministic scenarios, stochastic programming and robust optimization address renewable and demand uncertainty.

Research gaps identified in the review

Inconsistent metrics

Different baselines and test conditions make comparisons unreliable.

Limited physical validation

Simulation results may miss converter saturation, communication delays, noise, protection and thermal constraints.

Weak cross-technology comparability

Ratings, costs, efficiencies, losses and system boundaries differ between studies.

Service conflicts

Shared power, energy and SOC constraints can create trade-offs between services.

Uncertainty and extreme events

Long renewable deficits, component failures and reserve adequacy need stronger evaluation.

Incomplete lifecycle assessment

Economic and environmental effects are not consistently measured over the system lifetime.

Prioritized research agenda

1 **Standardize benchmarks**

Define common islanded-microgrid scenarios, load/generation profiles, control baselines and HESS-specific metrics.

2 **Strengthen validation**

Progress from simulation to controller-in-the-loop, HIL, laboratory tests and—where feasible—field demonstration.

3 **Coordinate services explicitly**

Model shared converter and SOC constraints; quantify trade-offs between frequency response, balancing and reserves.

4 **Evaluate lifecycle value**

Include degradation, replacement, conversion and standby losses, capital and operating cost, safety and environmental impacts.

Goal: move from isolated demonstrations of success toward reproducible, practically meaningful comparisons.

Conclusions

- HESS can help address rapid power imbalance, renewable variability and stability challenges in low-inertia islanded microgrids.
- Battery–supercapacitor systems suit fast transients; battery–flywheel systems suit repeated high-power cycling; battery–hydrogen systems can support longer-duration needs.
- Applications span frequency support, renewable smoothing, energy management, voltage regulation and resilience.
- Emerging research emphasizes multi-timescale coordination, multi-service scheduling, integrated conversion, technology diversification and uncertainty-aware operation.
- No storage combination should be declared best without common test conditions, credible validation and whole-life assessment.

Better simulated performance is not enough: evidence must be reproducible and relevant to realistic islanded operation.

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Thank you

Questions and discussion