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# Mobile Energy Storage (MES): A Grid-Edge Technology for Power Redistribution and Resilience Enhancement

**Yang Geng,[1,2] Hao Tang,[3] Wenjie Ji,[4,5] and Borong Lin[1,2,*]**
[1]School of Architecture, Tsinghua University, Beijing 100084, China
[2]Key Laboratory of Eco Planning and Green Building, Ministry of Education, Tsinghua University, Beijing 100084, China
[3]Institute of Smart City and Intelligent Transportation, Southwest Jiaotong University, Chengdu 611756, China
[4]School of Mechanical Engineering, Beijing Institute of Technology, Beijing 100081, China
[5]Non-silicon Micro-nano Manufacturing Key Laboratory, School of Mechanical Engineering, Beijing Institute of Technology, Beijing 100081, China
*Correspondence: linbr@tsinghua.edu.cn
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The global energy transition, characterized by the accelerating deployment of renewable energy sources, has introduced significant volatility into existing electrical grids. Managing this fluctuation requires immense energy storage capacity, not just for financial arbitrage but fundamentally for maintaining system stability, including essential services like peaking and frequency regulation. Simultaneously, climate change has amplified the frequency and severity of extreme weather events, making robust grid resilience—the ability to withstand and rapidly recover from outages—a paramount necessity for energy system planners.

This evolving landscape mandates a fundamental shift away from monolithic storage solutions toward a layered, diversified energy storage architecture. The new power system requires three distinct but complementary paradigms: Fixed Energy Storage (FES), which provides bulk capacity; Vehicle-to-Grid (V2G) technology, which offers distributed flexibility; and Mobile Energy Storage (MES), which provides emergent, tactical power redistribution capabilities.

MES represents the critical tactical component in this trio. Its inherent ability to move location-independent power to the point of failure offers a strategic advantage that FES and V2G cannot match. The strategic importance of MES extends beyond standard market metrics; its primary value proposition lies in enhancing resilience and providing essential logistical insurance against sustained economic disruption caused by unpredictable, localized grid failures.[1]

## COMPARATIVE ANALYSIS: FES, V2G, AND MES

Effective integration of energy storage requires a clear understanding of the operational roles and inherent limitations of each technology class.[2]

### FES: The System Foundation

FES forms the backbone of grid stability, focused on centralized, bulk services, typically operating at the MWh to GWh scale. FES systems are vital for absorbing high levels of renewable generation and providing large-scale services like peaking support. However, the fundamental limitation of FES is its immobility. Once sited and interconnected, its capacity is fixed to a single geographical location, making it vulnerable to localized disasters that affect its site or immediate transmission links.

### V2G: The Distributed Resource

V2G technology leverages electric vehicles (EVs) as a scalable, distributed storage resource. V2G allows EVs to function as mobile, flexible storage assets that, when aggregated, can be integrated into the grid to enhance local stability and manage fluctuating generation. While V2G offers expansive capacity potential, its utilization is constrained by individual battery size and is subject to complex optimization challenges based on owner driving schedules and battery health considerations.

### MES: The Tactical Responder

MES systems are distinct, encompassing both specialized towable battery energy storage systems and self-mobile vehicle-based units. MES functions as a specialized “large outdoor power bank”, providing essential tactical flexibility. The core advantage of MES is its ability to be deployed rapidly and dynamically to the exact location of need during unexpected outages or extreme events. Crucially, MES often possesses grid-forming capabilities, allowing it to initiate microgrids and harvest power from stranded Distributed Energy Resources (DERs) even when the primary distribution infrastructure is down.

MES thus serves as a logistical hedge against the inherent vulnerability of static infrastructure. If a localized event, such as a major storm, causes a single point of failure that isolates a fixed energy storage asset or a generation source, MES retains the ability to bypass damaged lines and restore critical service by transporting energy physically across the grid's periphery.[3]

## DIVERSE MES TECHNOLOGIES

To realize its full potential for power redistribution, MES must be deployed at scales compatible with existing heavy transportation infrastructure, focusing on trucks and the national rail network.

### Truck-Based MES (TMES)

The development of Truck-Based MES (TMES) represents a pivotal step in scaling tactical power assets, leveraging the existing infrastructure of the heavy-duty transportation sector. TMES units are uniquely valuable for their "last-mile" mobility, allowing them to fill operational gaps that fixed infrastructure cannot address. Their primary strategic application lies in bolstering resilience against localized failures or supporting temporary large events. TMES can charge from intact substations or stranded generation assets (like isolated wind farms) and physically transport power to affected areas, bypassing damaged distribution lines.

### Rail-Based MES (RMES)

Rail-Based MES (RMES) represents the zenith of terrestrial capacity, utiliz-

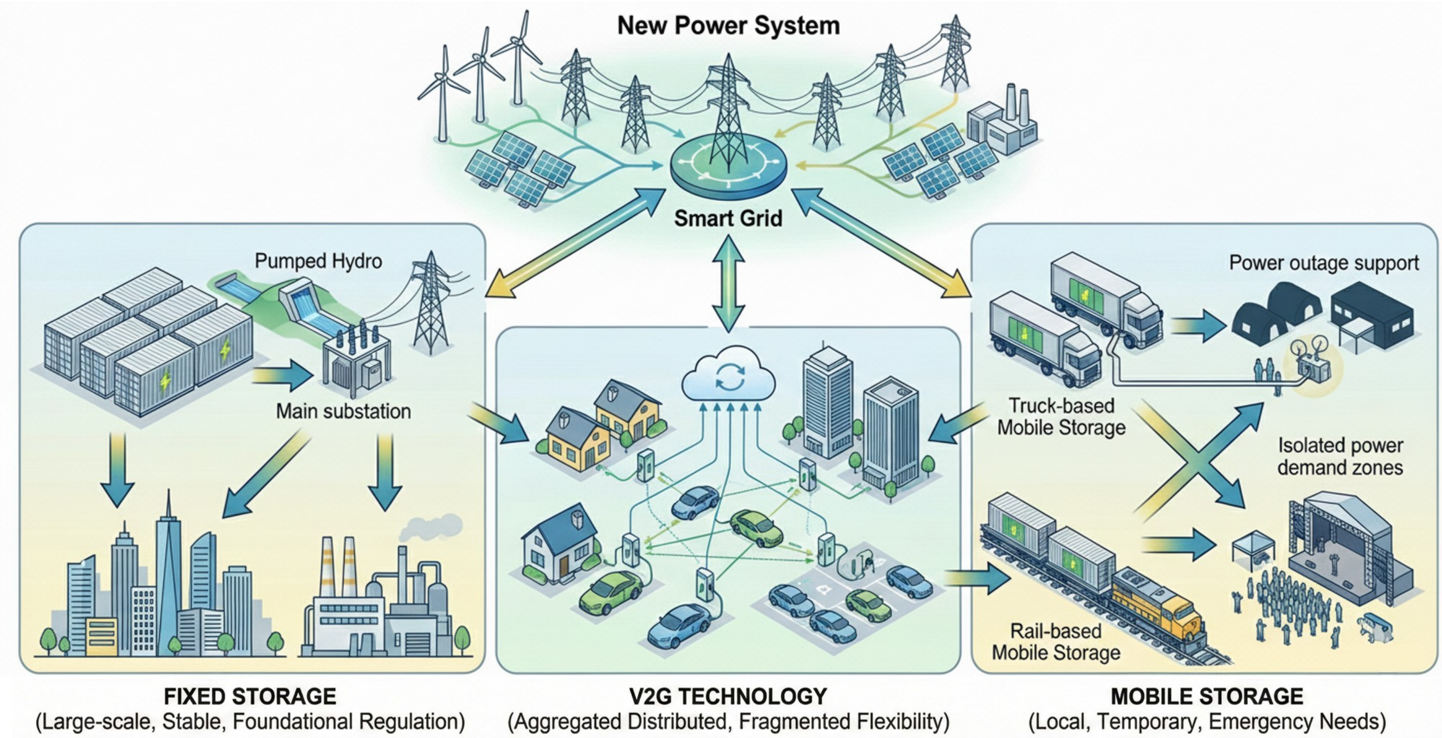


**Figure 1. Multi-Layered Collaborative Energy Storage System for New Power System Construction.**

ing the national rail network for large-scale energy transport.4 RMES functions as a "Grid-in-a-Box" or dynamic transmission alternative, capable of deferring expensive static transmission investments. Rail lines provide ideal vectors for injecting large volumes of clean energy into former industrial hubs or retired coal plants, effectively converting them into dynamic energy nodes.

### Maritime MES (MMES) and Modular Systems

Expanding beyond land, Maritime MES (MMES) utilizes electric vessels and power barges to serve coastal cities and island communities. These "floating batteries" can dock at major ports to provide gigawatt-scale emergency backup or frequency regulation services, effectively acting as mobile peaker plants without local emissions. Furthermore, Modular MES—smaller, containerized units deployable by standard freight or even airlift—offers granular flexibility. These interoperable "energy pallets" can be stacked to scale capacity up or down rapidly, ideal for urban centers with space constraints or remote disaster zones inaccessible to heavy semi-trucks.

## KEY CHALLENGES FOR MES APPLICATIONS

Despite the transformative potential of MES, its widespread deployment faces a confluence of technical, logistical, and regulatory challenges that must be systematically resolved.

### Optimization and Modeling Complexity

Scheduling and routing MES during an extreme event is an intrinsically complex, real-time optimization challenge.[5] Effective MES response to temporary large events or sudden power outages requires a novel service restoration method that employs a joint robust optimization framework. This model must simultaneously coordinate the scheduling of the islanding power supply, the dynamic movement and charging/discharging of the MES fleet, and the deployment of power line repair crews.

Furthermore, the complexity is compounded by the need to incorporate uncertainties (such as variable load and battery degradation) while handling a considerable quantity of integer decision variables. Particularly, scheduling must account for real-time infrastructure damage, utilizing complex models like the Davidson-WebertAkcelik traffic impedance function to analyze roadway conditions and accurately model travel times under extreme event scenarios.

### Operational and Interoperability Challenges

Deployment of MES is fundamentally a logistical challenge that extends beyond energy storage itself. Mobilizing and operating MES requires resolving significant operational considerations related to disconnecting the battery from its typical daily use, overcoming deployment logistics, and ensuring proper matching of system capability with specific emergency needs. In addition, the process of rapidly interconnecting a mobile asset to a damaged distribution system is complex. Challenges include securing expedited interconnection processes, managing timelines and associated costs, and ensuring interoperability between the MES unit, on-site generators, and the facility' s load.

### Regulatory and Market Uncertainty

The policy framework governing energy storage has historically lagged behind technological advancements, creating uncertainty that hampers investment. Within international and domestic regulatory frameworks, the role and position of MES assets have often lacked the clarity provided for other core elements in the power system. This uncertainty limits the investment climate for flexible mechanisms of MES.

## PATHWAYS TO MES IMPLEMENTATION

Unlocking the value of MES requires concrete solutions and forward-looking strategies in optimization, technology, and regulation.

### Solving the Optimization Puzzle: Digital Twins and AI

The complexity of scheduling mobile assets during chaotic outage scenarios can be addressed through Artificial Intelligence (AI) and Digital Twin technologies. Future grid operators will utilize high-fidelity digital twins of the transmission and transportation networks to simulate outage scenarios in real-time. AI-driven "Joint Robust Optimization" algorithms can then dynamically route MES fleets, predicting traffic impedance and matching battery state-of-charge with critical load priorities instantaneously.

### Technological Standardization and Interoperability

To overcome operational hurdles, the industry must move toward universal interconnection standards. Future MES units should feature "plug-and-play" standardized coupling interfaces, allowing a truck from Utility A to seamlessly connect to a substation in Utility B's territory. Additionally, advancing grid-forming inverter technology is crucial, enabling MES units to black-start isolated grid sections without relying on an external voltage reference.

### Regulatory Recommendations

Defining a New Asset Class Regulatory uncertainty remains the stiffest barrier. We recommend that policymakers define MES as a distinct "Transmission and Resilience Asset" class, separate from generation or load. Regulators should introduce market mechanisms that specifically remunerate mobility and availability, not just energy delivery. This "logistical insurance premium" would incentivize investment in mobile fleets. Furthermore, emergency interconnection protocols should be established, bypassing the lengthy studies required for permanent storage installations.

## SUMMARY AND PERSPECTIVE

MES is poised to become an indispensable, strategic asset in the modern energy infrastructure. Its unparalleled capability for tactical power redistribution and resilience directly addresses the gaps created by the static nature of traditional energy storage system components. The imperative now is to transition from recognizing this technical potential to implementing the necessary policy and logistical frameworks that enable widespread integration.

From a systematic perspective, the future construction of the new power system hinges on the complementary synergy of FES, V2G, and MES, creating a robust, multi-layered energy storage system (Figure 1). The enduring significance of diversified energy storage is that it eliminates the systemic vulnerability inherent in a single-resource approach. Each technology operates with clear roles. FES systems provide the necessary bulk energy services (regional frequency regulation and market arbitrage). V2G fleets provide high-speed distributed flexibility (hyper-local stability and demand response). MES units are reserved for dynamic relocation and resilience (tactical emergency deployment). This synergy drives sophisticated integrated energy management solutions that optimize resource use locationally and temporally.

The deployment of hybrid energy storage systems, combining technologies with complementary characteristics, inherently enhances overall system performance and stability. This layered approach ensures that the grid can simultaneously address bulk capacity, distributed flexibility, and dynamic relocation needs, maximizing resilience against both market volatility and catastrophic physical failure.

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## DECLARATION OF INTERESTS

The authors declare no competing interests.