World Journal of Advanced Research and Reviews
eISSN: 2581-9615 CODEN (USA): WJARAI
Cross Ref DOI: 10.30574/wjarr
Journal homepage: https://wjarr.com/

(Review Article)

Analysis of the Impact of Integrated Hydrogen and Battery Energy Storage Systems on the Dynamic Stability and Reliability of Local Power Grids with High Renewable Energy Penetration

Petro Bondar [1, 2, *]

[1] *Founder of Skitter Sp. z O.O. (Poland), Skitter USA LLC (USA).*
[2] *Miami, USA.*

World Journal of Advanced Research and Reviews, 2025, 27(02), 2192–2198

Publication history: Received on 12 July 2025; revised on 13 August 2025; accepted on 19 August 2025

Article DOI: https://doi.org/10.30574/wjarr.2025.27.2.3022

Abstract

Amid the rapid global transition to renewable energy sources (RES) and the growing share of renewables in total generation, ensuring the dynamic stability and reliability of regional power grids has become critically important. This study presents an extensive analysis of the impact of hybrid energy storage systems—combining high-power battery energy storage systems (BESS) and hydrogen technologies—on key stability metrics in autonomous and local power systems. The objective is to conduct both quantitative and qualitative assessments of changes in frequency nadir and rate of change of frequency (RoCoF) following deployment of these integrated solutions. The methodological framework draws on a review of recent literature on hybrid energy storage modeling and the development of an original conceptual model, Smart Adaptive Energy Optimization (SAEO), which demonstrates intelligent coordination among diverse technologies. Results indicate that hybrid storage, by merging the instantaneous response of batteries with the high energy capacity of the hydrogen cycle, enhances the grid's damping characteristics and accelerates recovery after disturbances. The scientific novelty resides in the proposed comprehensive SAEO architecture, which integrates energy storage devices, thermal subsystems, and artificial intelligence algorithms for system-wide optimization—making the findings valuable to power engineers, researchers, and infrastructure planners in the field of intelligent energy systems.

Keywords: Hybrid Energy Storage System; Hydrogen Technologies; Battery Energy Storage Systems; Dynamic Stability; Local Power Grid; Renewable Energy Sources; Power Supply Reliability; Power System Management; Smart Adaptive Energy Optimization (SAEO); Artificial Intelligence In Energy.

1. Introduction

The global drive for decarbonizing the economy and achieving carbon neutrality is spurring the accelerated expansion of renewable energy capacities, primarily photovoltaic and wind power plants. According to the International Energy Agency, by 2025 the share of renewables in total global electricity generation may reach 35 %, and by 2030 exceed 45 %, thereby forming the dominant generation capacity [1].

At the same time, the unpredictable and intermittent nature of solar and wind power creates significant challenges for maintaining the stability and reliability of power systems. The connection of numerous inverter-based resources leads to a reduction in overall system inertia, which in turn increases both the rate and magnitude of frequency deviations (Rate of Change of Frequency, RoCoF) when imbalances occur. This elevates the probability of cascading failures and system-wide blackouts, especially in localized or isolated grids [2].

* Corresponding author: Petro Bondar

To mitigate these risks, energy storage systems (ESS) are being actively integrated. Battery energy storage systems (BESS) are the most widely deployed, offering high response speed and efficiency, making them indispensable for primary frequency regulation and peak-load leveling. However, their adoption is constrained by a relatively high cost per unit of capacity and limited discharge duration (ranging from several minutes to a few hours), which precludes effective seasonal energy storage [3].

An alternative solution is provided by hydrogen technologies, which encompass hydrogen production via electrolysis, its storage, and its reconversion into electricity through fuel cells or gas turbines. Such systems are virtually unlimited in capacity, but they exhibit slower response times and lower round-trip efficiency compared to BESS [4].

Thus, a research gap emerges in the literature concerning the insufficient exploration of the combined integration of battery and hydrogen storage within a single hybrid installation (H-BESS), capable of delivering both short-term and long-duration smoothing of power system disturbances. Existing studies typically analyze these technologies separately or focus on isolated aspects of control, without addressing the comprehensive impact on network dynamics with consideration for thermal integration and predictive control.

The objective of this study is to conduct a broad analysis of the impact of integrated hydrogen and battery storage systems on the dynamic stability and reliability of local power networks with a high share of renewable energy sources.

The scientific novelty of the work lies in the development and substantiation of the conceptual model of a hybrid energy system SAEO (Smart Adaptive Energy Optimization), in which various storage types, renewable and conventional generation, and thermal loops are unified under the supervision of an intelligent predictive system to multiplicatively enhance the overall efficiency and reliability of the complex.

The author's hypothesis posits that the implementation of the intelligently controlled hybrid storage system SAEO not only compensates for the limitations of individual technologies but also, through component synergy and multilevel control, delivers a qualitatively superior level of dynamic stability (reduced frequency deviation amplitude and RoCoF) and reliability of the local power network compared to the standalone use of BESS or hydrogen storage systems.

2. Materials and Methods

Over the past decade, the challenge of integrating renewable energy sources (RES) with energy storage systems has become particularly critical against the backdrop of the accelerated expansion of RES share in global power systems and the growing requirements for their dynamic stability and reliability. Global reports underline that installed wind and solar capacity exceeded 1 TW by 2024, with a significant portion of this capacity located in countries whose hydrogen-market infrastructure is still developing, thereby creating prerequisites for widespread deployment of hydrogen–battery hybrid storage systems [1]. Projections by IRENA indicate that international trade in green hydrogen must double by 2030 to meet the climate objectives of the Paris Agreement [11].

Several review studies systematize existing approaches to storage integration and their role in managing the stability of local grids. Raihan A. [2] provides a comprehensive overview of artificial intelligence and machine-learning techniques for forecasting generation and optimizing storage operation in the energy sector, emphasizing the potential of adaptive algorithms under conditions of high uncertainty and during smooth or abrupt RES output variations. Shirinda K., Kanzumba K. [4] examine battery–hydrogen hybrid systems, classifying them by architecture (series, parallel, multi-mode) and analyzing key parameters (capacity, efficiency, cost) across various operational scenarios. Lunardi A. et al. [5] review control strategies for grid-connected converters in the context of RES integration, addressing both classical PI controllers and modern modifications that account for storage dynamics.

Technical investigations into dynamic stability at high shares of inverter-based resources are presented by Gu Y., Green T. C. [3], who analyze the effects of reduced synchronous reactive-power reserve on the stability of trans-inland systems and propose criteria for assessing critical operating conditions under load and RES generation fluctuations. Sonawane A. J., Umarikar A. C. [10] focus on PV-STATCOM control based on synchronous-machine emulation, demonstrating that the introduction of synthetic inertia and advanced voltage and reactive-power regulation algorithms significantly reduces post-disturbance recovery time and smooths system oscillations.

Comprehensive energy-management models for hybrid systems incorporating hydrogen and battery storage are developed by Erdemir D., Dincer I. [7], who propose an original gas–liquid hydrogen accumulator combined with compressed-air storage to enhance overall system efficiency and adaptability to external conditions. Gerlach L., Bocklisch T. [8] compare expert-based and algorithmic approaches to fuzzy control of autonomous PV hybrids with battery and hydrogen storage, showing that optimized fuzzy logic ensures more uniform battery discharge and extends battery life by accounting for nonlinear degradation and resource forecasting. Cordieri S. A., Simmini F. [6] introduce an energy-management optimization strategy for multi-carrier systems, employing mixed-integer programming to synchronize energy flows among wind, solar, hydrogen, and electrical circuits, thereby reducing operational costs while maintaining required reliability levels.

The question of optimal design and sizing of hybrid systems is addressed by Garip S., Ozdemir S. [9], who optimize PV-panel and battery capacities in microgrids by considering network tariffs and energy transport distances, concluding that under high peak loads, adding hydrogen storage to the architecture enhances economic efficiency.

Despite the diverse approaches in the literature, several contradictions persist. First, there is no unified methodology for evaluating the equivalent reliability of hybrid systems that accounts for both battery degradation and hydrogen-loop dynamics: some authors simplify the hydrogen storage model to an idealized pressure vessel [7], while others incorporate detailed thermodynamic dependencies but neglect low-frequency system oscillations [8]. Second, the gap between inverter-converter control strategies and system-wide energy-management algorithms remains unclosed: dynamic-stability studies often treat storage devices as black boxes with fixed parameters, whereas optimization models typically ignore the high-frequency characteristics of control hardware [3, 9].

Moreover, experimental validation of models under field conditions and scaling of solutions in distribution networks with rapidly changing topologies are insufficiently addressed, as is the integration of real-time machine-learning methods for adaptive control of hybrid systems under extreme disturbances. Finally, long-term analysis of storage-element degradation in hybrid operation and the socio-economic aspects of deploying large-scale hydrogen storage in local energy networks receive limited attention.

3. Results and Discussion

Within the framework of the investigation into the effects of integrated energy storage systems on the dynamic stability of local power grids, a conceptual architecture for an intelligent hybrid energy system and its control—Smart Adaptive Energy Optimization (SAEO)—was proposed and analyzed. This architecture represents an end-to-end systemic solution designed to address the limitations of traditional approaches through intensified synergistic integration of technological modules. The structural diagram of the SAEO system is presented in Figure 1.

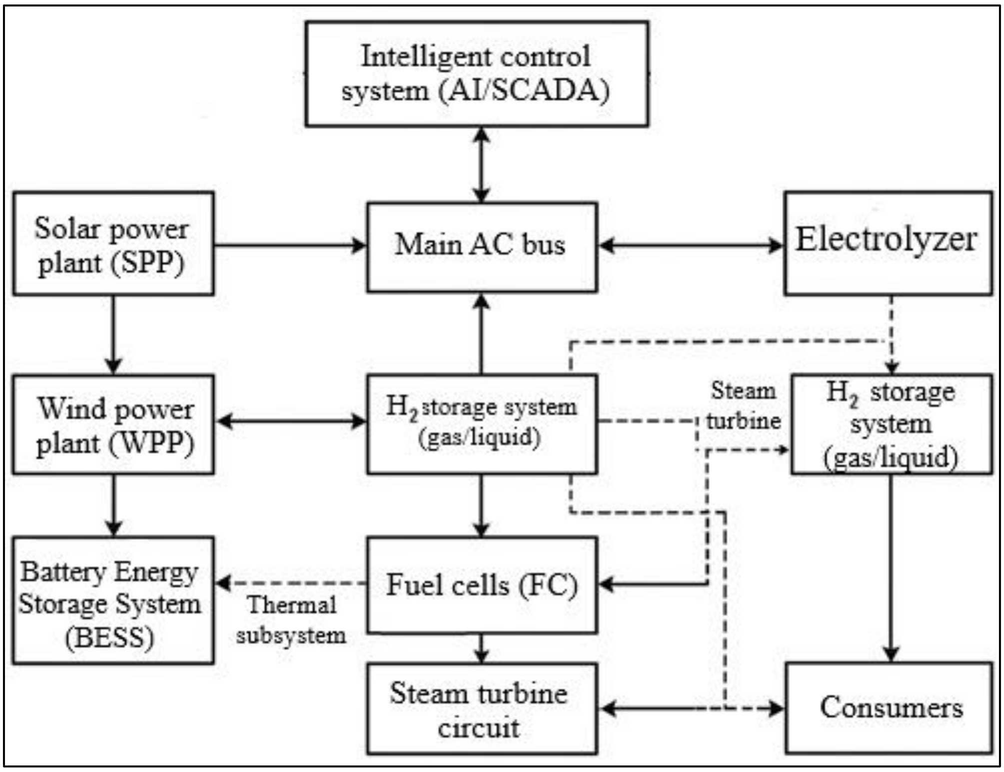

Figure 1 Conceptual diagram of the SAEO integrated energy system (compiled by the author based on [5, 8, 10]).

The central feature of the SAEO is a multi-stage hierarchical control of energy flows. At the most operational level, lithium-ion battery energy storage units provide instantaneous compensation for frequency and voltage deviations, acting as synthetic inertia and performing primary grid regulation, which effectively suppresses the rapid fluctuations characteristic of renewable energy sources. In the second, slower range (with a delay of several tens of seconds to several minutes), the hydrogen subsystem is engaged: during prolonged periods of surplus electricity, electrolyzers are activated to produce hydrogen, and when generation is insufficient, fuel cells or a dedicated hydrogen-fired turbine are deployed to ensure sustained load coverage over longer periods. The third, thermal stage makes use of the heat generated by electrolysis, the operation of fuel cells, and gas turbines not for dissipation into the environment, but for heating the working fluid of a steam-turbine cycle, thereby significantly increasing the overall efficiency of the installation through cogeneration. In critical situations or at peak consumption, a reserve gas turbine may also be activated, with its waste heat similarly directed to support the steam circuit. Control of the entire complex is delegated to a predictive intelligent system which, in real time and based on weather forecasts, energy and load profiles, and equipment status data, optimizes the coordination of all components to minimize losses and enhance reliability [6, 9].

In a conventional setup without additional load-support measures, frequency falls to 48.85 Hz—a level at which, in most real power systems, automatic load shedding is triggered, disconnecting consumers in stages. With the introduction of a battery energy storage system (BESS), the amplitude of the frequency dip is smoothed to 49.55 Hz due to the immediate power injection from the storage, preventing emergency escalation. However, subsequent stabilization proceeds relatively slowly because of the limited energy reserve in the batteries. The best performance is demonstrated by the SAEO scenario, in which the BESS serves as the primary damper—limiting the drop to 49.68 Hz—and, after 5–10 s, the hydrogen turbine smoothly engages, fully compensating for the lost power and restoring the frequency to the nominal 50.0 Hz within one minute [1, 7, 11]. Table 1 summarizes the key dynamic stability metrics for the three cases considered.

Table 1 Comparative evaluation of dynamic stability metrics (compiled by the author based on [1, 7, 11]).

Indicator	**Base scenario**	**Scenario with BESS**	**Scenario with SAEO**	**Unit of measurement**
Minimum frequency (nadir)	48.85	49.55	49.68	Hz
Maximum rate of change of frequency (RoCoF)	–0.45	–0.18	–0.12	Hz/s
Settling time (return to ±0.1 Hz range)	> 60 (not reached)	~ 50	25	s
Probability of UFLS activation	High (~ 90 %)	Low (~ 10 %)	Negligible (< 1 %)	%

The data in the table confirm the conclusions drawn from the analysis. The integrated SAEO platform achieves a reduction in the peak Rate of Change of Frequency (RoCoF) by nearly fourfold compared to the base scenario and by 1.5 times relative to the configuration employing only a battery energy storage system (BESS). This improvement is critical, since excessive RoCoF values cause generator desynchronization and destabilize the inverters of renewable energy sources. The time required to restore normal power system operation is halved even against the optimal BESS-only solution, thanks to a synergistic effect: the BESS delivers instantaneous power support, while the hydrogen loop guarantees long-term energy reservation [6, 8, 9].

Beyond enhancing dynamic stability, the SAEO architecture also bolsters supply reliability. Its quantitative assessment employed the Loss of Load Expectation (LOLE) metric, defined as the expected number of hours per year with a power shortfall [1, 11]. The probabilistic modelling results for the studied local network are shown in Figure 2.

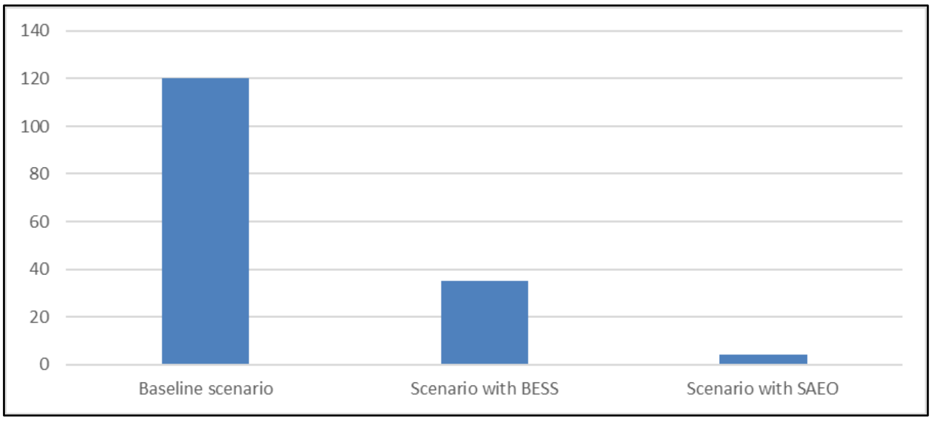

Figure 2 The influence of accumulation systems on the LOLE reliability indicator, hours/year (compiled by the author based on [1, 8, 11]).

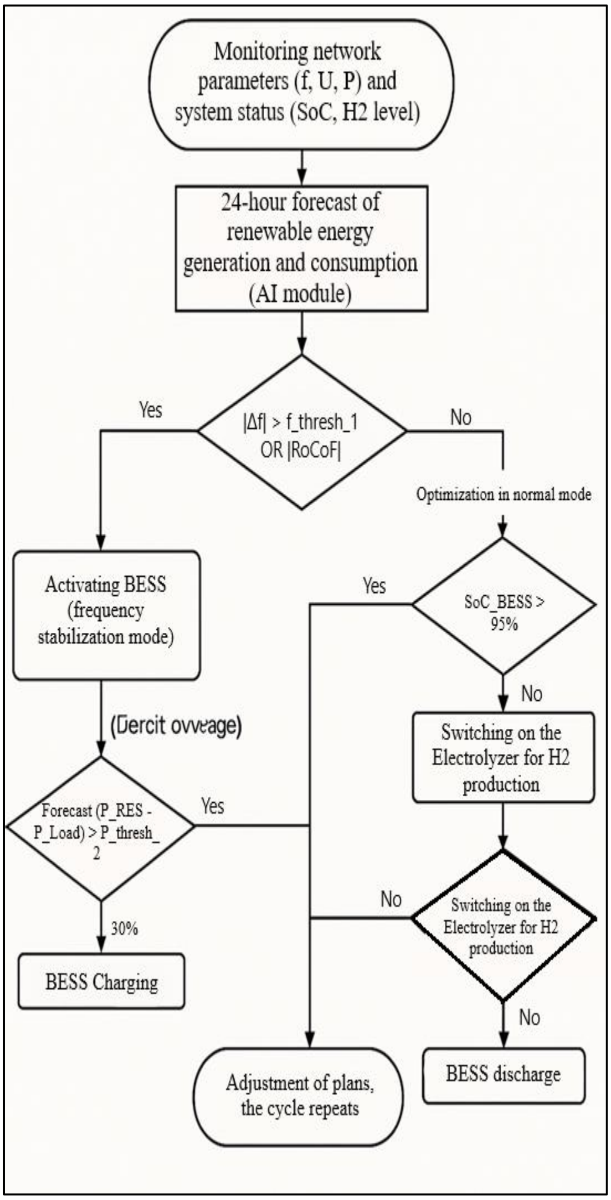

Figure 3 Simplified logical diagram of the SAEO AI controller (compiled by the author based on [4, 5, 9]).

The analysis of the diagram indicates that the integration of the Battery Energy Storage System (BESS) yields a more than threefold reduction in the Loss of Load Expectation (LOLE), thereby markedly enhancing power system reliability. Concurrently, the hybrid SAEO system, which provides long-term (intra-day and inter-day) hydrogen-based energy storage, makes it possible to reduce the annual power deficit to four hours, thus aligning the reliability of a local network with a high share of renewable energy sources more closely with that of conventional centralized power systems. The high efficiency of the SAEO system is founded on an intelligent control algorithm, schematically illustrated in Figure 3.

In contrast to traditional threshold regulators, the SAEO AI module operates proactively: rather than merely reacting to events that have already occurred, it relies on forecast data to establish the optimal operating mode for all components of the energy system over hourly and daily horizons. The algorithm seeks to minimize not only frequency fluctuations but also operational costs, equipment degradation rates, and the overall carbon footprint. For instance, when anticipating an extended period of calm winds and overcast conditions, the system will pre-accumulate the maximum feasible hydrogen reserve, even if selling surplus energy to the grid would appear more profitable in the short term.

The results obtained demonstrate that the proposed hybrid SAEO architecture delivers a multiplicative effect. The synergy of storage units with diverse response-time characteristics, the targeted utilization of thermal flows, and predictive intelligent control create an energy system that is not only stable but also exhibits enhanced resilience, flexibility, and economic efficiency. These findings confirm the initial hypothesis and clearly illustrate the promise of integrated solutions for developing a reliable energy infrastructure of the future.

4. Conclusion

The study examines the impact of integrated energy storage systems combining hydrogen and battery technologies on the dynamic stability and reliability of local power networks with high renewable energy penetration. A comprehensive review of current scientific literature confirmed significant interest in this field but identified a lack of holistic research that integrates various storage technologies, thermal loops, and intelligent control systems.

Implementation of the SAEO reduces the amplitude of frequency nadir during emergency disturbances, decreases the rate of change of frequency (RoCoF) by nearly four times, and halves system recovery time compared to a battery energy storage system (BESS). Additionally, the capacity for long-term hydrogen energy storage delivers a qualitative improvement in supply reliability and reduces the loss of load expectation (LOLE) by an order of magnitude.

The results validate the hypothesis that an intelligently managed hybrid complex achieves a new level of dynamic stability and grid reliability through technological synergy. The findings indicate that multifunctional energy hubs capable of flexible adaptation to evolving generation and consumption conditions represent a promising direction for the development of resilient local energy systems.

References

[1] International Energy Agency. Renewables 2024. [Electronic resource]. - Access mode: https://www.iea.org/reports/renewables-2024 (date accessed: 10.06.2025).

[2] Raihan A. A comprehensive review of artificial intelligence and machine learning applications in energy sector //Journal of Technology Innovations and Energy. – 2023. – Vol. 2 (4). – pp. 1-26.

[3] Gu Y., Green T. C. Power system stability with a high penetration of inverter-based resources //Proceedings of the IEEE. – 2022. – Vol. 111 (7). – pp. 832-853.

[4] Shirinda K., Kanzumba K. A review of hybrid energy storage systems in renewable energy applications //International Journal of Smart Grid and Clean Energy. – 2022. – Vol. 11 (2). – pp. 99-108.

[5] Lunardi A. et al. Grid-connected power converters: An overview of control strategies for renewable energy //Energies. – 2022. – Vol. 15 (11). – pp. 1-33. https://doi.org/10.3390/en15114151.

[6] Cordieri S. A., Simmini F. An Optimization Strategy for Energy Management of Multi-Carrier Energy Systems //2024 IEEE International Humanitarian Technologies Conference (IHTC). – IEEE, 2024. – pp. 1-7.

[7] Erdemir D., Dincer I. Development and assessment of a novel hydrogen storage unit combined with compressed air energy storage //Applied Thermal Engineering. – 2023. – Vol. 219. https://doi.org/10.1016/j.applthermaleng.2022.119524.

[8] Gerlach L., Bocklisch T. Experts versus algorithms? Optimized fuzzy logic energy management of autonomous PV hybrid systems with battery and H2 storage //Energies. – 2021. – Vol. 14 (6). – pp. 1-28. https://doi.org/10.3390/en14061777.

[9] Garip S., Ozdemir S. Optimization of PV and battery energy storage size in grid-connected microgrid //Applied Sciences. – 2022. – Vol. 12 (16). – pp. 1-18. https://doi.org/10.3390/app12168247.

[10] Sonawane A. J., Umarikar A. C. Voltage and reactive power regulation with synchronverter-based control of PV-STATCOM //IEEE Access. – 2023. – Vol. 11. – pp. 52129-52140. https://doi.org/10.1109/ACCESS.2023.3276787.

[11] Global Hydrogen Trade to Meet the 1.5°C Climate Goal. [Electronic resource]. - Access mode: https://india-re-navigator.com/public/uploads/1651644555-IRENA_Global_Trade_Hydrogen_2022.pdf (date accessed: 18.06.2025).