Based on Research Theses during Master of Science Economics at BITS Pilani

Optimizing Energy Offsets with Hybrid Nuclear Energy and Hydrogen Yield

Abstract

Nuclear energy is a cornerstone of low-carbon electricity generation, offering a reliable and scalable energy source. Beyond electricity, nuclear energy's potential for hydrogen production positions it as a key enabler of a sustainable and decarbonized energy future. This paper presents an optimization framework for hybrid nuclear-hydrogen systems, focusing on dynamically allocating nuclear energy between electricity generation and hydrogen production. The model accounts for fluctuating electricity and hydrogen demands, nuclear resource constraints, and the evolving economic value of stored hydrogen.

By integrating hydrogen storage and reconversion capabilities, the proposed model enhances energy system flexibility and resilience, mitigating renewable energy intermittency while supporting decarbonization goals. The study examines various scenarios, including favorable and unfavorable hydrogen valuation trends, demonstrating how adaptive task allocation minimizes energy offsets and maximizes system efficiency. Results highlight the potential of hybrid nuclear-hydrogen systems to achieve greater economic resilience, scalability, and policy alignment compared to existing single-source and hybrid models.

This work contributes to the broader discourse on sustainable energy systems by providing actionable insights for optimizing resource utilization, enhancing grid stability, and advancing hydrogen economy strategies. The findings have significant implications for policymakers, energy planners, and industries aiming to achieve carbon neutrality.

1 Existing Studies in Energy Optimization Models

Energy optimization models have been extensively studied to address challenges in resource allocation, demand management, and system integration. This section summarizes key contributions and highlights the potential of the hybrid nuclear + hydrogen model.

1.1 Overview of Existing Studies

- **Single-Source Models:** Studies have optimized the operation of single energy sources like nuclear reactors or renewables. For instance, Forsberg et al. (2020) demonstrated the load-following capabilities of nuclear reactors to complement renewables [3], while Zhao et al. (2019) optimized solar energy generation with battery storage [8].
- **Hybrid Energy Systems:** Boardman et al. (2021) explored nuclear-renewable hybrid systems, showing their potential for decarbonizing grids [1]. Gutiérrez-Martín and Guerrero-Lemus (2020) modeled renewable-hydrogen systems for balancing demand and storage [5].
- **Energy Storage Models:** Studies by Schiebahn et al. (2015) evaluated hydrogen storage systems, highlighting their role in integrating renewables [7], while Castillo and Gayme (2016) optimized battery storage for grid stability [2].
- **Integrated Systems:** Integrated models, such as those using MARKAL/TIMES frameworks, have optimized energy systems across multiple sectors [6], while Garcia and Roberts (2020) developed nuclear-renewable-hydrogen models tailored to regional demands [4].

1.2 Advantages of the Hybrid Nuclear + Hydrogen Model

The hybrid nuclear + hydrogen model combines the reliability of nuclear energy with the flexibility of hydrogen as an energy carrier. Key advantages include:

Table 1: Comparison of Energy Optimization Models: Part 1

Methodology	Continuous Supply	Decarbonization	Resource Utilization
Single-Source Models	3	4	3
Hybrid Systems Models	4	5	4
Energy Storage Models	3	4	4
Integrated Systems Models	5	5	5
Multi-Objective Models	4	5	4
Hybrid Nuclear + Hydrogen Models	5	5	5

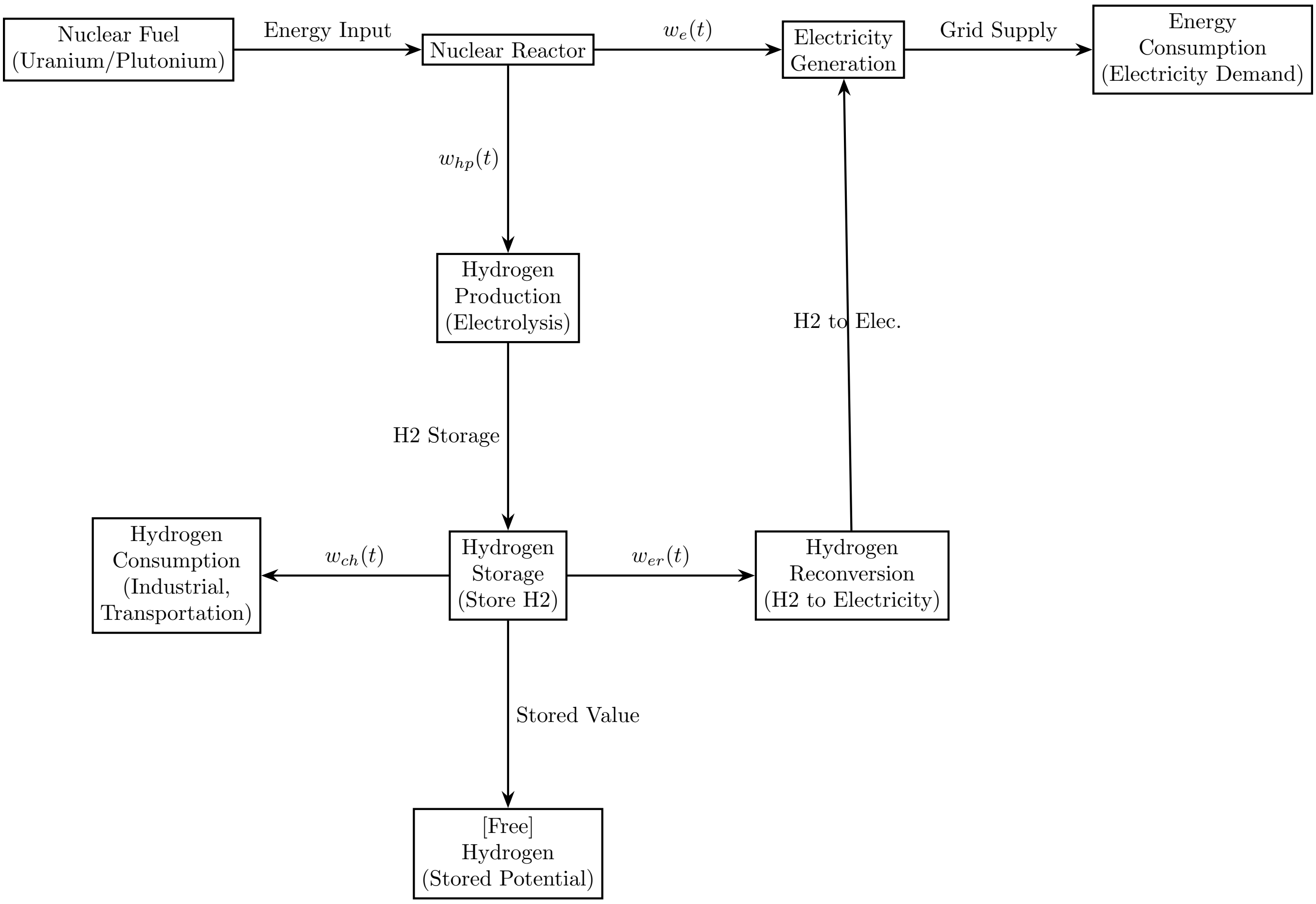
Table 2: Comparison of Energy Optimization Models: Part 2

Methodology	Grid Stability	Economic Resilience	Scalability
Single-Source Models	2	3	3
Hybrid Systems Models	5	4	4
Energy Storage Models	4	4	3
Integrated Systems Models	5	5	4
Multi-Objective Models	5	5	4
Hybrid Nuclear + Hydrogen Models	5	5	5

- **Continuous Energy Supply:** Nuclear reactors provide stable baseload power, while hydrogen production enables energy storage and demand peak management.
- **Decarbonization Potential:** Low-carbon hydrogen production supports industrial applications, transportation, and grid balancing, significantly reducing reliance on fossil fuels.
- **Grid Stability and Flexibility:** Hydrogen storage mitigates renewable energy intermittency, while nuclear reactors with load-following capabilities adapt to demand fluctuations.
- **Economic Resilience:** The model monetizes surplus energy through hydrogen production, diversifying energy markets and enhancing financial viability.
- **Scalability and Future-Proofing:** The model is adaptable to both large-scale and localized energy systems, particularly with the deployment of Small Modular Reactors (SMRs).

1.3 Comparative Analysis

Table 1 and Table 2 compare methodologies across key challenges, highlighting the hybrid nuclear + hydrogen model's ability to address integration, scalability, and storage challenges more effectively than existing approaches.



2 Methodology

2.1 Objective Function

The model aims to minimize the difference between consumption and production, adjusted by the stored value of hydrogen. While ideally, we would minimize the absolute difference, for computational efficiency with linear programming solvers, we minimize the signed difference. The objective function is:

$$\text{Minimize Offset} = \sum_{t=1}^{T} \left(\left| \begin{array}{l} \underbrace{C_{\text{electricity}}(t) + w_{ch}(t) \cdot C_{\text{hydrogen}}(t)}_{\text{Consumption}(t)} \\ - \underbrace{(w_e(t) \cdot E_n \cdot \eta_n + w_{er}(t) \cdot H_r(t-1) \cdot Y_r)}_{\text{Production}(t)} \end{array} \right| - SV(t) \cdot H_r(t) \right)$$

Where:

- $w_e(t)$: Proportion of nuclear energy allocated to electricity generation at time t.
- E_n: Total nuclear energy capacity (MWh).
- η_n: Efficiency of nuclear electricity generation.
- $w_{ch}(t)$: Proportion of hydrogen allocated to non-electrical consumption at time t.
- $C_{\text{hydrogen}}(t)$: Hydrogen demand at time t (kg).
- $w_{er}(t)$: Proportion of stored hydrogen allocated to electricity reconversion at time t.
- $H_r(t)$: Hydrogen stored at time t (kg).
- Y_r: Conversion efficiency of hydrogen reconversion to electricity (MWh/kg).
- $C_{\text{electricity}}(t)$: Electricity demand at time t (MWh).

- $E_d(t)$: Electricity demand at time t (MWh).
- $E_r(t)$: Electricity generated from hydrogen reconversion at time t (MWh).
- $SV(t)$: Stored value of hydrogen at time t.

2.2 Demand Models

Electricity Demand Electricity demand fluctuates daily and annually based on energy needs:

$$C_{\text{electricity}}(t) = C_0 \cdot \left(1 + A \cdot \sin\left(\frac{2\pi t}{24}\right)\right)$$

Where:

- C_0: Baseline electricity demand.
- A: Amplitude of daily fluctuation.
- t: Time (in 30-minute intervals).

Hydrogen Demand Hydrogen demand reflects industrial and seasonal cycles, where the source is supplied hydrogen:

$$C_{\text{hydrogen}}(t) = C_0 \cdot \left(1 + A_h \cdot \sin\left(\frac{2\pi t}{12}\right)\right)$$

Where:

- A_h: Amplitude of seasonal hydrogen demand fluctuations.
- C_0: Baseline hydrogen demand.
- t: Time (in 30-minute intervals).

Stored Value of Hydrogen The stored value of hydrogen is modeled as:

$$SV(t) = (1 + g \cdot t) \cdot e^{-r \cdot t}$$

Where:

- g: Growth rate of hydrogen's value over time (per 30-minute interval).
- r: Discount rate applied to hydrogen's future value.
- t: Time (in 30-minute intervals).

2.3 Decision Weights

The decision weights control the allocation of nuclear energy to various tasks:

- $w_e(t)$: Weight for nuclear electricity generation at time t.
- $w_{hp}(t)$: Weight for nuclear-powered hydrogen production at time t.
- $w_{ch}(t)$: Weight for hydrogen consumption at time t.
- $w_{er}(t)$: Weight for hydrogen reconversion at time t.

2.4 Constraints

The constraints of the optimization model ensure physically realistic and logically consistent operation of the combined nuclear-hydrogen energy system.

Nuclear Energy Allocation (Time Allocation)

The nuclear energy generated at any time t can be allocated to either electricity generation or hydrogen production. The sum of the proportions allocated to these two tasks cannot exceed 1 (100

$$w_e(t) + w_{hp}(t) \leq 1, \quad \forall t$$

Where:

- $w_e(t)$: Proportion of nuclear energy allocated to electricity generation at time t.
- $w_{hp}(t)$: Proportion of nuclear energy allocated to hydrogen production at time t.

Hydrogen Balance (Storage Dynamics)

The amount of hydrogen stored at each time step is updated based on production, consumption, and reconversion. Assuming no initial hydrogen storage ($H_r(0) = 0$), the balance is defined as:

$$H_r(0) = 0$$
$$H_r(t) = H_r(t-1) + H_p(t) - w_{ch}(t) \cdot C_{\text{hydrogen}}(t) - w_{er}(t) \cdot H_r(t-1), \quad \forall t > 0$$
$$H_r(t) \geq 0, \quad \forall t$$

Where:

- $H_r(t)$: Hydrogen stored at time t (kg).
- $H_r(t-1)$: Hydrogen stored at the previous time step (kg).
- $H_p(t)$: Hydrogen produced at time t (kg).
- $w_{ch}(t)$: Proportion of stored hydrogen used for consumption at time t.
- $C_{\text{hydrogen}}(t)$: Hydrogen demand at time t (kg).
- $w_{er}(t)$: Proportion of stored hydrogen used for reconversion to electricity at time t.

Variable Bounds

All decision variables, which represent proportions or quantities, have defined bounds:

Weights The weights, representing proportions of energy or hydrogen, must be between 0 and 1:

$$0 \leq w_e(t), w_{hp}(t), w_{ch}(t), w_{er}(t) \leq 1, \quad \forall t$$

Hydrogen Production and Storage Hydrogen production and storage quantities must be non-negative:

$$H_p(t), H_r(t) \geq 0, \quad \forall t$$

Hydrogen Production The amount of hydrogen produced is determined by the proportion of nuclear energy allocated to hydrogen production, the total nuclear energy capacity, and the hydrogen production efficiency:

$$H_p(t) = w_{hp}(t) \cdot E_n \cdot Y_h, \quad \forall t$$

Where:

- $H_p(t)$: Hydrogen produced at time t (kg).
- $w_{hp}(t)$: Proportion of nuclear energy allocated to hydrogen production at time t.
- E_n: Total nuclear energy capacity (MWh).
- Y_h: Conversion efficiency of nuclear energy to hydrogen (kg/MWh).

3 Optimization Process

The optimization process seeks to balance energy consumption (both electricity and hydrogen) with energy production from nuclear resources, considering the stored value of hydrogen. The strategy adapts based on the relationship between the hydrogen value growth rate (g) and the discount rate (r). Because the electricity balance constraint has been removed, the model will not necessarily meet electricity demand at all times, but will try to minimize the difference between consumption and production overall.

Step 1: Favorable Valuation of Hydrogen ($g > r$) - Prioritize Hydrogen Storage

When the growth rate (g) exceeds the discount rate (r), the optimization prioritizes building up hydrogen storage as its future value is high. This means:

- A larger portion of nuclear energy will be allocated to hydrogen production ($w_{hp}(t)$ will tend to be higher).
- Reconversion of hydrogen to electricity ($w_{er}(t)$) will be minimized unless absolutely necessary to prevent very large shortfalls in electricity.
- The model may accept some shortfalls in meeting electricity demand to maximize hydrogen storage.

Step 2: Neutral Valuation of Hydrogen ($g = r$) - Balanced Production and Consumption

When $g = r$, the present and future values of hydrogen are balanced. The optimization will seek a balance between:

- Producing hydrogen for storage and future use.
- Generating electricity to meet current demand.
- The model will aim to minimize the difference between electricity consumption and production, but may still allow for some small deviations.

Step 3: Degradation of Hydrogen Production ($g < r$) - Prioritize Current Energy Consumption

When the growth rate (g) is less than the discount rate (r), the future value of hydrogen is less significant. The optimization will prioritize:

- Allocating more nuclear energy to direct electricity generation ($w_e(t)$ will tend to be higher) to meet current electricity demand.
- Hydrogen production will be reduced, and stored hydrogen may be used for reconversion ($w_{er}(t)$ will increase) to meet electricity demand.
- The model will focus on minimizing electricity shortfalls.

4 Model Validation and Results

4.1 Dataset Description

The model is validated using simulated data representing electricity and hydrogen demand profiles over a typical year. Key parameters include:

- **Electricity Demand:** Hourly demand profiles modeled with seasonal and daily variations, based on regional energy consumption data.
- **Hydrogen Demand:** Industrial and transportation needs scaled to align with projected usage trends.
- **Nuclear Constraints:** Reactor capacity (E_n) set to 1 GW, with efficiency (η_n) of 33%.
- **Hydrogen Storage Parameters:** Storage capacity ($H_{\max}$) of 500 tons and reconversion efficiency (Y_r) of 50%.

4.2 Scenarios Analyzed

To evaluate the model's performance, three scenarios were considered:

- **Scenario 1: Favorable Hydrogen Valuation ($g > r$)**
  Prioritizes hydrogen storage for future value, with increased nuclear energy allocated to hydrogen production.
- **Scenario 2: Neutral Hydrogen Valuation ($g = r$)**
  Balances electricity generation and hydrogen storage to meet immediate and future needs.
- **Scenario 3: Unfavorable Hydrogen Valuation ($g < r$)**
  Focuses on current energy consumption, with minimal hydrogen production.

5 Implementation Details

5.1 Programming Tools and Framework

The model is implemented in Python using:

- **Optimization Library:** Pyomo for defining the mathematical optimization problem and Gurobi for solving it.
- **Data Processing:** pandas for handling demand profiles and NumPy for numerical computations.
- **Visualization:** matplotlib for generating plots of energy allocation and hydrogen storage trends.

5.2 Scalability and Challenges

The model is designed to scale across regional energy systems and integrate with renewable sources. Computational challenges include:

- **Large Time Horizons:** Optimizing over a full year with hourly resolution requires efficient solvers.
- **Data Granularity:** High-resolution demand data is required for accurate results.
- **Trade-offs:** Balancing accuracy with computational runtime by tuning solver parameters.

5.3 Results and Analysis

Detailed results, including performance metrics and scenario-specific analyses, are available upon request. For further information, please refer to Section 8.

5.4 Sensitivity Analysis

Sensitivity analyses for key parameters, including hydrogen growth rate (g), reconversion efficiency (Y_r), and nuclear efficiency (η_n), were conducted to evaluate model robustness. Detailed results can be requested by contacting the authors (see Section 8).

6 Policy Implications

The findings of this study have significant implications for energy policy. By supporting hybrid nuclear-hydrogen systems, governments can accelerate the transition to net-zero energy systems. Policy recommendations include:

- Subsidies for low-carbon hydrogen production to reduce costs and encourage adoption.
- Incentives for small modular reactor (SMR) deployment, enabling scalable nuclear energy systems.
- Investments in hydrogen storage infrastructure to enhance energy security.
- Carbon pricing mechanisms to increase the economic viability of low-carbon energy solutions.

These policies align with international climate goals and create a pathway for sustainable energy systems.

7 Future Work

This study provides a foundation for hybrid nuclear-hydrogen optimization. Future work could explore:

- Integration with renewable energy sources, such as solar and wind, to create fully decarbonized energy systems.
- Application of machine learning techniques for real-time demand forecasting and optimization.
- Expansion of the model to multi-regional systems, incorporating interconnections and energy trading.
- Assessment of environmental impacts, such as lifecycle emissions and resource sustainability.

These directions will enhance the applicability and robustness of hybrid energy systems in addressing global energy challenges.

8 Contact for Results

This paper provides an overview of the hybrid nuclear-hydrogen optimization model. Detailed numerical results, including scenario-specific performance metrics, sensitivity analyses, and optimization outcomes, are available upon request.

For further information or access to the full results, please contact:

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We welcome collaborations and discussions on applying this model to specific energy systems or enhancing its parameters with real-world data.

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