2023 August

# Synergistic Solutions for Energy Storage Optimization in Microgrid Systems: The Struggle Against Entropy

Samson Bienstock

*Written for Educational Purposes*

**ABSTRACT**

Of the numerous science-based concepts a student faces within a standard high-school curriculum, the Second Law of Thermodynamics is perhaps the most intuitive. A hot cup of coffee cools and a droplet of food coloring disperses—intuitions formalized by: $\Delta S \geq 0$, stating that the randomness of any system invariably increases. This fundamental law of the universe poses a challenge to energy storage system designers who seek to achieve for our electricity supply what refrigeration once achieved for our food supply. The inefficiency inherent in energy storage systems stems from their need to counteract the natural tendency of energy to dissipate. Addressing this challenge holds the potential to usher in a new epoch of power generation systems, and as a means to this end, the Microgrid (MG) concept has emerged. This novel strategy for decentralized electricity distribution can fulfill modern energy needs beyond the capabilities of the fossil-fuel-dependent classical grid. This paper aims to interlink modern research on intelligent energy storage system design within MG systems. While we cannot rewrite the laws of physics, we can orchestrate a harmonious integration of energy storage devices through the pursuit of better storage media, control strategies, and configurations.

## 1. Introduction

Cities worldwide rely on the macro grid, an energy distribution system designed for the sole purpose of transmitting fossil-fuel-derived power to end-users. With a unidirectional and inefficient design, the macro grid lacks effective pathways for integrating modern solar and wind generators. And while these renewable energy (RE) systems become more techno-economically viable, the fossil-fuel reserves dwindle, leading to geopolitical conflict on top of adding to the often-neglected pollution-layer blanketing the Earth.

A new era of innovation has arrived. August 16th, 2023, marks the one-year anniversary of the passing of the IRA, a legislation that has skyrocketed domestic manufacturing and sale of solar panels and wind turbines. This surge has indicated a pivotal step toward a sustainable future. However, the seamless integration of RE-based power systems is held back by the obvious issue of meteorological variability and the resulting intermittency of electricity generation. For its ability to solve this challenge head-on, Energy storage system (ESS) attracts unprecedented research attention as the enabler of a decarbonized future.

In parallel with the clean-energy revolution is the digital transformation. This global shift, considered the fourth phase of industrial evolution and coined "Industry 4.0", is marked by extensive connectivity, unprecedented data exchange, the rise of "smart" systems, and artificial intelligence. Within this context, the paradigm of decentralized electricity presents a poetic merge of the pressing climate crisis with the era of smartification.

To ensure precision, context, and standardization, a functional definition of a microgrid is formulated: Microgrid (MG or μGrid) is a locally based distributed power system typically in the kilowatt range that consists of distributed generators, energy management system, storage apparatus, user loads, and an elective link to the macro grid. The localized configuration of μGrid design is the factor that contributes to its many benefits such as flexibility, resilience, and sustainability.

Energy storage systems stand as a base of successful microgrids [64]. A methodical analysis of an amalgamation of studies concerning Energy Storage Systems (ESSs) in μGrids culminated in this paper. Among the works reviewed, a catalog of prevalent themes has been assembled and is delineated below. The ensuing sections encompass three core topics: 2. Energy Storage Technologies, 3. ESS Control Strategies, 4. ESS Configurations and 5. Conclusions.

## 2. Energy Storage System Technologies

Snow-skiing is a fascinating sport and an enjoyable pastime. An on-mountain-thought-experimenter might consider themself a human-battery. Consider first "charging mode", where gravitational potential energy enters the human-system through the work done by the chairlift. The downhill incline of the slope serves as "discharge-mode" where the potential energy converts to blissful kinetic energy. This thought exercise hints at pumped hydro storage, expounded in section 2.4.

In μGrid applications, a plethora of storage mediums are considered by researchers and engineers trying to control the flow of energy. Review paper [1] provided a starting point for my exploration, outlining types of ESS configurations and mediums for MG applications. Another overview [2] examined MG architectures wholistically, proved their ability to improve power quality, and highlighted the importance of energy storage. [3] Looked at the differences between grid-scale and μGrid-scale energy storage and emphasized the trend of μGrid as the modern energy paradigm.

From here, I dove into the various aspects of microgrid energy storage. Originally, I intended on studying the different technologies that existed only, but it quickly became apparent that an energy storage system is only as good as its control method, configuration, sizing, and monitoring. Thus, there became more than one section in this paper. However, the remainder of this section provides a concise explanation of the top energy storage technologies as well as an overview of their suitability for MG system applications.

### 2.1. Electromechanical Energy Storage Systems

Both conventional rechargeable batteries and flow batteries (FBs) populate the spectrum of electromechanical storage technologies, the most expansive realm of energy storage devices. Among these, Battery Energy Storage Systems (BESSs) have emerged as a pivotal solution in overcoming the intermittency of renewable energy sources (RES). Their significance arises from their operational foundation rooted in electrochemical reactions. As the name suggests, these reactions control the conversion between electrical and chemical energy where, at their core, anode and cathode materials serve as distinct sites for oxidation and reduction. Anodic oxidation reactions give electrons to the external circuit, powering loads and signifying discharge. An accrued surplus of positively charged ions (cations) simultaneously migrates toward the cathode through an electrolyte, which allows for ion movement but restricts electron flow. In charging, cations regain electrons from an external circuit, migrating back to the anode for re-intercalation in the layers of the material's atomic structure.

One pressing challenge within the field of batteries is known as state-of-X determination, which proves to be significantly more intricate than gauging the gasoline remaining in a combustion vehicle's tank. In both state-of-charge (SoC) and state-of-health (SoH) estimation, researchers have explored innovative methodologies which focus on both model-based and data-driven approaches. These techniques include neural networks, Digital Twin technology, and real-world data, and aim to enhance battery system performances [85] [86].

The field of BESS applications within MG is most rich with research. [30] offers a vital overview of BESS performance in μGrids. [27] Hails lithium-ion as the optimal choice for most scenarios. Optimizing control strategies incorporating BESS is explored in [28], [29], [32], [33], [36] and [38], while [37] examines voltage and frequency regulation using BESS and dynamic communication strategies. Addressing economic implications, [34] and [35] seek algorithms for determining optimal BESS capacity, concluding that ultimately, the diverse nature of ESS mediums complicate the creation of a comprehensive sizing model. Popular electrolyte configurations are presented below:

#### 2.1.1. Lead-Acid Batteries

Lead-acid (PbA, LA) batteries have a long-standing history as the conventional choice for electric power system applications, dating back to 1860 [40]. Despite their maturity and economic advantages, LA bears the drawback of a relatively short lifespan of about 500-1000 cycles. In noteworthy study [31], LA storage plays a role in a wind-solar-diesel-BESS system. The study optimizes LA storage but highlights the significant limitations posed by the short lifespan for PbA battery applications.

#### 2.1.2. Lithium-ion Batteries

Lithium metal stands out as a battery anode material due to its lightweight, high voltage, and impressive conductivity [40]. The comparison drawn in [27] between lead-acid and lithium-ion batteries distinctly favors the Li-ion model, indicating a lower LCOE.

However, literature does outline several degradation concerns [28]. These problems include the unavoidable development of a solid electrolyte interface (SEI) layer, posing a challenge that modern chemical engineering struggles to surmount, alongside the loss of active materials and occurrence of lithium plating.

#### 2.1.3. Flow Batteries

In the redox reaction of flow batteries (FBs, RFBs), electricity is similarly generated from the redox reaction between electrolytes separated by an ion-selective membrane. However, since the electrolytes are stored in separated external tanks, the energy stored is decoupled from the power generation capacity [1] [59]. This separation allows for independent scaling of energy capacity and power capacity, hinting at more flexibility in future battery design. The emergence of FBs as an energy storage solution with potential can be seen by the success of Iron-Air battery startup Form Energy as well as ESS Inc.

[41] Conducts analysis of the performance of Vanadium RFBs in microgrids and finds them highly suitable for large-scale applications. [42] Compares LA, Li-ion, and RFB, noting that flow batteries live in a category of their own due to the altered electrochemical arrangement.

#### 2.1.4. Emerging Electrochemical Batteries

Lithium-Iron-Phosphate ($LiFePO_4$), sodium-sulfur (NaS), solid-state, and metal-air batteries are all recognized in the literature as emerging storage technologies warranting further research and development. The ability to enhance energy density and cycle life will facilitate their integration into microgrid energy storage applications.

### 2.2. Superconducting Magnetic Energy Storage Systems

This storage system represents a superior feat in the context of overcoming of the second law of thermodynamics. In superconducting storage, energy is stored in the magnetic fields generated by unhindered current flow through superconducting coils. These materials possess a unique quality in that they exhibit near-zero electrical resistivity at a specific temperature. Refer to Figure 1 for visual representation:

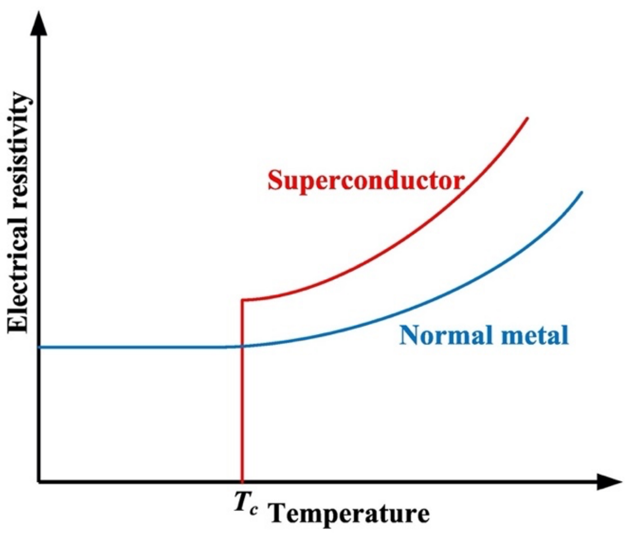


*Figure 1: Superconducting versus Non-Superconducting Material Behavior*

Hence, an advantage of a Superconducting Magnetic Energy Storage System (SMESS) is its exceptional efficiency levels, reaching up to 97% [1] [47].

Another advantage comes from the high discharge-rate and power level. These merits align notably with the vulnerabilities of BESS [47] [50]. Reference [50] lead to discovery of a challenge then studied in [52], which addresses SMES design intricacies through the application of a fuzzy logic controller (FLC). This controller adeptly optimizes the charge and discharge power flows of the generator and storage system(s).

In SMES, geometric configurations include the Solenoid and Toroid design, which have differences in their shape, magnetic field configuration, and application suitability. The analysis of their suitability for application is left as a proposed further area of research.

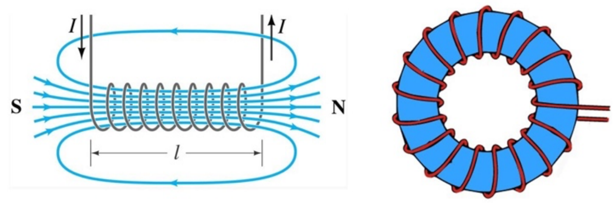


*Figure 2: Solenoid (left) versus Toroid (right) geometries for inductance calculation in SMES*

### 2.3. Flywheel Energy Storage Systems

The flywheel energy storage system (FESS) stores kinetic energy in the revolution of a massive disk. The enticing benefits of FESS lie in its outstanding demand response agility, as discussed in [55]. The study highlights that FESS, akin to its cousin, SMES, boasts high power density and rapid reaction time, suiting these technologies more for the sprint than the marathon. References [53] and [56] use MATLAB/Simulink to showcase the efficacy of MG models that include FESS. [54] Demonstrates FESS as a solution to off-grid MG applications, showcasing FESS as a formidable contender.

The primary inhibitor to flywheel energy storage (FES) is energy loss due to friction, which can be mitigated by magnetic bearings. Researchers have investigated both active magnetic and passive magnetic bearing technologies for creating a stable levitation platform for the flywheel's uninhibited rotation.

### 2.4. Pumped Hydro Storage Systems

Pumped hydro takes the lead as the world's most widely adopted storage solution. In pumped hydro storage systems (PHSS), charging and discharge entail the movement of water between upper and lower reservoirs, leveraging the cost-effective capture of gravitational potential energy.

A glimpse into the efficacy of this medium is offered by [65], which describes a MG system in rural Columbia in which solar PV production is paired with a micro-PHSS. Further examinations like [59] and [62] explore harmonious relationships between BESS and PHS. A distinction is drawn between storage device and storage system, with PHS being the stalwart of the latter. [64] unveils the concept of micro-PHS as a promising solution for reliable microgrid operation. [61] shows the suitability of PHS for a wind energy-based islanded MG, comparing PHS to hydrogen energy storage.

A particularly obvious drawback of PHS is constrained site selection. This limitation aligns with the theme of μGrid case-by-case customizability being a necessary feature in future designs.

**2.5. Thermal Energy Storage Systems**

In theory, thermal energy storage system (TESS) presents a natural solution, where there is huge demand for thermal energy and plenty of thermal energy available. Further, an advantage of TESS is the simplicity of material requirements; Systems can be built of simple carbon-based materials with desirable specific heat capacity. However, in practical implementations, heat transfer management encounters challenges that stem from the laws of thermal-fluid systems. Ensuring effective storage and control of thermal energy systems necessitates overcoming the tendency of heat to dissipate (a fancy way of saying insulation).

[66] Serves as a detailed overview, leading to the conclusion that TES obviates fossil fuel burning. Two distinct types of TES are described: sensible and latent storage. Charge and discharge of the former involves a change in temperature, while for the latter, energy is stored and released through an isothermal phase-change of the material.

In the literature, microgrid applications are overshadowed by concentrated solar panel (CSP), nuclear reactor, and combined heating and power (CHP) applications. For microgrid TES, applications are limited compared to other technologies. In the existing research: [68] and [70] coordinate BESS and TES storage in their optimization studies of μGrid. [69] conducts a techno-economic feasibility study on CSP in a hybrid energy system which leverages low-cost thermal storage. Finally, [71] eventually finds that TES applications to grid systems are limited. Startup-companies like Antora Energy are at the cutting-edge of this technology space, aiming to electrify heavy industry for zero-carbon heat and power.

**2.6. Compressed Air Energy Storage Systems**

Compressed Air Energy Storage (CAES) exists among those technologies considered as having reached technical maturity [72]. CAES is a large-scale storage solution with efficiencies and capital costs comparable to pumped hydro storage. CAES operation has similarities to the Natural Gas Power Plant, with the notable difference that the compression and expansion cycles are decoupled to achieve the desired energy buffer.

[73] Investigates the potential of a novel variation: Adiabatic CAES (A-CAES), which uses TES to store and reuse heat generated in compression. Several Megawatt scale A-CAES plants were constructed and are in the experimental stage around the world. Though academic works point to the potential benefits of this technology, it suffers from few studies that focus on the modeling of CAES systems. One such study, [74], concludes CAES is a simple and efficient way of improving the integration of fluctuating Wind power into the electricity supply.

### 2.7. Supercapacitor Energy Storage Systems

Supercapacitor (SCs) storage devices store electrical energy in an electrostatic field between two charged electrodes. The lack of chemical reactions allows for rapid charge and discharge cycles. This technology therefore exhibits high power density and can be charged and discharged without degradation. Most modern SC research aims to improve the energy density by using high-surface area materials [1]. [75] presents an optimized control study for SCES. SCESS are suitable for combined applications with BESS.

### 2.8. Hybrid Energy Storage Systems

Presently, existing ESTs (energy storage technologies) struggle with the spectrum of frequency and voltage needs of power networks. Hybrid Energy Storage Systems (HESS) can exploit the advantages of multiple energy storage mediums, acting as a holistic remedy for better execution of various objectives, including RES integration, peak shaving, and power quality [82].

For these systems, control and configuration play a vital role [76]. A hybrid electric-thermal energy storage has been proposed as an optimal solution, which greatly improved energy efficiency in [78]. [77] Utilizes novel algorithms to maximize solar and wind penetration using various types of HESS. Other popular configurations often cited are battery-flywheel, batter-battery, and battery-SMES.

## 3. Energy Management System Control

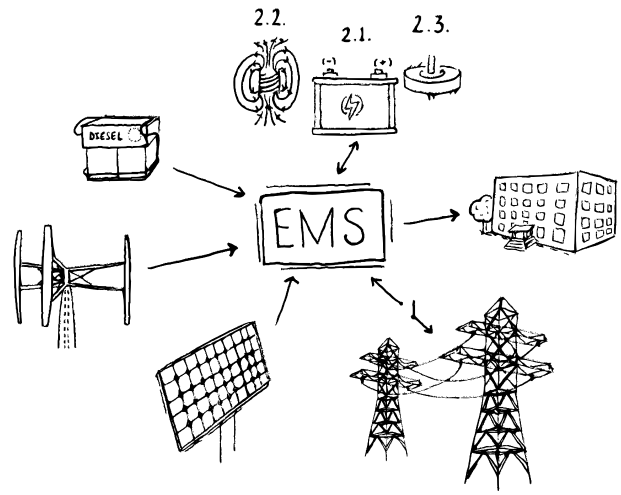


*Figure 3: Energy Router Schematic in Microgrid*

One cannot overstate the importance of properly routing power flow in a microgrid—a truth applicable regardless of generator, storage, and load architecture. The most crucial feature of an MG is its capability to behave as a coordinated module [5]. With advanced monitoring, forecasting, and proper control, the EMS can implement ESS applications such as load leveling, peak shaving, uninterruptable power supply, and energy arbitrage.

The contemporary EMS has the primary goal of meeting complex demand with available generation from renewable sources, stored energy, and grid power, termed power balancing. Studies [5]-[10] highlight the importance of EMS control-strategy-optimization in the context of MG applications. There's a strong indication that Hybrid energy storage systems and community-level ESS solutions are emerging as key trends being investigated in the field of EMS.

### 3.1. Demand Management: Load Leveling and Peak Shaving

In macro grid, peak power plants are built solely to serve in times of peak demand—an expensive and inefficient approach. The MG concept's localized flexibility enables a more efficient power system. In this network, successful control algorithms can yield substantial energy cost savings for prosumers who both contribute and consume from the grid. [17] Offers a stark overview of microgrid control, detailing primary, secondary, and tertiary control roles, and highlighting challenges in distributed energy resource (DER) integration, underscoring the need for advanced control. [18]-[20] present novel algorithms, models, and optimization methods for control strategy experimentation aimed at achieving the benefits of load leveling and peak shaving in μGrids.

Load leveling stores excess energy during low demand and releases it during peaks, while peak shaving shifts energy-consuming activities to off-peak times. Batteries discharge to achieve appropriate voltage and frequency regulation. When the grid's power surpasses power demanded, frequency rises akin to how your legs spin faster upon easing the gear of the bicycle. In electrical systems, higher frequency indicates generation excess, and thus batteries should be charged. This high-level explanation underpins an EMS's power balancing mechanism.

### 3.2. Renewable Energy Integration

As mentioned, ESSs and EMSs aim to realize high RE penetration in power systems. [21] optimizes net present cost for maximum RE integration using thermal storage and fuel cells. The results of the optimization are sizeable, achieving a 24% carbon emissions reduction by optimizing EMS control. [22] Examines advanced strategies for energy management of a solar, wind, and tidal-driven DC microgrid.

### 3.3. Uninterruptable Power Supply

In a world where electricity remains a luxury for approximately 1 billion people, the concept of microgrids provides transformative innovation opportunity: to achieve power resilience at the local level without the prohibitive costs associated with constructing expensive grid infrastructure. The μGrid has an ability to ensure power quality and uninterruptable power supply (UPS). In [23] research on UPS explores control strategies designed for a DC microgrid with a focus on achieving reliability in both grid-connected and islanded modes. The authors underscored the critical role of power electronic converters in enhancing the overall performance of ESSs. [24] proves the significance of optimizing capacity (ESS sizing) to achieve reliable power output, reduce wind energy losses, and enhance economic viability of well-designed energy storage configurations.

### 3.4. Energy Arbitrage

Arbitrage, in the context of energy systems, is the practice of capitalizing on price differentials of electricity at various points and time. [25] elucidates the multifaceted strategies that ESS in MGs can employ to achieve energy arbitrage. Here, the strategy hinges on skillfully navigating RE behavior and executing an arbitrage maneuver through a peer-to-peer energy trading algorithm, securing increased profitability while contributing to stability and efficiency.

### 3.5. Control Schemes

Schemes of distributed control and centralized control dictate how control decisions are made within a system, bearing importance to MG design. These control schemes are highly related to distributed versus aggregated configuration (the physical organization) of MG components which is discussed in the subsequent section.

In a distributed control system, decision-making authority is dispersed among nodes within a network, which can all make decisions based on local information. This scheme provides resilience and flexibility but incurs more complex management. In centralized control systems, decision-making authority is concentrated at a central entity which makes decisions for the entire system based on global information.

## 4. Aggregated Versus Distributed ESS Configurations

An ESS can be inserted in many places in the microgrid depending on its foreseen purpose. The two different configurations of ESSs in a renewable μGrid are aggregated ESS and distributed ESS, architectures who partially determine the performance and application characteristics of the entire system.

Aggregated ESS consists of a large energy storage facility with dedicated housing in the microgrid. It must achieve both have huge energy capacity and high-power output ability [84].

For the distributed configuration, ESS units are directly coupled to individual DERs with various interfaces. An advantage of the separate connection lies in that power electronics can be optimized for each pair to reduce costs and maximize efficiency. A disadvantage is that the power produced unavoidably increases power flow complexity, which may result in more losses. In future MGs, a mixture of aggregated and distributed ESS might be a preferable solution [3].

## 5. Themes and Analysis

Within the probed literature, one prevailing theme encapsulates the idea that HESSs possess a unique ability to harness and amplify the benefits of different ESTs. This ability might effectively mitigate the inherent weaknesses that individual ESTs exhibit. The most common example is the combination of technology which excels in rapid bursts of power with another that offers prolonged energy delivery. If an ensemble of diverse ESTs can be realized effectively, MG systems stand to gain maximum power balancing ability from energy storage. The benefits also extend to grid stability and resilience, through creation of systems which can more dynamically adapt to complicating fluctuations in demand. Overall, the use of HESS adeptly fosters adaptability and resilience in a new energy landscape where both of those characteristics are mandatory.

A more general conclusion within the realm of energy storage innovation is as follows: the research devoted to developing better media for energy storage may entail dedicating years to achieve incremental enhancements of battery performance. In contrast, an alternative avenue involves investing in refining a control algorithm. This literature review concludes that the endeavor of control optimization has the potential to unlock the most rapid enhancements in ESS performance, in contrast to other research directions. This finding reveals the accelerated return-on-investment in topology and control optimization. Succinctly, while the physical advancements in energy storage technologies (ESTs) occur slowly, the optimization of resource utilization can occur much more rapidly.

## References

[1] Faisal, M., Hannan, M. A., Ker, P. J., Hussain, A., Mansor, M. B., and Blaabjerg, F. Review of Energy Storage System Technologies in Microgrid Applications: Issues and Challenges. IEEE Access 6 (May 2018): 35143-35164. doi: 10.1109/ACCESS.2018.2841407.

[2] Lubna Mariam, Malabika Basu, and Michael F. Conlon. Microgrid: Architecture, Policy and Future Trends. Renewable and Sustainable Energy Reviews 64 (October 2016): 477-489. ISSN 1364-0321. https://doi.org/10.1016/j.rser.2016.06.037.(https://www.sciencedirect.com/science/article/pii/S1364032116302635)

[3] Xingguo Tan, Qingmin Li, and Hui Wang. Advances and Trends of Energy Storage Technology in Microgrid. International Journal of Electrical Power & Energy Systems 44, no. 1 (2013): 179-191. ISSN 0142-0615. https://doi.org/10.1016/j.ijepes.2012.07.015.

[4] Al-Saadi, Mudhafar, Maher Al-Greer, and Michael Short. Strategies for Controlling Microgrid Networks with Energy Storage Systems: A Review. Energies 14, no. 21 (November 2021): 7234. https://doi.org/10.3390/en14217234.

[5] Chaudhary, G., Lamb, J. J., Burheim, O. S., & Austbø, B. (2021). Review of Energy Storage and Energy Management System Control Strategies in Microgrids. Energies, 14(16), 4929. https://doi.org/10.3390/en14164929.

[6] Kandari, R., Neeraj, N., & Micallef, A. (2023). Review on Recent Strategies for Integrating Energy Storage Systems in Microgrids. Energies, 16(1), 317. https://doi.org/10.3390/en16010317.

[7] Choudhury, S. (2022). Review of energy storage system technologies integration to microgrid: Types, control strategies, issues, and future prospects. Journal of Energy Storage, 48, 103966. https://doi.org/10.1016/j.est.2022.103966.

[8] Benavides, D., Arévalo, P., Gonzalez, L. G., & Aguado, J. A. (2020). Analysis of Different Energy Storage Technologies for Microgrids Energy Management. E3S Web of Conferences, 173, 03004. https://doi.org/10.1051/e3sconf/202017303004.

[9] Wasiak, I., Pawelek, R., & Mienski, R. (2014). Energy storage application in low-voltage microgrids for energy management and power quality improvement. IET Generation, Transmission & Distribution. Advance online publication. https://doi.org/10.1049/iet-gtd.2012.0687.

[10] Pamulapati, T., Cavus, M., Odigwe, I., Allahham, A., Walker, S., & Giaouris, D. (2023). A Review of Microgrid Energy Management Strategies from the Energy Trilemma Perspective. Energies, 16(1), 289. https://doi.org/10.3390/en16010289.

[11] Katsanevakis, M., Stewart, R. A., & Lu, J. (2017). Aggregated applications and benefits of energy storage systems with application-specific control methods: A review. Renewable and Sustainable Energy Reviews, 75, 719-741. https://doi.org/10.1016/j.rser.2016.11.050.

[12] Pham, T. T., Kuo, T.-C., & Bui, D. M. (2020). Reliability evaluation of an aggregate battery energy storage system in microgrids under dynamic operation. International Journal of Electrical Power & Energy Systems, 118, 105786. https://doi.org/10.1016/j.ijepes.2019.105786.

[13] Ali, A. Y., Basit, A., Ahmad, T., Qamar, A., & Iqbal, J. (2020). Optimizing coordinated control of distributed energy storage system in microgrid to improve battery life. Computers & Electrical Engineering, 86, 106741. https://doi.org/10.1016/j.compeleceng.2020.106741.

[14] Sikorski, T., Jasiński, M., Ropuszyńska-Surma, E., Węglarz, M., Kaczorowska, D., Kostyla, P., Leonowicz, Z., Lis, R., Rezmer, J., Rojewski, W., Sobierajski, M., Szymańda, J., Bejmert, D., Janik, P., & Solak, B. (2020). A Case Study on Distributed Energy Resources and Energy-Storage Systems in a Virtual Power Plant Concept: Technical Aspects. Energies, 13(12), 3086. https://doi.org/10.3390/en13123086.

[15] Dimitrov, P., Piroddi, L., & Prandini, M. (2016). Distributed allocation of a shared energy storage system in a microgrid. In 2016 American Control Conference (ACC) (pp. 3551-3556). Boston, MA, USA. https://doi.org/10.1109/ACC.2016.7525464.

[16] Yongqiang, Z., & Tianjing, W. (2018). Comparison of centralised and distributed energy storage configuration for AC/DC hybrid microgrid. Journal of Energy (Open Access). Advance online publication. https://doi.org/10.1049/joe.2017.0649.

[17] Olivares, D. E., et al. (2014). Trends in Microgrid Control. IEEE Transactions on Smart Grid, 5(4), 1905-1919. https://doi.org/10.1109/TSG.2013.2295514.

[18] Mehrjerdi, H. (2019). Simultaneous load leveling and voltage profile improvement in distribution networks by optimal battery storage planning. Energy, 181, 916-926. https://doi.org/10.1016/j.energy.2019.06.021.

*[19] Uddin, M., Romlie, M. F., Abdullah, M. F., Tan, C., Shafiullah, G. M., & Bakar, A. H. A. (2020). A novel peak shaving algorithm for islanded microgrid using battery energy storage system. Energy, 196, 117084. https://doi.org/10.1016/j.energy.2020.117084.*

*[20] Kuźniak, R., Pawelec, A., Bartosik, A., & Pawełczyk, M. (2022). Determination of the Electricity Storage Power and Capacity for Cooperation with the Microgrid Implementing the Peak Shaving Strategy in Selected Industrial Enterprises. Energies, 15(13), 4793. https://doi.org/10.3390/en15134793.*

*[21] Tooryan, F., HassanzadehFard, H., Collins, E. R., Jin, S., & Ramezani, B. (2020). Smart integration of renewable energy resources, electrical, and thermal energy storage in microgrid applications. Energy, 212, 118716. https://doi.org/10.1016/j.energy.2020.118716.*

*[22] Soliman, M. S., Belkhier, Y., Ullah, N., Achour, A., Alharbi, Y. M., Al Alahmadi, A. A., Abeida, H., & Khraisat, Y. S. H. (2021). Supervisory energy management of a hybrid battery/PV/tidal/wind sources integrated in DC-microgrid energy storage system. Energy Reports, 7, 7728-7740. https://doi.org/10.1016/j.egyr.2021.11.056.*

*[23] Emara, D., Ezzat, M., Abdelaziz, A. Y., Mahmoud, K., Lehtonen, M., & Darwish, M. M. F. (2021). Novel Control Strategy for Enhancing Microgrid Operation Connected to Photovoltaic Generation and Energy Storage Systems. Electronics, 10(11), 1261. https://doi.org/10.3390/electronics10111261.*

*[24] Nazir, M. S., Abdalla, A. N., Wang, Y., Chu, Z., Jie, J., Tian, P., Jiang, M., Khan, I., Sanjeevikumar, P., & Tang, Y. (2020). Optimization configuration of energy storage capacity based on the microgrid reliable output power. Journal of Energy Storage, 32, 101866. https://doi.org/10.1016/j.est.2020.101866.*

*[25] Nezamabadi, H., & Vahidinasab, V. (2021). Arbitrage Strategy of Renewable-Based Microgrids via Peer-to-Peer Energy-Trading. IEEE Transactions on Sustainable Energy, 12(2), 1372-1382. https://doi.org/10.1109/TSTE.2020.3045216.*

*[26] Ndiaye, A., Locment, F., De Bernardinis, A., Sechilariu, M., & Redondo-Iglesias, E. (2022). A Techno-Economic Analysis of Energy Storage Components of Microgrids for Improving Energy Management Strategies. Energies, 15(4), 1556. https://doi.org/10.3390/en15041556.*

*[27] Dhundhara, S., Verma, Y. P., & Williams, A. (2018). Techno-economic analysis of the lithium-ion and lead-acid battery in microgrid systems. Energy Conversion and Management, 177, 122-142. https://doi.org/10.1016/j.enconman.2018.09.030.*

*[28] Wei, Y., Wang, S., Han, X., Lu, L., Li, W., Zhang, F., & Ouyang, M. (2022). Toward more realistic microgrid optimization: Experiment and high-efficient model of Li-ion battery degradation under dynamic conditions. eTransportation, 14, 100200. https://doi.org/10.1016/j.etran.2022.100200.*

*[29] Farrokhabadi, M., König, S., Cañizares, C. A., Bhattacharya, K., & Leibfried, T. (2018). Battery Energy Storage System Models for Microgrid Stability Analysis and Dynamic Simulation. IEEE Transactions on Power Systems, 33(2), 2301-2312. https://doi.org/10.1109/TPWRS.2017.2740163.*

*[30] Zarate-Perez, E., Rosales-Asensio, E., González-Martínez, A., de Simón-Martín, M., & Colmenar-Santos, A. (2022). Battery energy storage performance in microgrids: A scientific mapping perspective. Energy Reports, 8(Supplement 9), 259-268. https://doi.org/10.1016/j.egyr.2022.06.116.*

*[31] Zhao, B., Zhang, X., Chen, J., Wang, C., & Guo, L. (2013). Operation Optimization of Standalone Microgrids Considering Lifetime Characteristics of Battery Energy Storage System. IEEE Transactions on Sustainable Energy, 4(4), 934-943. https://doi.org/10.1109/TSTE.2013.2248400.*

*[32] Wang, Y., Tan, K. T., & So, P. L. (2013). Coordinated control of battery energy storage system in a microgrid. In 2013 IEEE PES Asia-Pacific Power and Energy Engineering Conference (APPEEC) (pp. 1-6). Hong Kong, China. https://doi.org/10.1109/APPEEC.2013.6837211.*

*[33] Kerdphol, T., Fuji, K., Mitani, Y., Watanabe, M., & Qudaih, Y. (2016). Optimization of a battery energy storage system using particle swarm optimization for stand-alone microgrids. International Journal of Electrical Power & Energy Systems, 81, 32-39. https://doi.org/10.1016/j.ijepes.2016.02.006.*

*[34] Khalid, A., Stevenson, A., & Sarwat, A. I. (2021). Overview of Technical Specifications for Grid-Connected Microgrid Battery Energy Storage Systems. IEEE Access, 9, 163554-163593. https://doi.org/10.1109/ACCESS.2021.3132223.*

*[35] Alsaidan, I., Khodaei, A., & Gao, W. (2018). A Comprehensive Battery Energy Storage Optimal Sizing Model for Microgrid Applications. IEEE Transactions on Power Systems, 33(4), 3968-3980. https://doi.org/10.1109/TPWRS.2017.2769639.*

*[36] Morstyn, T., Hredzak, B., Aguilera, R., & Agelidis, V. (2017). Model Predictive Control for Distributed Microgrid Battery Energy Storage Systems. IEEE Transactions on Control Systems Technology. Advance online publication. https://doi.org/10.1109/TCST.2017.2699159.*

[37] Zhao, H., Hong, M., Lin, W., & Loparo, K. A. (2019). Voltage and Frequency Regulation of Microgrid With Battery Energy Storage Systems. IEEE Transactions on Smart Grid, 10(1), 414-424. https://doi.org/10.1109/TSG.2017.2741668.

[38] T. Zhao and Z. Ding. (2018). Cooperative Optimal Control of Battery Energy Storage System Under Wind Uncertainties in a Microgrid. IEEE Transactions on Power Systems, vol. 33, no. 2, 2292-2300. doi: 10.1109/TPWRS.2017.2741672.

[39] Raju, K., Ganesan, S., Subramaniam, U., Ghodke, A., Madurai Elavarasan, R., & Bhaskar Ranjana, M. (2020). Investigation on Sizing of Voltage Source for a Battery Energy Storage System in Microgrid With Renewable Energy Sources. IEEE Access, 8, 188861. https://doi.org/10.1109/ACCESS.2020.3030729.

[40] Brasil, C. F., & Melo, C. L. S. (2017). A comparative study of lead-acid batteries and lithium iron phosphate batteries used in microgrid systems. In 2017 Brazilian Power Electronics Conference (COBEP) (pp. 1-7). Juiz de Fora, Brazil. https://doi.org/10.1109/COBEP.2017.8257424.

[41] Huang, Z., & Mu, A. (2021). Research and analysis of performance improvement of vanadium redox flow battery in microgrid: A technology review. Energy Reviews, 21, 6716. https://doi.org/10.1002/er.6716.

[42] Mulleriyawage, U., & Shen, W. (2019). A Review of Battery Energy Storage Systems for Residential DC Microgrids and Their Economical Comparisons. DEStech Transactions on Environment, Energy and Earth Sciences, 27856. https://doi.org/10.12783/dteees/iceee2018/27856.

[43] Magsumbol, J.-A. V., Rosales, M. A., Palconit, M. G. B., Concepcion II, R. S., Bandala, A. A., Vicerra, R. R. P., Sybingco, E., Culaba, A., & Dadios, E. P. (2022). A Review of Smart Battery Management Systems for LiFePO4: Key Issues and Estimation Techniques for Microgrids. Journal of Advanced Computational Intelligence and Intelligent Informatics, 26(5), 824-833. https://doi.org/10.20965/jaciii.2022.p0824.

[44] Jin, J. X., Wang, J., Yang, R. H., Zhang, T. L., Mu, S., Fan, Y. J., & Xing, Y. Q. (2021). A superconducting magnetic energy storage with dual functions of active filtering and power fluctuation suppression for photovoltaic microgrid. Journal of Energy Storage, 38, 102508. https://doi.org/10.1016/j.est.2021.102508.

[45] Molina, M. G., & Mercado, P. E. (2011). Power Flow Stabilization and Control of Microgrid with Wind Generation by Superconducting Magnetic Energy Storage. IEEE Transactions on Power Electronics, 26(3), 910-922. https://doi.org/10.1109/TPEL.2010.2097609.

[46] Vulusala G, V. S., & Madichetty, S. (2017). Application of superconducting magnetic energy storage in electrical power and energy systems: a review. Energy Reports, 3, 148-162. https://doi.org/10.1016/j.egyr.2017.05.008.

[47] Kotb, K. M., Elmorshedy, M. F., Salama, H. S., & Dán, A. (2022). Enriching the stability of solar/wind DC microgrids using battery and superconducting magnetic energy storage based fuzzy logic control. Journal of Energy Storage, 45, 103751. https://doi.org/10.1016/j.est.2021.103751.

[48] Kouache, I., Sebaa, M., Bey, M., Allaoui, T., & Denai, M. (2020). A new approach to demand response in a microgrid based on coordination control between smart meter and distributed superconducting magnetic energy storage unit. Journal of Energy Storage, 32, 101748. https://doi.org/10.1016/j.est.2020.101748.

[49] Salama, H. S., Aly, M. M., Abdel-Akher, M., & Vokony, I. (2019). Frequency and voltage control of microgrid with high WECS penetration during wind gusts using superconducting magnetic energy storage. Electrical Engineering, 101, 771–786. https://doi.org/10.1007/s00202-019-00818-6.

[50] Adetokun, B. B., Oghorada, O., & Abubakar, S. J. (2022). Superconducting magnetic energy storage systems: Prospects and challenges for renewable energy applications. Journal of Energy Storage, 55(Part C), 105663. https://doi.org/10.1016/j.est.2022.105663.

[51] Annapoorani, K. I., Rajaguru, V., Padmanabhan, S. A., Kumar, K. M., & Venkatachalam, S. (2022). Fuzzy logic-based integral controller for load frequency control in an isolated micro-grid with superconducting magnetic energy storage unit. Materials Today: Proceedings, 58(Part 1), 244-250. https://doi.org/10.1016/j.matpr.2022.02.103.

[52] Vulusala, G. V. S., & Madichetty, S. (2017). Application of superconducting magnetic energy storage in electrical power and energy systems: A review. International Journal of Energy Research, [Preprint]. https://doi.org/10.1002/er.3773

[53] Nguyen, T.-T., Yoo, H.-J., & Kim, H.-M. (2015). A Flywheel Energy Storage System Based on a Doubly Fed Induction Machine and Battery for Microgrid Control. Energies, 8(6), 5074-5089. https://doi.org/10.3390/en8065074

[54] Kikusato, H., Ustun, T. S., Suzuki, M., Sugahara, S., Hashimoto, J., Otani, K., Ikeda, N., Komuro, I., Yokoi, H., & Takahashi, K. (2022). Flywheel energy storage system based microgrid controller design and PHIL testing. Energy Reports, 8(Supplement 10), 470-475. https://doi.org/10.1016/j.egyr.2022.05.221.

[55] Khodadoost Arani, A. A., Karami, H., Gharehpetian, G. B., & Hejazi, M. S. A. (2017). Review of Flywheel Energy Storage Systems structures and applications in power systems and microgrids. Renewable and Sustainable Energy Reviews, 69, 9-18. https://doi.org/10.1016/j.rser.2016.11.166.

*[56] Arghandeh, R., Pipattanasomporn, M., & Rahman, S. (2012). Flywheel Energy Storage Systems for Ride-through Applications in a Facility Microgrid. IEEE Transactions on Smart Grid, 3(4), 1955-1962. doi: 10.1109/TSG.2012.2212468.*

*[57] G. O. Suvire, M. G. Molina and P. E. Mercado. (2012) Improving the Integration of Wind Power Generation Into AC Microgrids Using Flywheel Energy Storage. IEEE Transactions on Smart Grid, vol. 3, no. 4, pp. 1945-1954, doi: 10.1109/TSG.2012.2208769.*

*[58] Aly, A., Kassem, A., Sayed, K., & Aboelhassan, I. (2019). Design of Microgrid with Flywheel Energy Storage System Using HOMER Software for Case Study. In 2019 International Conference on Innovative Trends in Computer Engineering (ITCE) (pp. 485-491). doi: 10.1109/ITCE.2019.8646441.*

*[59] Coban, H. H., Rehman, A., & Mousa, M. (2022). Load Frequency Control of Microgrid System by Battery and Pumped-Hydro Energy Storage. Water, 14(11), 1818. https://doi.org/10.3390/w14111818.*

*[60] Mousavi, N., Kothapalli, G., Habibi, D., Das, C. K., & Baniasadi, A. (2020). A novel photovoltaic-pumped hydro storage microgrid applicable to rural areas. Applied Energy, 262, 114284. https://doi.org/10.1016/j.apenergy.2019.114284.*

*[61] Islam, S. M. (2012). Increasing wind energy penetration level using pumped hydro storage in island micro-grid system. International Journal of Energy and Environmental Engineering, 3(Article number: 9). https://doi.org/10.1186/2251-6832-3-9*

*[62] Ahmadi, S., Tostado-Véliz, M., Ghadimi, A. A., Miveh, M. R., & Jurado, F. (2022). A novel interval-based formulation for optimal scheduling of microgrids with pumped-hydro and battery energy storage under uncertainty. International Journal of Energy Research. Advance online publication. https://doi.org/10.1002/er.8058*

*[63] Samu, R., Al-Ghussain, L., Fahrioglu, M., & Taylan, O. (2018). Techno-Economic Analysis of Photovoltaic-Hydrogen Fuel Cell/Pumped Hydro Storage System for Micro Grid Applications: Case Study in Cyprus. In 2018 IEEE Photovoltaic Specialists Conference (PVSC) (pp. 1-4). IEEE. https://doi.org/10.1109/PVCon.2018.8523976.*

*[64] Dhundhara, S., & Verma, Y. P. (2020). Application of micro pump hydro energy storage for reliable operation of microgrid system. IET Renewable Power Generation. Advance online publication. https://doi.org/10.1049/iet-rpg.2019.0822.*

*[65] Guignard, N., Cristofari, C., Debusschere, V., Garbuio, L., & Le Mao, T. (2022). Micro Pumped Hydro Energy Storage: Sketching a Sustainable Hybrid Solution for Colombian Off-Grid Communities. Sustainability, 14(24), 16734. https://doi.org/10.3390/su142416734.*

*[66] Alva, G., Lin, Y., & Fang, G. (2018). An overview of thermal energy storage systems. Energy, 144, 341-378. https://doi.org/10.1016/j.energy.2017.12.037.*

*[67] Mohammadi, S., & Mohammadi, A. (2014). Stochastic scenario-based model and investigating size of battery energy storage and thermal energy storage for micro-grid. International Journal of Electrical Power & Energy Systems, 61, 531-546. https://doi.org/10.1016/j.ijepes.2014.03.041.*

*[68] Li, Z., Wu, L., Xu, Y., Moazeni, S., & Tang, Z. (2022). Multi-Stage Real-Time Operation of a Multi-Energy Microgrid With Electrical and Thermal Energy Storage Assets: A Data-Driven MPC-ADP Approach. IEEE Transactions on Smart Grid, 13(1), 213-226. doi: 10.1109/TSG.2021.3119972.*

*[69] Aguilar-Jiménez, J.A., Velázquez, N., Acuña, A., Cota, R., González, E., González, L., López, R., & Islas, S. (2018). Techno-economic analysis of a hybrid PV-CSP system with thermal energy storage applied to isolated microgrids. Solar Energy, 174, 55-65. doi: 10.1016/j.solener.2018.08.078.*

*[70] B. Mohandes, S. Acharya, M. S. E. Moursi, A. S. Al-Sumaiti, H. Doukas and S. Sgouridis, "Optimal Design of an Islanded Microgrid With Load Shifting Mechanism Between Electrical and Thermal Energy Storage Systems," in IEEE Transactions on Power Systems, vol. 35, no. 4, pp. 2642-2657, July 2020, doi: 10.1109/TPWRS.2020.2969575.*

*[71] Enescu, D., Chicco, G., Porumb, R., & Seritan, G. (2020). Thermal Energy Storage for Grid Applications: Current Status and Emerging Trends. Energies, 13(2), 340. doi: 10.3390/en13020340.*

*[72] Ibrahim, H., Belmokhtar, K., & Ghandour, M. (2015). Investigation of Usage of Compressed Air Energy Storage for Power Generation System Improving - Application in a Microgrid Integrating Wind Energy. Energy Procedia, 73, 305-316. doi: 10.1016/j.egypro.2015.07.694.*

*[73] Li, Y., Miao, S., Luo, X., Yin, B., Han, J., & Wang, J. (2020). Dynamic modelling and techno-economic analysis of adiabatic compressed air energy storage for emergency back-up power in supporting microgrid. Applied Energy, 261, 114448. doi: 10.1016/j.apenergy.2019.114448.*

*[74] Gao, J., Chen, J. J., Qi, B. X., Zhao, Y. L., Peng, K., & Zhang, X. H. (2021). A cost-effective two-stage optimization model for microgrid planning and scheduling with compressed air energy storage and preventive maintenance. International Journal of Electrical Power & Energy Systems, 125, 106547. doi: 10.1016/j.ijepes.2020.106547.*

[75] Inthamoussou, F., Pegueroles-Queralt, J., & Bianchi, F. (2013). Control of a Supercapacitor Energy Storage System for Microgrid Applications. IEEE Transactions on Energy Conversion, 28(3), 690-697. https://doi.org/10.1109/TEC.2013.2260752

[76] Hajiaghasi, S., Salemnia, A., & Hamzeh, M. (2019). Hybrid energy storage system for microgrids applications: A review. Journal of Energy Storage, 21, 543-570. https://doi.org/10.1016/j.est.2018.12.017

[77] Amirthalakshmi, T. M., Ramesh, S., Prabu, R. T., Ramkumar, G., Sahoo, S., Thomas, P., Ramalingam, R. J., Al-Lohedan, H., Al-Dhayan, D. M., & Sureshkumar, S. (2022). A Novel Approach in Hybrid Energy Storage System for Maximizing Solar PV Energy Penetration in Microgrid. Journal of Renewable Energy, 2022(Article ID 3559837), 1-13. https://doi.org/10.1155/2022/3559837

[78] Dong, H., Fu, Y., Jia, Q., & Wen, X. (2022). Optimal dispatch of integrated energy microgrid considering hybrid structured electric-thermal energy storage. Renewable Energy, 199, 628-639. https://doi.org/10.1016/j.renene.2022.09.027

[79] Jing, W., Lai, C. H., Wong, S. H. W., & Wong, M. L. D. (2017). Battery-supercapacitor hybrid energy storage system in standalone DC microgrids: A review. IET Renewable Power Generation, 11(5), 623-634. https://doi.org/10.1049/iet-rpg.2016.0500

[80] Khalid, M. (2019). A Review on the Selected Applications of Battery-Supercapacitor Hybrid Energy Storage Systems for Microgrids. Energies, 12(23), 4559. https://doi.org/10.3390/en12234559

[81] Bocklisch, T. (2016). Hybrid energy storage approach for renewable energy applications. Journal of Energy Storage, 8, 311-319. https://doi.org/10.1016/j.est.2016.01.004

[82] Etxeberria, A., Vechiu, I., Camblong, H., & Vinassa, J. M. (2010). Hybrid Energy Storage Systems for renewable Energy Sources Integration in microgrids: A review. In 2010 Conference Proceedings IPEC (pp. 532-537). https://doi.org/10.1109/IPECON.2010.5697053

[83] Jarnut, M., Wermiński, S., & Waśkowicz, B. (2017). Comparative analysis of selected energy storage technologies for prosumer-owned microgrids. Renewable and Sustainable Energy Reviews, 74, 925-937. https://doi.org/10.1016/j.rser.2017.02.084

[84] Gao, D. W. (2015). Energy Storage for Sustainable Microgrid. Academic Press. ISBN: 9780128033753

[85] Park, H. A., Byeon, G., Son, W., Jo, H. C., Kim, J., & Kim, S. (2020). Digital Twin for Operation of Microgrid: Optimal Scheduling in Virtual Space of Digital Twin. Energies, 13(20), 5504. https://doi.org/10.3390/en13205504

[86] Chen, M., Ma, G., Liu, W., Zeng, N., & Luo, X. (2023). An overview of data-driven battery health estimation technology for battery management system. Neurocomputing, 532, 152-169. ISSN 0925-2312. https://doi.org/10.1016/j.neucom.2023.02.031. (https://www.sciencedirect.com/science/article/pii/S0925231223001686)