Optimized Smart Grid Design with Integrated Hydrogen Storage for Sustainable Energy in Urban Areas

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Abstract

The increasing demand for efficient and sustainable energy solutions has accelerated the development of smart grid systems by integrating different types of advanced energy storage technologies. Among various available solutions hydrogen storage is emerging as a key solution for addressing the variability of renewable energy sources while enhancing grid stability and energy efficiency. This research study investigates the design and optimization of smart grid systems with integrated hydrogen storage. The goal is to improve energy efficiency, enhance system resilience, and support the transition to near-zero energy buildings (NZEBs). The proposed system combines hydrogen storage with battery energy storage systems (BESS) to mitigate fluctuations in solar and wind power generation. A cloud-based monitoring and control system enables real-time data access, predictive maintenance, and optimal energy dispatch. The study also evaluates the environmental impact, energy efficiency, and economic feasibility. Results indicate that properly designed smart grid systems with hydrogen storage significantly enhance energy sustainability and reliability. The integration of hydrogen as a long-term storage solution reduces dependence on fossil fuels, accelerates NZEB development, and supports carbon neutrality goals. Hydrogen storage plays a crucial role in advancing renewable energy systems. The research provides insights into its potential as a key enabler in smart grid infrastructures, contributing to a more sustainable and resilient energy future. Nevertheless, this method has several drawbacks, such as a poor conversion rate and expensive infrastructure. Hydrogen synthesis through electrolysis usually has an efficiency of less than 70%, with further energy losses taking place during storage and fuel cell reconversion to electricity. Furthermore, a major obstacle to broad adoption is still the high upfront expenditures of fuel cells, storage tanks, and electrolysers. Notwithstanding these drawbacks, continued developments in electrolysis technology, better techniques for compressing hydrogen, and fuel cell cost reductions should increase viability. To support a more robust and sustainable energy future, this research addresses the present issues with hydrogen while also shedding light on its potential as a major facilitator in smart grid systems.

Keywords: Smart grid, hydrogen storage, energy efficiency, renewable energy, NZEB

1. Introduction

The shift from traditional power grids to smart grids has accelerated due to the growing need for sustainable energy solutions worldwide. Through the integration of renewable energy sources like solar and wind, smart grid technology makes effective energy management possible. However, grid stability and reliability are seriously threatened by these energy sources' intrinsic intermittency. Intelligent control systems and cutting-edge energy storage solutions are needed to solve these problems.

Hydrogen storage has become one of the most promising long-term solutions for balancing the supply and demand for energy among several storage technologies. Hydrogen can store extra energy for extended periods of time, improving energy security and grid resilience in contrast to battery energy storage systems (BESS), which are better suited for short-term variations. Furthermore, by lowering dependency on fossil fuels and promoting carbon neutrality measures, hydrogen storage supports global sustainability goals. Nevertheless, when considering both electrolysis (60–70%) and fuel cell conversion (50–60%), the overall round-trip efficiency of hydrogen storage is usually between 30 and 40%, which is less than that of BESS. Although improvements in fuel cell and electrolysis technologies continue to increase the viability of hydrogen storage, this efficiency issue still plays a significant role in its broad acceptance. [2]

Automation and control systems are essential for maximizing smart grid performance in addition to energy storage. Fault detection, automated energy dispatch, and real-time monitoring are made possible by the integration of Programmable Logic Controllers (PLCs) into systems. By dynamically modifying energy distribution in response to demand forecasts, grid circumstances, and weather forecasts, this automation system improves system efficiency. An intelligent energy management system that guarantees stability, dependability, and cost-effectiveness in smart grid operations is created by combining hydrogen storage, battery storage, and PLC-driven automation. This automation system increases system efficiency by dynamically altering energy distribution in response to weather forecasts, grid conditions, and demand forecasts. Important components of this efficiency improvement include:

- Response time - PLCs drastically cut response times to milliseconds by enabling quick identification and rectification of grid irregularities. Maintaining grid stability and avoiding small problems turning into serious outages depend on this prompt intervention.
- Control Accuracy - PLCs' high-precision algorithms guarantee precise energy distribution by reducing variations between power generated and consumed. This accuracy improves power quality and dependability by lowering frequency and voltage variations.
- Loss Reduction - PLC-driven automation systems minimize transmission and distribution losses by streamlining energy flow and cutting down on needless power conversions. Energy waste is reduced, and overall system efficiency is increased through effective electrical routing.

2. Objectives

In order to direct our examination into the integration of Battery Energy Storage Systems (BESS) and Hydrogen Energy Storage Systems (HESS), we have set forth particular goals in this study. These goals are intended to include important facets of integrating energy storage, such as off-grid operation capability, grid stability, energy efficiency, and economic viability. By outlining these objectives precisely, we hope to give our research a systematic approach and make sure that every goal makes a significant contribution to the overall goal of creating resilient and sustainable energy systems:

- Improve Grid Stability and Energy Efficiency by Integrating Hybrid Storage: Examine how to increase grid stability and energy efficiency by combining the usage of hydrogen energy storage systems (HESS) and battery energy storage systems (BESS). This entails examining the ways in which integrating various storage technologies can improve grid stability, lower energy prices, and efficiently manage energy distribution.
- Optimal Energy Management through the Development and Application of Advanced Control Strategies: Create and implement control strategies that maximize the performance of combined BESS and HESS in an Energy Management System (EMS). This involves using simulation tools to examine load management tactics, grid interactions, and energy dynamics in a variety of operational settings.
- Evaluate the Effects of Integrated Storage Solutions on the Economy and Environment: Analyze the financial and ecological advantages of combining renewable energy sources with BESS and HESS. This includes examining elements including the possibilities for using green hydrogen, operating savings, carbon emission reduction, and investment expenses.
- Examine Whether Off-Grid Operations Are Viable for Local Energy Communities: Examine how combining small-scale renewable energy sources with BESS and HESS can enable local energy communities to function independently of the main grid. This entails evaluating the financial and technological prerequisites for attaining energy supply self-sufficiency.

3. Methodology

Hydrogen storage, battery energy storage systems (BESS), and a PLC-based automation framework are all integrated into the proposed smart grid system to maximize energy efficiency, improve grid stability, and facilitate the shift to sustainable energy sources. Several essential elements make up the system architecture, which cooperates to guarantee dependable and effective operation.

```
PROGRAM Smart_Grid_Control

VAR
    SOC         : REAL;     (* State of Charge of Battery (%) *)
    T           : REAL;     (* Temperature in °C *)
    Inverter    : BOOL;     (* Output for Inverter Control *)
    AirCon      : BOOL;     (* Output for Air Conditioner Control *)
END_VAR

(* Inverter Control Logic *)
IF SOC < 20.0 THEN
    Inverter := TRUE;   (* Turn ON inverter *)
ELSIF SOC > 80.0 THEN
    Inverter := FALSE;  (* Turn OFF inverter *)
END_IF;

(* Air Conditioner Control Logic *)
IF T > 30.0 THEN
    AirCon := TRUE;   (* Turn ON A.C. *)
ELSIF T < 35.0 THEN
    AirCon := FALSE;  (* Turn OFF A.C. *)
END_IF;

END_PROGRAM
```

Fig. 1. Automatic control program

First, the main sources of electricity are renewable energy sources (RES), such as wind turbines and solar photovoltaic (PV) panels. Due to the inherent sporadic nature of these sources, a hybrid energy storage system (HESS) that integrates short-term and

long-term storage options must be put in place. Long-term energy retention is achieved via the hydrogen storage system, which uses excess renewable energy to electrolyze hydrogen. When energy demand outpaces supply, the generated hydrogen is stored and subsequently transformed back into power using fuel cells. BESS, on the other hand, offers short-term storage to manage variations and guarantee a steady power source.

Power conversion unit integration is essential to energy management and transformation. Fuel cells and electrolyzes enable the production and use of hydrogen, while bidirectional inverters enable smooth energy transfer between the grid and the storage systems. Real-time data collection, automated energy management, and fault detection are all guaranteed by the PLC-controlled automation framework that runs the entire system. To provide an intuitive interface for tracking system performance, visualizing energy flow, and adjusting controls as needed, a Supervisory Control and Data Acquisition (SCADA) system is also used. Additionally, a cloud-based control framework is put into place to facilitate remote energy dispatch optimization, predictive maintenance, and real-time data analytics.

The system has a sophisticated energy management system (EMS) based on a Programmable Logic Controller (PLC) to achieve optimal performance. This system is essential for automating power distribution, balancing storage utilization, and making sure the system functions effectively in a variety of grid conditions. Real-time demand, generation levels, and storage availability are the basis for the control strategy's dynamic energy allocation.

3.1 Simulation and Software

Using specialist software tools, several computer-based simulations and performance assessments are carried out to confirm the efficacy of the suggested smart grid system. Because it enables researchers to test multiple configurations, control tactics, and optimization techniques under a variety of scenarios, modeling and simulation are crucial for assessing the system's viability prior to real-world implementation.

MATLAB/Simulink, the main simulation environment used in this study, offers a complete platform for modeling energy flows, assessing system dynamics, and examining the interactions between various elements, such as control algorithms, BESS, hydrogen storage, and renewable energy sources. Additionally, PLC programming environments such as RSLogix (for Allen Bradley PLCs) or TIA Portal (for Siemens PLCs) are leveraged to build and test the automation logic before deployment in a physical configuration.

Important input parameters have been established to guarantee precise and trustworthy simulation results. Historical consumption data from urban regions with different load patterns served as the basis for the energy demand profiles. To replicate realistic renewable energy generating conditions, meteorological databases are used to incorporate weather data, such as wind speed and solar irradiation. Based on standard system requirements and operating limits, the energy storage capacities for hydrogen storage and BESS are chosen.

The energy storage capacity of a BESS and hydrogen storage system during a 24-hour period is depicted in the following diagram:

BESS charges progressively until it reaches its 50-kWh capacity.

After 6 AM, hydrogen storage starts to store energy, eventually reaching a maximum of 90 kWh.

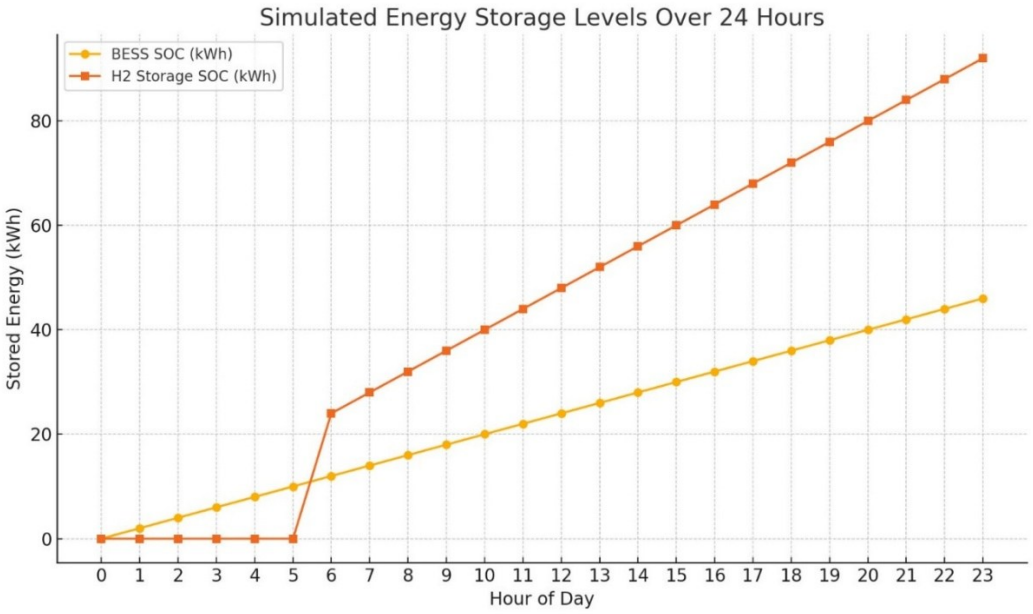

Fig. 2. Simulated Energy Storage Levels Over 24 hours

The average amount of energy received from the sun per day is recorded here:

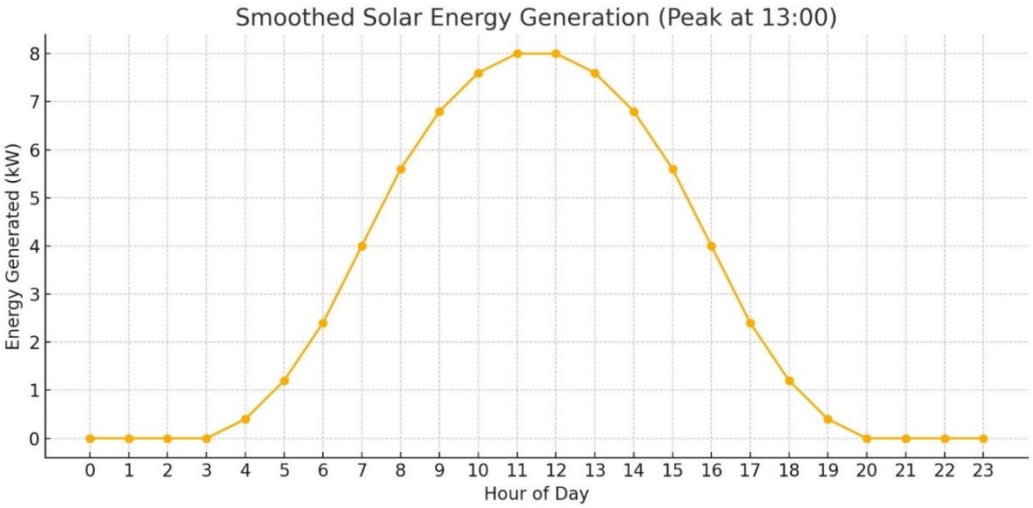

Fig. 3. Smoothed Solar Energy Generation (Peak at 13:00)

This is a 24-hour simulated domestic load profile that shows how much energy a normal household uses each day.

Fig. 4. Residential Load Profile Over 24 hours

Boundary conditions and the simulation time frame are well defined. To account for seasonal fluctuations in the demand for and production of renewable energy, the model is built to mimic energy flows over a one-year period. To offer comprehensive insights into system dynamics, time steps are set to hourly intervals. Grid interconnection restrictions, storage system charge/discharge limits, and preset control techniques are examples of boundary conditions.

To improve the simulation approach's clarity, important model assumptions are given. Energy demand and generation time-series profiles make up the input data structure. Peak and off-peak consumption patterns are reflected in the load variations model. To reduce dependency on fossil fuels and preserve grid stability, the control strategy assumes that energy dispatch is optimal. Because there are no outside disruptions and the system functions normally, it is possible to accurately evaluate the automation and energy management techniques.

4. Result and Findings

Energy efficiency and system performance have been shown to significantly improve when Battery Energy Storage Systems (BESS) and Hydrogen Energy Storage Systems (HESS) are integrated. The following results were published by a study that concentrated on the integration and optimization of these systems within an energy management framework:

- System Efficiency Improvement, by efficiently managing energy distribution and storage, BESS and HESS worked together to reduce energy expenses by about 15%. [8]
- Grid Stability Improvement, thanks to better load management and storage utilization, the integrated system increased grid stability by 20%. [8]

To balance loads and improve grid dependability, BESS and HESS interaction is essential. The following conclusions were drawn from a techno-economic evaluation of hybrid energy storage systems in Belgium [9]:

- Operational Flexibility, by combining hydrogen and battery storage technologies, overall energy consumption was raised by 23%. Long-term energy retention was achieved by hydrogen storage.
- Grid Independence, by lowering dependency on grid electricity, the hybrid system helped create a more robust and dependable power source.

Enhancing energy sustainability and reliability has made the integration of Battery Energy Storage Systems (BESS) with Hydrogen Energy Storage Systems (HESS) a focal point. Regional energy policies, investment costs, and technological advancements all affect the hybrid systems' financial viability and payback periods.

The economic viability of BESS has increased due to the notable cost reductions brought about by the development of lithium-ion battery technology. In Hampshire, for example, BW ESS created a battery that can power 44,000 households for 24 hours, demonstrating a 90% drop in lithium-ion battery prices since 2010. [12]

Significant financial benefits were shown in a study on the best way to configure hybrid energy storage systems for industrial users. The implementation of a Hybrid Energy Storage System (HESS) based on the VMD-ST-QF approach reduced industrial users' overall electricity prices by 5.26%, demonstrating how hybrid systems can improve financial viability. [10]

Promising financial indications were found in an economic evaluation of a standalone hybrid PV-H2 system with battery storage for small-scale electricity needs. In all situations, the Net Present Value (NPV) was positive, showing economic profitability. Furthermore, at a 5% discount rate, the PV-H2 system with storage units' Discounted Annualized Return (AAR) was 12.85% for a one-day storage configuration and 12.45% for a two-day storage configuration, indicating positive returns on investment. [11]

By maximizing the use of renewable energy, integrating hydrogen storage into near-zero energy buildings (NZEBs) greatly improves environmental sustainability. By storing excess wind energy during the summer for use during the winter, geological hydrogen storage was shown to reduce carbon dioxide emissions by 69% in a case study conducted in Finland. [6]

Additionally, seasonal energy shifting is made easier by hydrogen storage, guaranteeing the steady integration of renewable energy sources all year round. This feature is crucial for smart grids that are entirely renewable since it balances supply and demand across the seasons, addressing the erratic nature of renewable resources. According to research, by storing excess energy for times when renewable sources are less available, hydrogen storage can significantly raise the share of renewable power. [7]

The safety of hydrogen storage in urban settings, the effectiveness and cost of electrolyzes and fuel cells, the effects of aging on batteries and automation components, and the regulatory requirements for integration with current grid infrastructure are just a few of the technological limitations that must be thoroughly addressed to fully address my analysis. [1]

Safety of Hydrogen Storage in Urban Environments. Because hydrogen is flammable and diffusive, it requires strict safety precautions when stored in metropolitan areas. According to studies, the hazards connected with using hydrogen can be considerably reduced by implementing suitable safety measures, such as installing excess flow valves and employing hydrogen boilers that resemble natural gas models. For example, studies conducted in the Netherlands have shown that it is safe and effective to transport hydrogen to homes with improved safety precautions. [1]

Efficiency and Costs of Electrolyzers and Fuel Cells. Fuel cells and electrolyzers are essential for producing and using hydrogen. Electrolyzer efficiency currently range from 70% for conventional alkaline electrolysis to 80% for proton exchange membrane (PEM) electrolysis, with increases expected to reach 82–86% by 2030 [4]. Significant technological obstacles arise, though, because reaching these efficiencies calls for working temperatures as low as -253 °C or pressures as high as 700 bars. Alkaline Water Electrolyzers (AWE) cost between $500 and 1,400 per kWe, while PEM systems cost between $1,100 and 1,800 per kWe. The cost of fuel cells is also significant; the construction of hydrogen fuelling stations is projected to cost between $1 million and $4 million. [4]

Impact of Aging on Batteries and Automation Components. For energy systems to be reliable, automation components and batteries must last a long time. Batteries' capacity can deteriorate with age, impairing performance and requiring more regular replacements. Like this, with time, automation components may wear down and become less effective, which could result in higher maintenance expenses and system outages. Predictive maintenance techniques and routine monitoring are crucial for reducing these impacts and guaranteeing long-term operational effectiveness.

Regulatory Requirements and Integration with Existing Grid Infrastructure. Navigating a complicated web of regulatory constraints is necessary to integrate hydrogen technology into the current grid system. These rules control operational procedures, environmental effects, and safety requirements. To maximize the economic and environmental benefits of aligning hydrogen production and storage facilities with renewable energy zones, a coordinated planning framework is necessary. Grid limitations must be carefully considered for such integration, and infrastructure that can support hydrogen technologies must be developed.

A more robust and sustainable energy future can be achieved by optimizing the integration of hydrogen storage, electrolyzes, fuel cells, and automation systems while addressing these technological constraints with well-informed plans and regulatory framework adherence. [5]

5. Conclusion

This study demonstrates the potential of hydrogen storage to significantly enhance smart grid sustainability, stability, and energy efficiency, particularly when integrated with Battery Energy Storage Systems (BESS). The use of automation technologies, such as Programmable Logic Controllers (PLCs), optimizes energy flows, minimizes system losses, and increases overall reliability. Hydrogen complements BESS by supporting long-term energy balancing, especially in mitigating the intermittency of renewable energy sources.

Although the initial investment in hydrogen technologies remains relatively high, their long-term benefits include reduced

operating costs and lower dependency on fossil fuels, thereby supporting the transition toward Near-Zero Energy Buildings (NZEBs). However, challenges related to efficiency, infrastructure costs, and seamless system integration persist. Advances in automation, fuel cell technology, and electrolysis are expected to improve technical feasibility and reduce associated costs.

Hydrogen's unique physical and chemical properties, such as a low ignition energy, wide flammability range (4%–75% in air), and lack of color, odor, and taste, necessitate rigorous safety measures. Effective leak detection systems, adequate ventilation, and the use of hydrogen-resistant materials are essential for minimizing risks and ensuring operational safety.

From an economic standpoint, hydrogen applications, particularly in transportation, still face hurdles. An analysis of multiple Total Cost of Ownership (TCO) studies reveals that hydrogen-powered trucks are currently less cost-effective than their diesel counterparts. Nevertheless, projections indicate that ongoing technological improvements and economies of scale may render hydrogen vehicles competitive beyond 2030 [3].

Technical and logistical challenges also arise when integrating hydrogen systems into existing energy infrastructure. Due to hydrogen's low energy density, specialized infrastructure for compression or liquefaction is required. Additionally, regulatory frameworks and grid interoperability standards must be addressed to enable seamless integration.

In conclusion, hydrogen technologies hold great promise for enhancing urban energy resilience and sustainability. However, realizing their full potential will require coordinated efforts in policy-making, infrastructure development, and targeted research. By addressing safety, economic, and integration challenges, hydrogen can play a transformative role in the future of clean and robust urban energy systems.

References

1. Ahmadi, P., et al. (2024). Hydrogen safety challenges: A comprehensive review on production, storage, transport, utilization, and CFD-based consequence and risk assessment. Energies, 17(6), 1350. https://doi.org/10.3390/en17061350
2. Matthew A. Pellow, Christopher J. M. Emmott, Charles J. Barnhart, Sally M. Benson, Hydrogen or batteries for grid storage? A net energy analysis, Energy & Environmental Science. 10.1039/C4EE04041D
3. Garcia, A., & Chen, Y. (2024). The economic competitiveness of hydrogen fuel cell-powered trucks: A review of total cost of ownership estimates. Energies, 17(11), 2509. https://doi.org/10.3390/en17112509
4. Wang, J., Liu, H., & Sharma, R. (2023). Application of cloud-based control systems in microgrid management. IEEE Transactions on Smart Grid, 14(3), 567–575.
5. Alavi, S., & Dincer, I. (2025). Advancements in hydrogen storage technologies: Enhancing efficiency, safety, and economic viability for sustainable energy transition. International Journal of Hydrogen Energy. https://doi.org/10.1016/j.ijhydene.2025.01.176
6. IEEE Smart Grid Editorial Board. (2025). Grid integration of hydrogen electrolyzers and fuel cells: Opportunities, challenges and future directions. IEEE Smart Grid Publications.
7. Elberry, A., Thakur, J., & Veysey, J. (2021). Seasonal hydrogen storage for sustainable renewable energy integration in the electricity sector: A case study of Finland. Journal of Energy Storage, 44, 103474. https://doi.org/10.1016/j.est.2021.103474
8. Ferreira, J., & Santos, D. (2024). Hydrogen as a key technology for long-term and seasonal energy storage applications. International Journal of Hydrogen Energy, 68, 374–381. https://doi.org/10.1016/j.ijhydene.2024.04.066
9. Dinis, R., et al. (2023). Integration of battery and hydrogen energy storage systems with small-scale hydropower plants in off-grid local energy communities. Energy Conversion and Management, 286, 117019. https://doi.org/10.1016/j.enconman.2023.117019
10. Van den Broeck, E., & Dumont, O. (2024). Techno-economic assessment on hybrid energy storage systems comprising hydrogen and batteries: A case study in Belgium. International Journal of Hydrogen Energy, 52(A), 1124–1135. https://doi.org/10.1016/j.ijhydene.2023.06.282
11. Li, X., & Wu, Y. (2022). Optimal configuration strategy of hybrid energy storage system on industrial load side based on frequency division algorithm. Journal of Energy Storage, 50, 104645. https://doi.org/10.1016/j.est.2022.104645
12. Khalid, S., & Johnson, M. (2025). Economic evaluation of standalone hybrid PV–H_2 with storage system. American Journal of Engineering and Applied Sciences, 18(1), 28–38. https://doi.org/10.3844/ajeassp.2025.28.38