

Synergistic Integration of Ammonia-Fed Gas Turbines and Concentrated Solar Power to Improve Power Plant Efficiency[#]

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ABSTRACT

Ammonia, a carbon-free fuel from renewable sources, faces low combustion efficiency in gas turbines. Converting it into hydrogen-rich gas improves efficiency. This study explores integrating ammonia-fed gas turbines with concentrated solar power (CSP), using solar energy to decompose ammonia into hydrogen-rich fuel on-site. Replacing ammonia with this fuel enhances thermal and combustion efficiency. The research evaluates operational parameters, showing a thermal efficiency increase of up to 3.5%. A thermodynamic analysis assesses efficiency and heat balance, while flame speed dependence on hydrogen-rich gas composition, pressure, temperature, and equivalence ratio is examined. Under gas turbine conditions, flame speeds reach 20–30 cm/s for a 1:3 ammonia-hydrogen blend. The findings demonstrate the potential of solar-driven ammonia cracking to optimize gas turbine performance.

Keywords: Ammonia, Hydrogen, Gas turbine, Renewable energy, Thermodynamic analysis

1. INTRODUCTION

The transition to CO₂-free power generation is critical for mitigating climate change, driving interest in sustainable fuels like ammonia. As a carbon-free hydrogen carrier, ammonia can be produced from renewables and combusted with minimal emissions, leveraging existing infrastructure [1,2]. However, its direct use in gas turbines suffers from low combustion efficiency due to slow flame speed and high quenching distance.

Blending ammonia with hydrogen or methane improves combustion performance, but challenges remain, including NO_x emissions and efficiency trade-offs

[3,4]. Recent studies demonstrate that even small hydrogen additions enhance flame stability, while hybrid fuels (e.g., NH₃/H₂/CH₄) can achieve efficiencies comparable to natural gas. Yet, hydrogen production costs and system modifications hinder widespread adoption.

An alternative approach is on-site ammonia decomposition into hydrogen-rich gas via thermochemical transformation (ATT), an endothermic process requiring external heat. Potential heat sources include electricity, combustion, gas turbine exhaust, or concentrated solar power (CSP). CSP is particularly promising, offering high-temperature heat (up to 1200°C) without fossil fuels. Recent work shows solar-driven ammonia cracking can achieve near-complete conversion, enabling efficient hydrogen production for power generation [5, 6, 7].

Integrating ammonia-fed gas turbines with CSP plants could address intermittency issues while boosting efficiency [8, 9, 10]. Solar energy decomposes ammonia into H₂-rich fuel, which is then combusted, improving thermal efficiency by up to 3.5%. Studies confirm the feasibility of such hybrid systems, but gaps remain in system design, operational optimization, and combustion dynamics under realistic gas turbine conditions.

This paper investigates the synergistic integration of CSP and ammonia-based power generation [11, 12]. Our results show that a 1:3 NH₃/H₂ blend achieves flame speeds of 20–30 cm/s under gas turbine conditions, validating its potential for retrofitting existing infrastructure. By bridging gaps in hybrid system design and combustion science, this work advances the viability of solar-ammonia solutions for decarbonized power generation.

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2. SCHEMATIC DIAGRAM AND METHODOLOGY

Ammonia shows promise as a carbon-free fuel but faces combustion challenges in gas turbines, including low flame speed, high NO_x emissions, and instability. These limitations require costly modifications to combustion chambers. In contrast, hydrogen offers superior combustion properties, such as high flame speed and stability, making it an ideal complement to ammonia.

A practical solution involves on-site hydrogen production through solar-driven ammonia decomposition. Concentrated solar power (CSP) can provide the heat needed to convert ammonia into hydrogen-rich fuel, improving combustion efficiency while leveraging ammonia's storage advantages. This hybrid approach combines the benefits of both fuels: hydrogen enhances combustibility, while ammonia serves as a renewable hydrogen carrier.

Thermodynamically, this "chemical pump" concept – using solar energy to upgrade ammonia's combustion properties – can increase system efficiency by up to 3.5%. For instance, a 1:3 ammonia-hydrogen blend achieves flame speeds of 20–30 cm/s, making it viable for existing gas turbines with minimal retrofitting. By integrating CSP with ammonia-based systems, this strategy addresses intermittency issues while enabling cleaner power generation.

In summary, solar-assisted ammonia-to-hydrogen conversion offers a pathway to overcome ammonia's combustion drawbacks, enhancing efficiency and reducing emissions in gas turbine applications.

The schematic diagram depicted in Fig. 1 illustrates the integrated solar ammonia-fed gas turbine system with a steam turbine. This system comprises three main subsystems: the ammonia reforming with hydrogen-rich storage, the gas turbine, and the steam turbine cycle. Within this scheme, ammonia undergoes a chemical reaction in the ammonia reformer, which is heated by solar energy, resulting in the production of hydrogen-rich gas as a product. To address the intermittency of solar radiation and ensure continuous operation, a hydrogen-rich gas storage system is incorporated into the scheme. The hydrogen-rich gas generated by the reformer is stored in a tank and later utilized as fuel for the gas turbine. Additionally, the exhaust heat from the gas turbine is used in a steam turbine cycle to further enhance energy efficiency. This integrated system effectively leverages solar energy to produce hydrogen-rich gas for power generation, thereby optimizing energy utilization and sustainability.

This CO_2 -free power plant design (Fig. 1) improves efficiency and sustainability through multiple innovations. Using hydrogen-rich gas instead of fossil fuels enables cleaner, more stable combustion while boosting system performance. Additionally, integrating solar energy at exceptionally high temperatures – far exceeding conventional solar cycles – significantly enhances energy conversion rates. The system also overcomes solar intermittency by storing hydrogen-rich gas during peak sunlight, ensuring uninterrupted power generation. Solar energy is used as heat sources for the

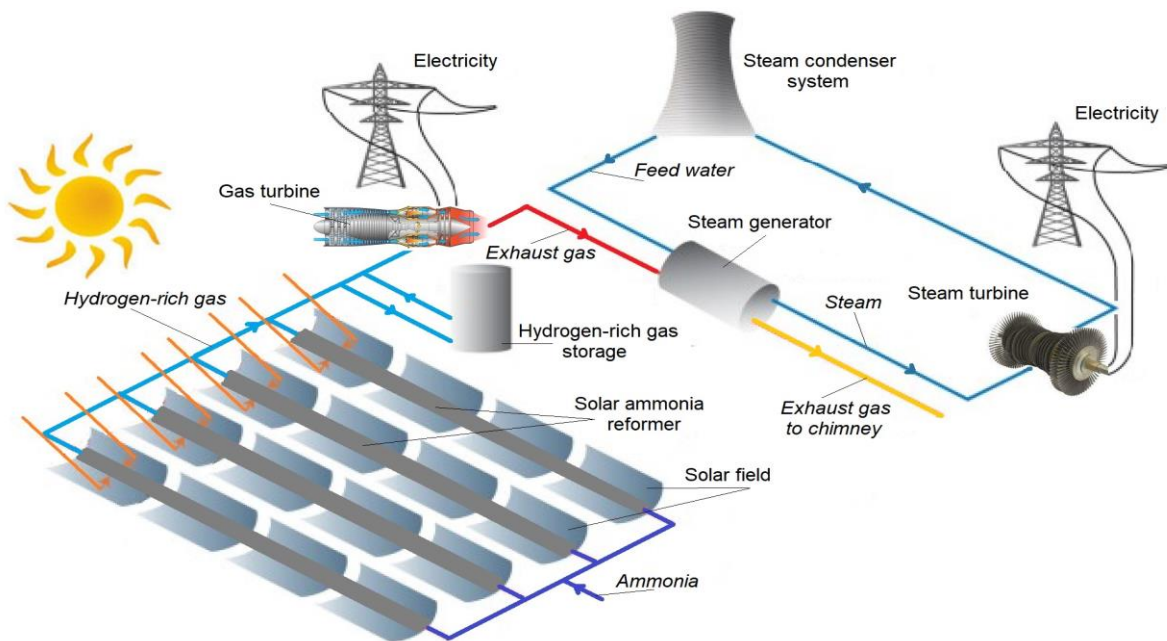
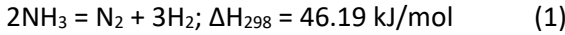


Fig. 1 Schematic diagram of integrated solar ammonia-fed gas turbine with bottom steam turbine [13]

endothermic reaction of ammonia decomposition to produce hydrogen-rich gas:



The design further increases practicality by enabling existing gas turbines to run on ammonia with minimal retrofitting. This adaptability reduces implementation costs and leverages current infrastructure, making the transition to low-carbon power more feasible. Together, these features create a reliable, high-efficiency solution that maximizes renewable energy use while maintaining operational flexibility.

A thermodynamic analysis was conducted to investigate the effect of various operational parameters on the thermal efficiency of novel system and to assess the income and outcome of energy balance. This analysis involved studying the relationship between different operating conditions, such as temperature, pressure, and flow rates, on the overall efficiency of the system. The thermodynamic analysis conducted in this research utilized Aspen HYSYS. A computational scheme of integrated solar ammonia-fed gas turbine with bottom steam turbine for thermodynamic analysis employed via Aspen HYSYS presented in Fig. 2.

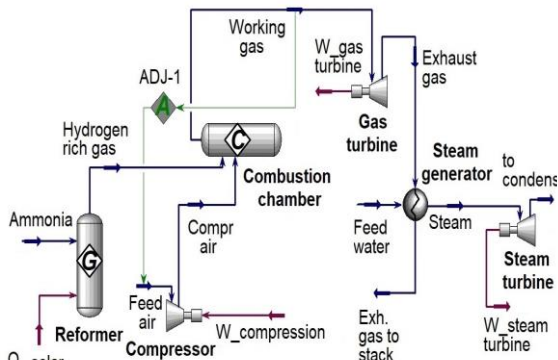


Fig. 2. Computational scheme for thermodynamic analysis

The proposed system configuration (Fig. 2) initiates with ammonia being processed in a solar-powered reformer. Solar thermal energy (Q_{solar}) serves two critical functions: it provides the necessary heat for the endothermic ammonia decomposition reaction while simultaneously heating the reaction products to the required operating temperature. The reformer output - a hydrogen-enriched gas mixture - combines with compressed air before entering the combustion chamber. Within the chamber, this mixture generates high-temperature combustion gases that power the turbine ($W_{gas_turbine}$), with residual heat subsequently utilized for steam generation in the bottoming cycle.

In this analysis, the thermal efficiency of proposed integrated power plant was compared with the thermal efficiency of simple integrated power plant where concentrated solar cycle is used for steam generation for steam turbine cycle.

3. RESULTS AND DISCUSSION

Ammonia decomposition is an endothermic process that generates more product moles than reactant moles. According to chemical equilibrium principles, higher temperatures drive this reaction forward while increased pressures inhibit product formation. The results of thermodynamics analysis (Fig. 3) demonstrate that optimal conversion occurs above 500°C at 10-20 bar, yielding a hydrogen-rich mixture (~75% H_2) with negligible residual ammonia [14]. These conditions align with thermodynamic predictions favoring endothermic reactions at elevated temperatures.

The data reveals that substantial hydrogen production (~75%) requires temperatures exceeding 500°C, though meaningful conversion begins as low as 200°C. Modern solar thermal plants can readily achieve these operating conditions, making solar-driven ammonia decomposition a promising route for renewable hydrogen production. This approach combines established chemical principles with sustainable energy technology to enable clean fuel generation.

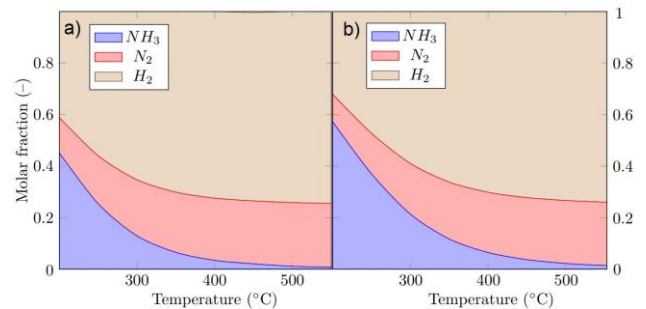


Fig. 3. Composition of the product gas of ammonia decomposition reaction: a) p=10bar; b) p=20bar

The integration of solar-assisted ammonia decomposition in gas turbine systems offers significant efficiency advantages over conventional solar-thermal approaches. Thermodynamic modeling reveals that systems incorporating ammonia reforming (Fig. 4a) outperform standard solar combined cycles (Fig. 4b), primarily because solar energy is converted into chemical energy that feeds the higher-efficiency gas turbine cycle rather than the steam cycle.

Analysis of pressure ratio effects (Fig. 4) shows consistent efficiency gains across turbine inlet temperatures (800-1400°C). At 500°C decomposition temperature, solar-enhanced systems achieve up to 3.2% higher efficiency by transforming solar heat into combustible hydrogen-rich gas. The efficiency

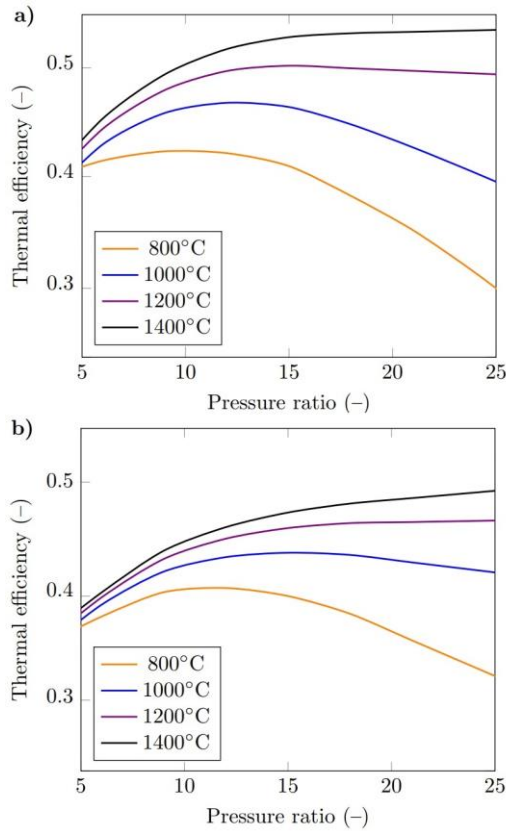


Fig. 4. Thermal efficiency of combined cycle power plant: a) with ammonia thermochemical decomposition; b) without ammonia.

improvement scales with decomposition temperature, as more solar energy becomes chemically stored in the fuel mixture.

A primary technical challenge in retrofitting conventional gas turbines for ammonia combustion lies in its slow flame propagation characteristics, which often result in incomplete fuel oxidation and diminished thermal efficiency. Traditional solutions involve enlarging the combustion chamber, but an alternative approach emerges through pre-combustion thermal decomposition. As evidenced in Fig. 3, this process yields a hydrogen-dominant fuel mixture at temperatures exceeding 500°C, effectively replacing ammonia's sluggish combustion with hydrogen's more favorable kinetics.

Our computational investigation, conducted using Chemkin-Pro and cross-verified with experimental

results, reveals several critical relationships shown in Fig.5. The analysis demonstrates that all hydrogen-ammonia blends achieve practically viable combustion velocities, even at relatively low hydrogen concentrations. The data further establishes that while elevated pre-combustion temperatures (characteristic of solar-integrated systems with 600-700°C output streams) enhance flame propagation, increased operating pressures exert a moderating influence on combustion rates. These findings collectively indicate that decomposed ammonia mixtures can satisfy the operational requirements of existing gas turbine

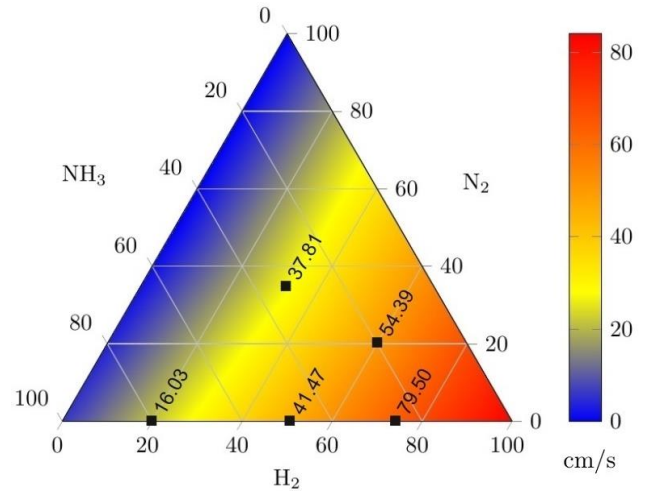


Fig. 5. Laminar flame speed for ammonia-hydrogen blends vs. temperature at $p=20\text{bar}$: points – experimental data

architectures without substantial hardware modifications, presenting a viable pathway for ammonia-based power generation.

4. CONCLUSION

This study introduces an innovative hybrid energy system that combines ammonia-fueled gas turbines with concentrated solar power technology. The proposed configuration utilizes solar thermal energy to catalytically reform ammonia into a hydrogen-enriched combustible mixture, overcoming the combustion limitations of pure ammonia. Through detailed analysis, we have characterized the system's combustion dynamics across a comprehensive operational range.

The research reveals several significant findings. For a 75% hydrogen mixture (N₂:H₂=1:3) under standard gas turbine conditions, we observe optimal flame propagation velocities of 20-30 cm/s. These combustion characteristics remain stable across the operational envelope, with flame speed demonstrating direct

proportionality to temperature and inverse relationship with pressure. The integrated system achieves notable performance improvements, delivering up to 3.5% greater thermal efficiency compared to conventional configurations. This enhancement results from more efficient energy utilization, where the gas turbine contributes 75% of total power output in the hybrid system versus just 60% in traditional designs. The inclusion of fuel storage capacity effectively addresses solar intermittency, ensuring consistent operation.

While these thermodynamic and combustion analyses establish the technical viability of the approach, several areas require further investigation. Future research should examine emission profiles, particularly NO_x formation, assess dynamic stability during load variations, and evaluate long-term material compatibility. The results demonstrate the potential of solar-ammonia hybrid systems as a promising solution for sustainable power generation with built-in energy storage capabilities.

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