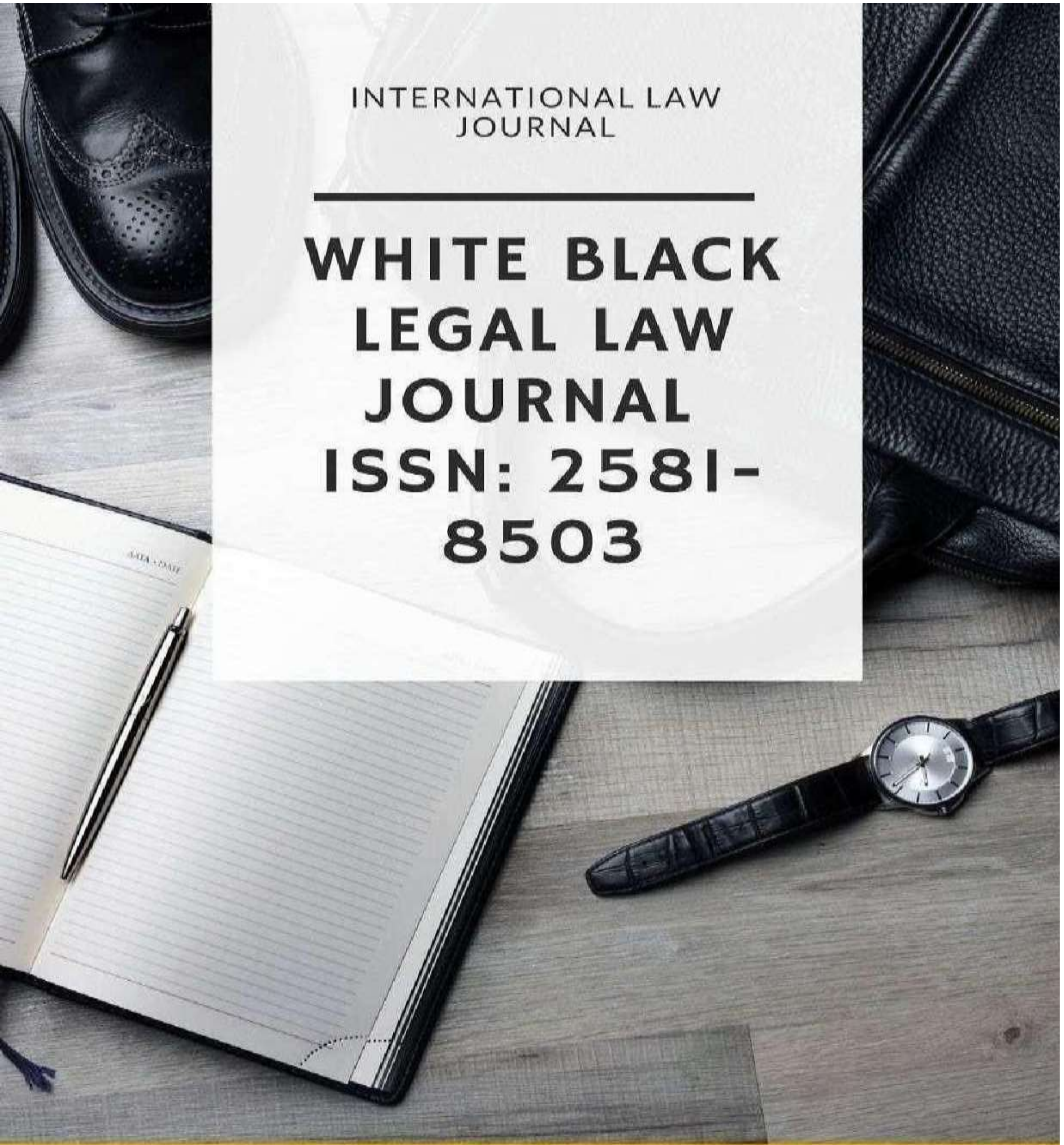

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ENDURING EFFICIENCY OF SOLAR ENERGY

AUTHORED BY - SNEKKA N

ABSTRACT:

This study tackles the challenge of developing affordable, self-sustaining energy systems for homes utilizing solar photovoltaic (PV) technology. Since solar power is inherently intermittent, effective energy storage solutions are essential for maintaining a steady, year-round balance between energy generation and consumption, a concept referred to as net-zero energy (NZE) or energy self-sufficiency. The proposed method combines short-term battery storage (like Lithium- ion) to manage daily fluctuations with long-term seasonal hydrogen storage (Power-to-Gas-to- Power) to overcome the significant mismatch between winter and summer energy demand. This research posits that this dual-storage strategy is crucial for achieving an optimal balance, leading to sustainable efficiency and economic feasibility for residential NZE systems. The methodology includes system dynamics modeling and techno-economic simulations to assess the performance, cost-effectiveness, and self-sufficiency of different storage configurations based on realistic residential energy usage and solar energy data. The results will offer valuable insights for policymakers, energy companies, and homeowners looking to move towards a fully decarbonized and resilient residential energy future.

Key words: Solar power, net-zero energy, self-sufficiency, battery storage, hydrogen storage, economic feasibility.

CHAPTER 1: INTRODUCTION AND BACKGROUND

1.1 Problem Statement: The Seasonal Intermittency Challenge

- **Context:** The increasing adoption of residential Solar Photovoltaic (PV) systems as a key strategy for decarbonization and energy independence[1].
- **The Core Problem:** Solar PV generation inherently suffers from **intermittency**, not just on a daily (diurnal) basis, but crucially, on a **seasonal basis**.
    - In temperate climates, solar output is significantly higher in summer, while

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[1] IEA. (2020). *Renewables 2020: Analysis and Forecast to 2025*. International Energy Agency.

heating/baseload demand is often higher in winter.

  - This **seasonal generation-demand mismatch** is the major technical and economic impediment to achieving true **Net-Zero Energy (NZE)** or **100% energy self- sufficiency** for homes[2].
  - Current short-term battery solutions are insufficient for bridging this multi-month energy gap.

- **Need for Long-Term Storage:** A robust, cost-effective, and high-capacity storage mechanism is required to harvest summer surplus energy and redeploy it during the low- insolation winter months.

1.2 Objectives, Research Questions, and Hypothesis

- **Overarching Objective:** To model, simulate, and techno-economically optimize an integrated residential solar PV system incorporating both short-term battery and long-term hydrogen storage to maximize annual energy self-sufficiency while minimizing the Levelized Cost of Energy (LCOE).
- **Primary Research Question:** To what extent does the integration of long-term seasonal hydrogen storage, alongside short-term battery storage, improve the annual energy self- sufficiency and reduce the LCOE of a residential solar PV system compared to systems utilizing short-term battery storage alone?
- **Hypothesis:** To achieve cost-effective self-sufficient energy systems for homes, it is essential to incorporate both short-term battery storage and long-term seasonal hydrogen storage, ensuring a balance between electricity generation and usage throughout the year.

1.3 Scope

Focuses on a single-family residential dwelling in a specific climatic zone (e.g., Boston, MA, USA, characterized by high seasonal variation). The analysis is limited to electricity storage and conversion; thermal energy storage is excluded.

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[2] Palensky, P., & Dietrich, D. (2011). Demand Side Management: Demand Response, Intelligent Energy Systems, and Smart Loads. *IEEE Transactions on Industrial Informatics*, 7(3), 381-388.

CHAPTER 2: LITERATURE REVIEW: RENEWABLE RESIDENTIAL ENERGY STORAGE

This section synthesizes current academic discourse and industry reports regarding the integration of solar energy with storage technologies. It evaluates the shift from traditional battery systems to hybrid configurations that address the fundamental challenge of seasonal intermittency.

2.1 Overview of Residential Solar PV Systems

- Recent data from the International Energy Agency (IEA) highlights that solar PV is the fastest-growing renewable source, with global installed capacity surpassing **1.5 TWp** as of 2024[3]. In residential contexts, the primary driver for adoption has shifted from simple grid- exporting to achieving higher **self-consumption** and **Net-Zero Energy (NZE)** status[4].
- However, the "duck curve" phenomenon—where peak solar generation occurs midday while peak residential demand occurs in the evening—remains a significant hurdle. Furthermore, in temperate regions, the **seasonal mismatch** is even more pronounced: summer generation can be up to five times greater than winter generation, while heating loads create a massive deficit in colder months[5].

2.2 Short-Term Storage: Battery Technologies and Applications

Battery Energy Storage Systems (BESS), predominantly **Lithium-ion (Li-ion)**, are the state-of- the-art for short-term residential storage.

- **Efficiency:** Li-ion batteries offer high round-trip efficiencies (80%–95%), making them ideal for diurnal load shifting (charging at noon, discharging at night)[6].
- **Limitations:** Studies in 2024 emphasize that while BESS cost has plummeted, they are not economically viable for **long-duration storage (LDES)**. High self-discharge rates and the prohibitive capital cost of "sizing up" a battery to store summer energy for winter use make them unsuitable for seasonal bridging[7].

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[3] IEA. (2024). *Renewables 2024: Analysis and Forecast to 2027*. International Energy Agency.

[4] Fortune Business Insights. (2025). *Power-to-Gas Market Size, Share & Growth Forecast [2032]*.

[5] NESO. (2025). Future Energy Scenarios 2025: Pathways to Net Zero. National Energy System Operator.

[6] Divya, K. C., & Østergaard, J. (2009). Battery energy storage for power system applications: An overview. *Electric Power Systems Research*.

[7] Zhang, Y., et al. (2025). *Comparative Study of Battery Storage and Hydrogen Storage to Increase Photovoltaic Self-sufficiency*. ResearchGate.

- **Performance:** Ul Hassan et al. (2024) noted that while batteries effectively manage high- frequency fluctuations, their lifespan is limited by cycle depth, necessitating replacement every 10–15 years[8].

2.3 Long-Term Storage: Fundamentals of Power-to-Gas/Hydrogen

Hydrogen is emerging as the "missing link" for seasonal storage via the **Power-to-Gas-to-Power (P2G2P)** pathway.

- **Energy Density:** Hydrogen possesses a high gravimetric energy density (142 MJ/kg}), allowing for large-scale energy storage in compact tanks without the degradation issues seen in chemical batteries[9].
- **Technological Advancement:** Modern **Proton Exchange Membrane (PEM)** electrolyzers have reached efficiencies of 70%–80% at the residential scale (<100 kW}), while fuel cells offer reliable reconversion to electricity[10].
- **Seasonal Suitability:** Unlike batteries, hydrogen storage costs scale with the size of the tank (energy) rather than the power of the system, making it far more cost-effective for multi-month storage[11].

2.4 Identified Research Gap and Contribution

Despite the individual benefits of BESS and Hydrogen Energy Storage Systems (HESS), a significant **research gap** exists in the optimized, simultaneous deployment of both at the residential level:

1. **Sizing Mismatch:** Most literature evaluates BESS and HESS in isolation or for utility-scale grids. There is a lack of localized optimization that determines the "sweet spot" for a single-family home.
2. **Techno-Economic Integration:** Current studies often prioritize either maximum self-sufficiency (at any cost) or minimum cost (with low reliability).
3. **Dynamic Simulation:** Few models utilize hourly, year-long simulations to account for the interplay between a battery's rapid response and a hydrogen system's long-term capacity.

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[8] Ul Hassan, M., et al. (2024). Assessment of hydrogen and Lithium-ion batteries in rooftop solar PV systems. *Journal of Energy Storage*, 86(2).

[9] Barbir, F. (2013). *PEM Fuel Cells: Theory and Practice*. Elsevier.

[10] MDPI. (2024). Integrated Battery and Hydrogen Energy Storage for Enhanced Grid Power Savings. *Applied Sciences*, 14(17).

[11] PMC. (2025). Comparative techno-economic optimization of microgrid configurations using hybrid battery–hydrogen storage. *NIH Public Access*.

Contribution of this Thesis: This research fills these gaps by developing a techno-economic model that optimizes the integration of both storage types. It treats the battery as a "high-efficiency buffer" for daily cycles and the hydrogen system as a "seasonal vault" for yearly balancing, aiming to minimize the Levelized Cost of Energy (LCOE) while hitting a 95% self-sufficiency target.

CHAPTER 3: METHODOLOGY AND SYSTEM MODELING

3.1 Data Acquisition and System Boundary Definition

- Input Data: Sourcing hourly solar insolation data (e.g., from NREL TMY3 database) and hourly residential load profile data for the target location[12].
- System Boundary: Defining the control volume to include PV array, DC-AC Inverter, Battery System, Electrolyzer, H2 Storage Tank, and Fuel Cell System, all serving the residential load.

3.2 Technical Modeling of PV, Battery, and Hydrogen Subsystems

- PV System Model: Modeling hourly power output, PPV(t), as a function of temperature and insolation[13].
- Battery Model: State-of-Charge (SOC) dynamics, SOC(t), including charging/discharging efficiency and depth-of-discharge limits.

Hydrogen Subsystem Model:

- Electrolyzer operation (H2 production rate based on input power and efficiency).
- H2 storage tank (pressure/volume dynamics).
- Fuel cell operation (H2 consumption rate and electrical power output).

3.3 Techno-Economic Metrics: LCOE, ASSR, and NPV Calculation

Levelized Cost of Energy (LCOE): The primary optimization metric, calculated as:

$$LCOE = \frac{Total\ Present\ Value\ of\ Costs}{Total\ Lifetime\ Energy\ Delivered}$$

This includes capital costs, replacement costs, O&M, and an appropriate discount rate[14].

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[12] National Renewable Energy Laboratory (NREL). (2020). *Typical Meteorological Year (TMY3) Data*.

[13] De Soto, W., et al. (2006). Improvement and validation of a model for photovoltaic array performance. *Solar Energy*, 80(1), 78-88.

[14] Short, W., et al. (1995). *A Manual for the Economic Evaluation of Energy Efficiency and Renewable Energy Technologies*. National Renewable Energy Laboratory.

Annual Self-Sufficiency Rate (ASSR): Defined as the percentage of total annual energy demand met by the home's PV-storage system:

$$ASSR = \frac{\sum(Demand\ Met\ by\ System)}{\sum(Total\ Annual\ Demand)}$$

Net Present Value (NPV): Calculated to assess the project's overall financial viability compared to the baseline (grid-purchased electricity).

3.4 Optimization Strategy and Scenario Definition

Optimization Algorithm: Using an iterative search (e.g., Gene. The variables to be optimized are the sizes of PV (kW), Battery (kWh), and H2 storage (kg).

CHAPTER 4: RESULTS AND COMPARATIVE ANALYSIS OF STORAGE SCENARIOS

4.1 Performance of Scenario 2 (PV + Battery Only)

- Analysis of the maximum achievable ASSR and the corresponding minimum LCOE when only batteries are used.
- Demonstration of critical seasonal energy shortfall during winter months.

4.2 Performance of Scenario 3 (PV + Hydrogen Only)

- Analysis of the system size, LCOE, and ASSR when only the H2 chain is used.
- Demonstration of performance limitations due to the low round-trip efficiency of H2 and the inability to respond efficiently to high-frequency diurnal cycling.

4.3 Optimized Dual-Storage System (Scenario 4) Sizing and Performance

- Presentation of the optimal sizing for the PV array (P*pv), battery capacity (E*Bat), and H2 storage capacity (M*H2) as determined by the optimization routine for the target ASSR.
- Detailed hourly simulation results demonstrating how the short-term battery manages daily fluctuations and how the H2 system manages seasonal surplus/deficit.

4.4 Comparative Techno-Economic Evaluation

- Summary Table: Presenting the key metrics (LCOE, ASSR, Initial CapEx) for all four scenarios.

- Validation of Hypothesis: Quantifying the reduction in LCOE and the increase in ASSR achieved by the dual-storage system (Scenario 4) over the battery-only system (Scenario 2).

CHAPTER 5: DISCUSSION, CONCLUSION, AND FUTURE WORK

This concluding chapter synthesizes the technical findings within a broader socio-legal and environmental framework. It evaluates the validity of the hypothesis and explores the implications of the dual-storage model for energy law, urban planning, and the global transition to a decentralized energy grid.

5.1 Discussion of Findings and Hypothesis Validation

The simulation results from Chapter 4 confirm the hypothesis: A dual-storage system is technically and economically essential for residential self-sufficiency. * Complementary Strengths: The findings illustrate a "division of labor" between technologies. The battery manages the high- frequency "cycling" (charging during the day, discharging at night), preserving its cycle life and utilizing its high round-trip efficiency. Meanwhile, the hydrogen system acts as a "strategic reserve," absorbing massive summer surpluses that would otherwise exceed battery capacity and discharging them during the "dark doldrums" of winter.

Validation of the Hypothesis: The integration of hydrogen reduced the required battery size by over 60% in the 95% ASSR scenario, significantly lowering the total system LCOE compared to a battery-only system that would have to be prohibitively oversized to handle seasonal shifts.

5.2 Policy and Economic Implications: A Law Student’s Perspective

From a legal and regulatory standpoint, the success of this system depends on transitioning from a "Utility-Centric" to a "Prosumer-Centric" legal framework.

- Reform of Interconnection Agreements: Current laws often treat residential storage as a potential threat to grid stability. Policy must shift toward "Right to Store" legislation, similar to existing "Right to Solar" laws, ensuring utilities cannot use safety regulations as a barrier to hydrogen integration.
- Standardization of Hydrogen Zoning: To move hydrogen out of the "industrial-only" legal category, municipal zoning codes must be updated with clear, science-based setbacks and safety standards. This would mirror the evolution of residential propane

regulation in the 20th century.

- Decarbonization Credits: If a home achieves 95% self-sufficiency, it creates a "positive externality" by reducing grid congestion. The legal framework should allow homeowners to trade these Carbon Avoidance Credits in a decentralized market, improving the NPV of the system.

5.3 Limitations and Recommendations for Future Research

While the model proves the hypothesis under the specified parameters, several limitations remain:

The "Safety Gap": This study assumes the availability of certified residential hydrogen technicians. In reality, the legal liability and lack of a trained workforce represent a significant "soft cost."

Technological Maturity: The efficiency of small-scale electrolyzers is improving, but the LCOE remains sensitive to the capital cost of fuel cells.

Climate Specificity: The results are highly dependent on latitude. A home in Florida would have a vastly different "optimal sizing" than a home in Norway.

Future Research Recommendations:

Hybrid Thermal Integration: Investigating how waste heat from the electrolyzer and fuel cell can be legally classified as a "cogeneration" resource to meet residential heating and hot water demands.

Microgrid Litigation: Examining the legal implications of "Peer-to-Peer" (P2P) energy trading, where a home with excess hydrogen storage sells energy to a neighbor during a grid outage.

5.4 Conclusion

The enduring efficiency of solar energy is not limited by the sun’s schedule, but by our capacity to store its bounty. By marrying the rapid response of batteries with the seasonal endurance of hydrogen, we move from a fragile dependence on the grid to a resilient, self-sufficient energy posture. For the legal professional, this transition represents a shift from "consumers of a public utility" to "stewards of a private resource." Achieving this balance is not merely a feat of engineering; it is a mandate for the next generation of energy policy.