Advanced Technologies Journal of University of Benghazi (ATJOUB)

ATJOUB (2026) 1 (1), DOI:
Perspective Article – System Engineering

A Philosophical Systems Engineering Perspective of Energy Storage for Electric Grids

Paulo Ribeiro[1], IEEE Life Fellow

[1]Federal University of Itajubá, Itajubá, Minas Gerais, Brazil.

Received: 26/12/2025, Revised: 28/12/2025, Accepted:31/12/2025, Available Online: 1/1/2026.

Abstract-

Energy storage has become an essential enabler of resilience, stability, and flexibility in today's electric grids. While standardized by some nominal measures, such as power capacity, energy density, and cost, the advanced storage technologies paved the way for wider requirements of system engineering that goes beyond their technical performance. This paper introduces a philosophical system engineering perspective of energy storage, viewing it as an approach of shaping time within complex power system architectures rather than simply storing energy. Relying on practical experience from large-scale military and utility applications, the analysis emphasizes lifecycle, integration, interoperability, degradation, and end-of-life management as major determiners of storage value. It is stated that no single storage technology can address the diverse requirements of the energy transition. Instead, future electric grids must rely on carefully engineered portfolios of complementary storage technologies, designed using systems engineering principles. The paper concludes that the primary challenge of energy storage is architectural rather than technological, requiring grids to be designed with temporal intelligence to balance immediacy, reliability, resilience, and long-term sustainability.

Keywords: Philosophical perspective; System Engineering; Energy Storage; Flywheels; Batteries.

1 - Introduction

Energy storage has long fascinated me, not only as an engineer who has worked with military and utility applications (with superconducting magnetic energy storage (SMES), Flywheels, and Batteries), but also as someone intrigued by its deeper meaning within the electric grid .

Storage sits at the intersection of physics, technology, and philosophy: it is where potential becomes purpose, where time itself becomes a resource to be shaped, delayed, or released.

From a practical short-term standpoint, energy storage has evolved from simple peak shaving and shifting to an essential enabler of grid flexibility, supporting stability, inertial response, renewable generation smoothing, and a wide range of ancillary services.

In transmission stages, it improves security and reliability, whereas in distribution systems, it supports resilience, congestion management, and hosting capacities of renewable resources.

Beyond its technical functions, a system engineering change exists, to recognize the energy storage not only as standalone source, but also as a dynamically active component within a complex ecosystem of electric grids. Its true value rooted from lifecycle thinking, design, integration, operation, degradation, and eventual repurpose. Only through this integrated view, the genuine contributions of energy storage to sustainability and grid integrity can be appreciated.

Advanced technologies such as High Temperature Superconducting Magnetic Energy Storage, Advanced Flywheels, Batteries, Liquid Air, Pumped Hydro, and the like, have to be assessed from a system engineering perspective. Figure 1 demonstrates a SE model development perspective [1].

In future, I hope to explore these layers, from technology families (electrochemical, mechanical, electromagnetic) to their philosophical and intrinsic implications, looking forward how storage connects the physical and temporal power systems' dimensions.

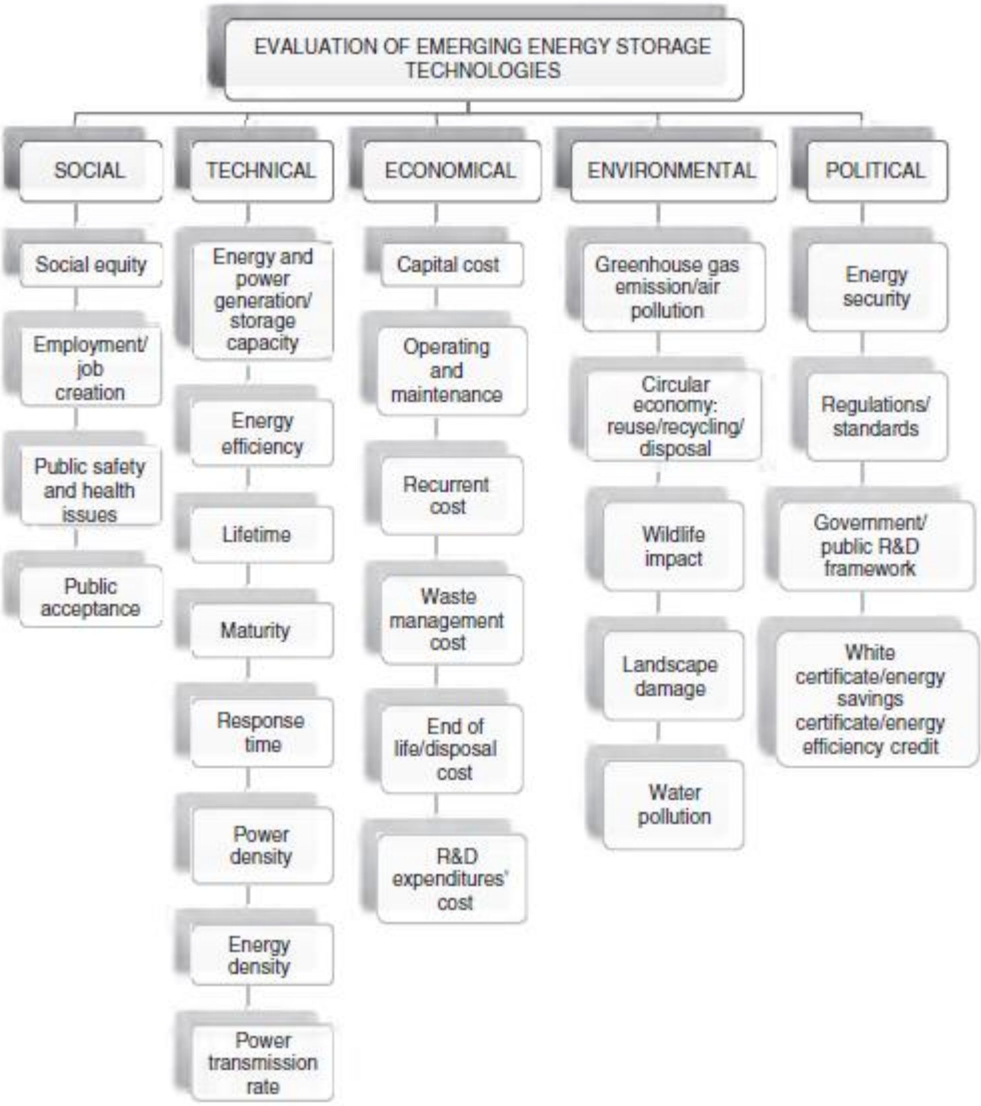

Fig. 1- Model Development Perspectives [1].

Energy storage keeps challenges in order to rethink what it means to design for time per se. In an age where immediacy predominates, storage includes patience, the engineering of delay as an action of wisdom. By system engineering discipline, storage can be perceived, not only as equipment, but also as balance discipline between present requirement and future needs, between transient event and surviving resilience.

The next sections discuss how such a perspective can illuminate both our grids and our thinking about energy, time, and purpose [2-10].

2 - A Philosophical Perspective of Energy Storage: Flywheels

Although these is a considerable development in the many ways of energy storage systems, flywheels stand salient for their elegant simplicity, where energy is neither held on chemistry nor in magnetism, but in motion itself. Through converting electrical energy into rotational kinetic energy, they feature instantaneous responses, higher efficiency, and virtually unlimited cycling capability.

In advanced processes, such as ship propulsion and electromagnetic launchers, flywheels offer mechanical inertia that can be harnessed for precision control and bridging physical and temporal power delivery dimensions.

One of the most complex projects I worked on was the Electromagnetic Aircraft Launch System (EMALS) for naval aircraft. My role was quite specific: to define the interface between the ship's prime power source (and the power quality impact) and the energy storage system based on a bank of flywheels. This was the project in which I learned a great deal of systems engineering that ensured proper performance, safety, and interoperability .

There is a special satisfaction in moving from the Preliminary Design Reviews to system testing, watching ideas become hardware and equations turn into motion. Yet it is also humbling to realize that your contribution is only one small part of a much larger symphony, one that succeeds only because others, across different subsystems, have performed their roles with the same precision, and because every interface has functioned as intended, ensuring seamless interoperability throughout the entire system.

As I look at the challenges of the electric grid of the future, I see flywheels as one of the technologies capable of making a profound difference. The EMALS, now operating on the USS Gerald R. Ford, delivers hundreds of megawatts within a few seconds through a linear induction motor to launch a single aircraft, a striking demonstration of controlled, high-power bursts .(*)

This same principle, scaled and adapted, could serve electric networks to provide short, powerful injections of energy that can help stabilize frequency and voltage during critical transitions.

In many ways, the story of energy storage with flywheels mirrors the story of the grid itself, both are about controlling momentum, storing potential, and releasing it at the right time.

3 - Batteries: From Burden to Backbone?

For much of modern electrical engineering history, batteries were considered as the Achilles' heel of power systems - fragile, expensive, short-lived, and unreliable. They powered flashlights, radios, and early portable electronics, but few people imagined they would one day support electric grids.

In just a few decades, batteries have undergone a deep diversion, not only in chemistry and performance, but also in meaning. Once a peripheral technology, they now rest at the core of debates on decarbonization, system resilience, renewables, mobility, autonomy, and geopolitical supply chains. What was once a constraint has become a strategic cooperator.

(*) According to the manufacturer General Atomics Electromagnetic Systems, the EMALS aboard Gerald R. Ford "successfully performed as designed" during the ship's Full Ship Shock Trials in mid-2021. The system successfully achieved and exceeded the Navy's target of 8,000 launches and recoveries.

Nowadays, batteries are being used to participate in frequency stability, assist share of renewables, handle disturbances, shift load, electrify transport, and enable fully digitalized control of power systems. But their rise also reveals a deeper truth, energy storage is not only about containing electrons, it is about shaping time as well. Batteries do not store energy as much as they decide when energy is the highest priority.

A landmark in battery storage history was the 10 MW / 40 MWh Chino project by Southern California Edison, commissioned in 1988 as part of an EPRI demonstration. Regarded as the first truly utility-scale battery energy storage systems (BESS), it proved that batteries could operate at grid level and helped lay the groundwork for today's large-scale storage formation. I personally later applied its interface topology when defining the coupling (Power Conditioning System) for the BWXT 30 MW / 60 seconds SMES project in 1996.

Afterward, BESS deployment has been rapidly accelerated. In Southern California alone, installations have exceeded 12 GW, while global installed capacity now exceeds 45 GW. What began as experimental demonstrations has evolved into a fundamental component of modern grid infrastructure. This surge highlights not just the progress of battery technology but the growing urgency to tackle challenges in control, integration, lifecycle management, and system interoperability.

From a systems engineering perspective, the value of a battery cannot be measured by energy and power density or cost per kWh alone. It must be understood through lifecycle thinking, extraction of minerals, manufacturing, integration, monitoring, safety, degradation, second life, recycling, and repurposing. A battery is only as useful as the ecosystem it belongs to. That is why batteries must also be examined in contrast to other time-shifting technologies: flywheels, pumped hydro, compressed air, hydrogen-based systems, and superconducting magnetic energy storage (SMES). Each stores time in different physical states, motion, magnetism, gravity, chemistry, or pressure. Each answers a different question about power, duration, and response. (For a summary of commercially available battery technologies - see below Table.1).

Table.1 Battery Technologies Compariosn

Battery Type	Chemistry / Variant	Typical Application	Key Advantages	Main Limitations
Lithium-ion (Li-ion)	LFP, NMC, NCA, LMO, LTO	EVs, grid storage, consumer electronics	High energy density, high round-trip efficiency, fast response	Thermal runaway risk, aging, cost of materials
Lead-Acid	Flooded, AGM, Gel	Backup power, UPS, telecom, small storage	Low cost, mature tech, recyclable	Low energy density, shorter cycle life
Sodium-Sulfur (NaS)	Molten salt	Grid-scale storage, peak shaving	Long discharge duration, high energy density	High operating temperature (~300 °C), safety concerns
Sodium-Nickel-Chloride (Zebra)	Molten salt	Transport, off-grid	Good safety, high operating temperature tolerance	Needs heat, slower response
Nickel-Cadmium (NiCd)	Alkaline	Aviation, industrial backup	Long life, wide temperature range	Cadmium toxicity, memory effect
Nickel-Metal Hydride (NiMH)	Alkaline	Hybrid vehicles, portable devices	Safer than Li-ion, good cycle life	Lower energy density, self-discharge
Flow Batteries	Vanadium Redox, Zn-Br, Fe-Cr	Long-duration grid storage	Decoupled power & energy, deep cycling	Lower power density, higher CapEx
Zinc-Air / Metal-Air	Rechargeable or primary	Remote power, emerging grid tech	Very high theoretical energy density	Limited cycle life (rechargeable versions still developing)

4- The Challenges Ahead

Despite extraordinary progress, the future of battery technology faces several unresolved systemic challenges:

- Material constraints
- End-of-life management

- Safety and urban deployment
- Standardization and interoperability
- Grid integration at scale
- Chemistry vs. architecture

5- Conclusion

Batteries alone will not solve the energy transition. Their success depends on how wisely they are embedded within system architectures that respect physical limits, application-specific roles, lifecycle constraints, and, above all, the engineering of time. Treated separately, batteries risk becoming yet further technological burden; understood systemically, they become powerful instruments of balance and flexibility. This system engineering perspective clearly stated that energy storage must be re-evaluated, not merely by its nominal values, such as power ratings, cost, and energy density, but also by how it reacts with network ecosystem, variability in generation, power system dynamics, control strategies, degradation mechanism, safety provisions, and terminal tracks.

The energy transition of energy thus requires pluralism rather than exclusiveness. Batteries must coexist and cooperate with other time-shifting technologies, flywheels, pumped hydro, SMES, compressed air, hydrogen, each storing energy in different physical states and answering different temporal questions of the grid.

Ultimately, the true challenge is not technological but architectural. The energy transition demands that we design grids not just for capacity and efficiency, but for temporal intelligence, the ability to decide when energy matters most. Systems engineering provides the discipline to see storage not as equipment, but as an integral element in shaping resilient, sustainable, and meaningful power systems for the long term.

Author's short bio: Paulo F. Ribeiro received the B.S.E.E. degree from the Federal University of Pernambuco, Recife, Brazil, and the Ph.D. degree from the University of Manchester, Manchester, UK. He was a Research Fellow with the NASA Glenn Research Center, Cleveland, USA, Electric Power Research Institute (EPRI), Palo Alto, USA, and Erskine Fellow with the University of Canterbury, Christchurch, New Zealand, and with the Brazilian Institute of Electric Energy (INERGE), Brazil. He is a Life Fellow of IEEE. He is a Full Professor with the Federal University of Itajubá, Itajubá, Minas Gerais, Brazil.

References

[1] “Future-Oriented Technology Assessment - A Manager’s Guide with Case Applications, Edited by Haydar Yalçın and Tugrul U. Daim, IEEE Press Series on Technology Management, Innovation, and Leadership, 2025.

[2] Superconducting power energy storage delivery systems for transmission and distribution applications, SF Kral, M Aslam, PF Ribeiro, X Huang, M Xu, American Power Conference, Chicago, 1996.

[3] Superconducting magnetic energy storage for power system dynamics and voltage stability, PF Ribeiro, G Neeley, S Kral, 1996, IEEE Meeting Presentation, 1996.

[4] Transient modeling and simulation of a SMES coil and the power electronics interface, AB Arsoy, Z Wang, Y Liu, PF Ribeiro, IEEE Transactions on Applied Superconductivity 9 (4), 4715-4724, 1999.

[5] EMALS Preliminary Design Review - Prime Power Interface to Flywheels Energy Storage / Power Quality, Paulo F Ribeiro, November 14-16, 2000, San Diego, California.

[6] Energy storage systems for advanced power applications, PF Ribeiro, BK Johnson, ML Crow, A Arsoy, Y Liu, Proceedings of the IEEE 89 (12), 1744-1756, 2001

[7] Interaction between a superconducting coil and the power electronics interface on a 100 MJ SMES system, M Steurer, CA Luongo, PR Ribeiro, S Eckroad IEEE transactions on applied superconductivity 13 (2), 1806-1809, 2003.

[8] Detailed modeling of superconducting magnetic energy storage (SMES) system, L Chen, Y Liu, AB Arsoy, PF Ribeiro, M Steurer, MR Iravani, IEEE Transactions on Power Delivery 21 (2), 699-710, 2006.

[9] Energy Storage at Different Voltage Levels: Technology, integration, and market aspects, by Ahmed F. Zobaa, Paulo F. Ribeiro, Shady H.E. Abdel Aleem, IET, 2018.

[10] Distributed Energy Storage in Urban Smart Grids, Paulo F. Ribeiro; Rafael S. Salles, IET, Published in 2023.

Cite this article as: Ribeiro, P. . (2026). A Philosophical Systems Engineering Perspective of Energy Storage for Electric Grids. Advanced Technologies Journal of University of Benghazi, 1(1), 5–14. Retrieved from https://journals.uob.edu.ly/index.php/ATJUOB/article/view/7511