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ijirset@gmail.com



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Discovering the Attractiveness of Hydrogen-Fuelled Gas Turbines in Future Energy Systems

Sanjay Bhat

Lead Product Specialist – CFD and Batteries, ALTAIR, USA

ABSTRACT: This study examines the competitiveness of hydrogen-fueled gas turbines in future energy systems, focusing on their potential role in balancing electricity grids with increasing variable renewable energy (VRE) sources. Analyzing data for the years 2030, 2040, and 2050, the study explores the impact of technological advancements, economic factors, and policy constraints on the adoption of hydrogen gas turbines. In 2030, high electrolyzer costs and limited transmission capacity constrain hydrogen turbine investments, requiring substantial increases in complementary fuel costs for economic viability. By 2040 and 2050, reductions in electrolyzer costs and the removal of transmission capacity constraints improve the competitiveness of hydrogen turbines, making them a more attractive option for meeting high electricity demand and low emissions targets. The findings suggest that while hydrogen gas turbines face short-term challenges, they hold significant promise for future energy systems, particularly with continued advancements and supportive policies. The study underscores the need for ongoing innovation and policy support to realize the full potential of hydrogen technology in achieving a sustainable energy transition.

KEYWORDS: VRE, Hydrogen-fueled gas turbines, Electrolyser costs, Future energy systems, Energy transition, Economic viability, Peak power generation, CCGT.

I. INTRODUCTION

To align with the Paris Agreement and mitigate human-induced climate change, increasing the share of variable renewable electricity (VRE) generation is essential. However, this shift introduces challenges for the electricity system, as it requires maintaining a constant balance between supply and demand. As VRE's share grows, the need for flexible and dispatchable power-generation technologies becomes more critical. To be in line with the Paris Agreement [1] and to mitigate anthropogenic climate change, an increased share of variable renewable electricity (VRE) generation is needed, which will present challenges for the electricity system given that supply and demand are required to be in equilibrium at all times. Consequently, with an increasing proportion of VRE, the value of flexible and dispatchable power-generation technologies will increase, although these technologies will have to be low-carbon or zero-carbon emitting types.

Gas turbines, known for their flexibility and dispatchability, are predominantly fueled by natural gas. Although gas turbines emit fewer greenhouse gases than coal-fired power plants, especially when used in combined cycle gas turbine (CCGT) configurations, their emissions still need significant reduction to comply with the Paris Agreement, which mandates carbon neutrality by mid-century. This has been emphasized by the European Investment Bank (EIB), which in its climate strategy in 2019 stated that they would no longer fund new projects with unabated fossil fuels, starting at the end of 2021 [2]. This issue was underscored by the European Investment Bank (EIB) in 2019 when it announced that, starting in 2021, it would cease funding projects involving unabated fossil fuels. The EIB set a stringent emissions limit of 250 gCO₂/kWh for projects it would support, a significant reduction from the previous 550 gCO₂/kWh limit. However, it seems unlikely that just one fuel will be competitive in this context, and there is also the possibility that gas turbines will be able to use several fuels and fuel mixes [3,4].

Given the thermodynamic limitations of further improving gas turbine efficiency, substantial emission reductions can only be achieved through fuel switching or the application of CCS. Options for low-carbon fuels include biogenic synthetic natural gas (SNG) and bio-oil, but it is unlikely that a single fuel will dominate the future energy landscape. Instead, gas turbines may need to operate on a variety of fuels and fuel mixtures.

Hydrogen is gaining significant attention as a versatile energy carrier that can decarbonize hard-to-abate sectors and provide flexibility in energy systems heavily reliant on VRE. Hydrogen can be produced by electrolyzers that operate in sync with VRE generation, with excess hydrogen stored for later use [5]. This capability to time-shift electricity

generation is increasingly valuable as VRE becomes more prevalent, positioning hydrogen-fueled gas turbines as a crucial component of future low-carbon energy systems.

As the world grapples with the urgent need to mitigate climate change and transition towards sustainable energy systems, hydrogen has emerged as a promising solution due to its potential to decarbonize various sectors. Among the myriad applications of hydrogen, its use in gas turbines stands out as a pivotal area of interest for researchers and policymakers alike [6]. Hydrogen-fueled gas turbines, which operate on hydrogen or hydrogen-enriched fuels, offer a unique pathway to achieve significant reductions in greenhouse gas emissions while providing reliable and efficient power generation. This technological advancement holds the promise of integrating hydrogen into existing energy infrastructure and supporting the broader transition to a low-carbon economy.

The competitiveness of hydrogen-fueled gas turbines in future energy systems hinges on several critical factors, including technological maturity, economic feasibility, and environmental impact. On a technological level, hydrogen combustion presents distinct challenges compared to traditional fossil fuels. These challenges include issues related to flame stability, NO_x emissions, and material compatibility [7]. Addressing these challenges requires ongoing research and development to enhance the performance and reliability of hydrogen turbines. Moreover, advancements in materials science and combustion technology are essential to overcome these barriers and make hydrogen turbines a viable alternative to conventional gas turbines.

Economic considerations also play a crucial role in determining the competitiveness of hydrogen-fueled gas turbines. The initial capital costs for hydrogen infrastructure, including production, storage, and distribution, are currently high compared to established fossil fuel systems. However, as the hydrogen economy scales up and technological advancements reduce costs, the economic landscape may shift. Additionally, the integration of hydrogen turbines into existing energy grids and their ability to complement renewable energy sources can provide valuable grid stability and reliability, which may further enhance their economic attractiveness.

Environmental impact is a fundamental aspect of evaluating the role of hydrogen-fueled gas turbines in future energy systems. Hydrogen combustion produces water vapor as its primary byproduct, eliminating carbon dioxide emissions from the combustion process. Green hydrogen, produced through electrolysis powered by renewable energy, offers the greatest environmental advantage [8]. Conversely, grey hydrogen, derived from fossil fuels with carbon capture and storage, provides fewer benefits. Thus, the alignment of hydrogen production methods with sustainability goals is essential for realizing the full potential of hydrogen turbines.

The exploration of hydrogen-fueled gas turbines as a competitive option in future energy systems involves a multifaceted analysis of technological, economic, and environmental factors. As research and development continue to advance, hydrogen turbines may become a cornerstone of sustainable power generation, supporting the transition to a cleaner and more resilient energy landscape [9]. Understanding these dynamics will be crucial for shaping policies and investments that drive the adoption of hydrogen technologies and achieve long-term energy and climate objectives.

II. LITERATURE REVIEW

The exploration of hydrogen-fueled gas turbines within future energy systems is supported by a growing body of literature that examines the technological, economic, and environmental aspects of this emerging technology. Hydrogen as an energy carrier has long been recognized for its potential to decarbonize various sectors, including transportation, industry, and power generation. In the context of gas turbines, hydrogen offers a pathway to significantly reduce carbon emissions while maintaining the flexibility and reliability essential for balancing increasingly renewable-dominated energy grids.

The technological feasibility of hydrogen combustion in gas turbines has been a focal point of research for several decades. Early studies concentrated on the fundamental combustion characteristics of hydrogen, such as flame speed, ignition temperature, and the formation of nitrogen oxides (NO_x). For instance, studies by Lefebvre and Ballal (2010) [11] have shown that hydrogen's high reactivity and wide flammability range pose challenges in achieving stable combustion while minimizing NO_x emissions. Recent advancements in combustion technology, including the development of lean-premixed combustion and catalytic combustion techniques, have significantly addressed these challenges. These innovations are critical in enabling hydrogen-fueled gas turbines to operate efficiently and with lower emissions, making them more competitive in a future energy system where environmental performance is paramount.

The economic viability of hydrogen-fueled gas turbines is another area of active research. Numerous studies have analyzed the cost dynamics of hydrogen production, storage, and transportation, as well as the impact of these costs on the overall competitiveness of hydrogen as a fuel for gas turbines. Hydrogen production costs are highly dependent on the method used, with green hydrogen—produced via electrolysis powered by renewable energy—being the most sustainable yet currently the most expensive option. According to IRENA (2020) [12], the cost of green hydrogen is expected to decrease significantly over the coming decades as electrolyzer technologies improve and the scale of renewable energy deployment increases. Additionally, studies by BNEF (2021) [13] and others highlight the importance of economies of scale and infrastructure development in reducing hydrogen costs and making hydrogen-fueled gas turbines more economically attractive compared to traditional natural gas turbines.

Environmental considerations form a crucial aspect of the literature on hydrogen-fueled gas turbines. The potential of hydrogen to enable near-zero emissions in power generation is one of its most compelling attributes. Hydrogen combustion results in water vapor as the primary byproduct, thus eliminating carbon dioxide (CO₂) emissions from the combustion process itself. However, the overall environmental impact of hydrogen-fueled gas turbines is intricately linked to the method of hydrogen production. Studies such as those by Saba et al. (2018) [14] emphasize the importance of using green hydrogen, produced via renewable energy sources, to achieve significant reductions in greenhouse gas emissions. Conversely, grey hydrogen, produced from natural gas through steam methane reforming (SMR) without carbon capture, still results in substantial CO₂ emissions, undermining the environmental benefits of using hydrogen in gas turbines. The literature underscores the need for a systemic approach to hydrogen production and utilization, ensuring that the entire value chain aligns with sustainability goals.

Integration of hydrogen-fueled gas turbines into energy systems with a high share of variable renewable energy (VRE) is another topic of considerable interest. The intermittency of VRE sources like wind and solar requires flexible and dispatchable power generation to maintain grid stability. Hydrogen-fueled gas turbines are seen as a promising solution to this challenge due to their ability to ramp up quickly and provide reliable power during periods of low renewable generation. Research by Heuberger et al. (2017) [15] and others demonstrates that hydrogen-fueled gas turbines could play a critical role in balancing future grids, particularly when paired with hydrogen storage systems that allow for time-shifting of energy production. This capability enhances the value proposition of hydrogen-fueled gas turbines in energy systems increasingly dominated by renewables. The competitiveness of hydrogen-fueled gas turbines is further examined through comparative analyses with other low-carbon technologies. Studies by Cebulla et al. (2017) [16] compare the costs, emissions, and operational characteristics of hydrogen-fueled gas turbines with alternatives such as battery storage, nuclear power, and carbon capture and storage (CCS) technologies. These studies generally find that while hydrogen-fueled gas turbines face higher upfront costs, their operational flexibility, scalability, and potential for deep decarbonisation make them valuable to future energy systems. The literature highlights the importance of policy frameworks and market incentives in driving the adoption of hydrogen technologies. Supportive policies, such as carbon pricing and renewable energy mandates, are key factors that could enhance the competitiveness of hydrogen-fueled gas turbines in the coming years.

III. METHODOLOGY

The methodology for exploring the competitiveness of hydrogen-fueled gas turbines in future energy systems involves a comprehensive, multi-disciplinary approach that integrates technical analysis, economic modeling, and environmental assessment. This research is structured around three primary phases: a technological feasibility study, an economic analysis, and an environmental impact assessment. Each phase employs a combination of qualitative and quantitative methods to provide a holistic evaluation of hydrogen-fueled gas turbines within the context of future energy systems.

The first phase of the research focuses on the technological feasibility of hydrogen-fueled gas turbines. This phase begins with a detailed literature review on hydrogen combustion in gas turbines, identifying key challenges such as flame stability, NO_x emissions, and material compatibility. Experimental data from previous studies are analyzed to understand the performance characteristics of hydrogen-fueled turbines, particularly in comparison to conventional natural gas turbines. Additionally, advanced computational fluid dynamics (CFD) simulations are conducted to model the combustion process of hydrogen in gas turbines. These simulations help to predict the behavior of hydrogen flames under different operating conditions, providing insights into potential areas for improvement in turbine design and operation. The results from the CFD simulations are validated against experimental data where available, ensuring the accuracy and reliability of the findings.

The second phase involves a comprehensive economic analysis to evaluate the cost competitiveness of hydrogen-fueled gas turbines. This analysis begins with the development of a cost model that incorporates the capital expenditure (CAPEX), operational expenditure (OPEX), and levelized cost of electricity (LCOE) for hydrogen-fueled turbines. The model is based on current and projected hydrogen production, storage, and transportation costs, drawing from data sources such as the International Renewable Energy Agency (IRENA) and BloombergNEF (BNEF). The economic analysis also considers different scenarios for hydrogen pricing, ranging from current market prices to future estimates based on economies of scale and technological advancements. Sensitivity analysis assesses the impact of key variables, such as hydrogen production costs and carbon pricing, on the overall competitiveness of hydrogen-fueled gas turbines. The results are compared with those of other low-carbon technologies, such as battery storage, nuclear power, and carbon capture and storage (CCS), to provide a relative assessment of hydrogen turbines in the future energy mix.

The final phase of the methodology is the environmental impact assessment, which examines the potential of hydrogen-fueled gas turbines to contribute to decarbonization efforts. This phase utilizes life cycle assessment (LCA) methodology to evaluate the environmental impacts associated with hydrogen production, transportation, and combustion in gas turbines. The LCA considers different hydrogen production pathways, including green hydrogen (produced via electrolysis using renewable energy) and grey hydrogen (produced from natural gas with or without carbon capture). The environmental impact of each pathway is assessed across various indicators, including global warming potential (GWP), acidification potential, and resource depletion. The results are then compared to the environmental impacts of conventional natural gas turbines and other low-carbon technologies. This comparison helps to identify the conditions under which hydrogen-fueled gas turbines provide the most significant environmental benefits.

Throughout the research, scenario analysis is employed to explore the potential role of hydrogen-fueled gas turbines under different future energy system configurations. These scenarios are developed based on varying levels of renewable energy penetration, hydrogen availability, and policy support for low-carbon technologies. The scenario analysis allows for the examination of hydrogen turbines' competitiveness under diverse conditions, providing insights into the potential pathways for their integration into the energy system.

This methodology provides a rigorous framework for assessing the competitiveness of hydrogen-fueled gas turbines in future energy systems. By integrating technological, economic, and environmental analyses, the research aims to offer a comprehensive understanding of the potential and challenges of hydrogen as a fuel for gas turbines, informing decisions on their role in the transition to a low-carbon energy future.

IV. RESULTS

The future roles of new hydrogen gas turbines

In the analysis of investments in new hydrogen gas turbines projected for the year 2030, the findings indicate that these turbines will face significant challenges in becoming competitive. The conditions under which hydrogen gas turbines might see investment are quite specific: they are more likely to be considered if there is a stringent requirement to reduce emissions, a high electricity demand, and no new investments in expanding transmission line capacity. Moreover, for hydrogen gas turbines to become attractive investments, the costs of alternative fuels like natural gas (NG) and biogas (BG) would need to be substantially higher—at least 50% more expensive than their baseline costs. The analysis in Figure 1 shows the impact of different cost increases for these fuels, with the three columns for each country representing scenarios where NG and BG costs are 50%, 75%, and 100% higher.

Even in scenarios where hydrogen gas turbines do manage to be competitive by 2030, the investments are split between open cycle gas turbines (OCGT) and combined cycle gas turbines (CCGT). In these cases, hydrogen is often mixed with biogas rather than used on its own.

Hydrogen-fueled gas turbines may have limited value for time-shifting electricity production (i.e., producing hydrogen, storing it, and then converting it back into electricity). This limited value is particularly evident in scenarios where CO₂ emissions are still allowed at significant levels and where the share of variable renewable energy (VRE) in the electricity mix is only moderate.

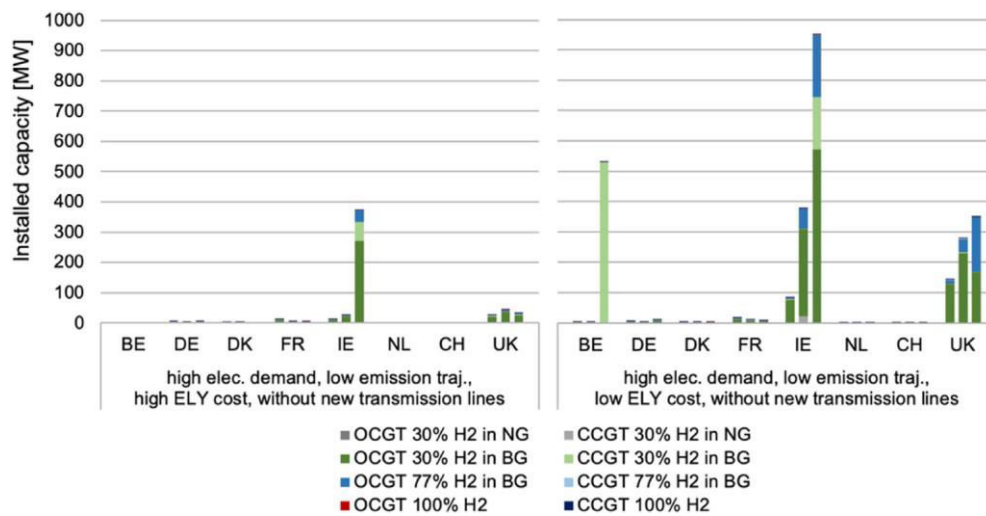


Figure 1: Illustrates the installed capacity of new hydrogen-compatible gas turbines in Scenario 1 for the year 2030.

For each country represented, the three columns show the impact of increasing fuel costs for natural gas (NG) and biogas (BG) by 50%, 75%, and 100% above the baseline cost. The figure is divided into two sub-plots, which differ based on the assumed cost of electrolyzers (ELY), with one sub-plot reflecting a "high" electrolyzer cost and the other reflecting a "low" electrolyzer cost.

Considering the impact of reduced electrolyzer costs by 2030, as shown in the right-hand plot of Figure 1, the results indicate significant investments in hydrogen gas turbines for countries like Ireland (IE) and the United Kingdom (UK), which had already invested when electrolyzer costs were higher. This outcome is expected because lowering the cost of electrolyzers decreases the cost associated with time-shifting electricity generation, thereby adding more value to the energy system. However, for most other countries such as Germany (DE), Denmark (DK), France (FR), the Netherlands (NL), and Switzerland (CH), the reduction in electrolyzer costs does not lead to increased investments in hydrogen-fueled gas turbines. This is because, despite the cheaper electrolyzers, there is no strong economic incentive for time-shifting electricity generation in these regions.

In Belgium (BE), significant investments in hydrogen gas turbines are observed only when electrolyzer costs are low and the cost of complementary fuels is doubled. This can be attributed to the nature of linear optimization models, where the optimal solution is typically a singular outcome. In this scenario, the changes in electrolyzer and fuel costs shift the optimal solution, making investments in hydrogen-fueled gas turbines favorable.

Moving to Scenario 1 for the year 2040, the investments are presented in Figure 4, with sub-plots (a) to (d) showing the results for four different combinations of emissions trajectory and electricity demand. Comparing sub-plots (a) and (c) with sub-plots (b) and (d), it becomes clear that the competitiveness of hydrogen gas turbines is primarily influenced by the emissions trajectory, with higher competitiveness under more stringent emission constraints, especially when coupled with high electricity demand.

By 2040, the majority of investments are directed towards new open cycle gas turbines (OCGT) that use a blend of 30% hydrogen with biogas. This trend suggests a strong demand for peak power generation but a relatively low demand for time-shifting, as the hydrogen mixing rate is at the lowest available level. Nevertheless, the investments in hydrogen gas turbines, along with electrolyzers and hydrogen storage, indicate that there are still some benefits to be gained from time-shifting, as it represents the cost-optimal solution that minimizes the overall system cost.

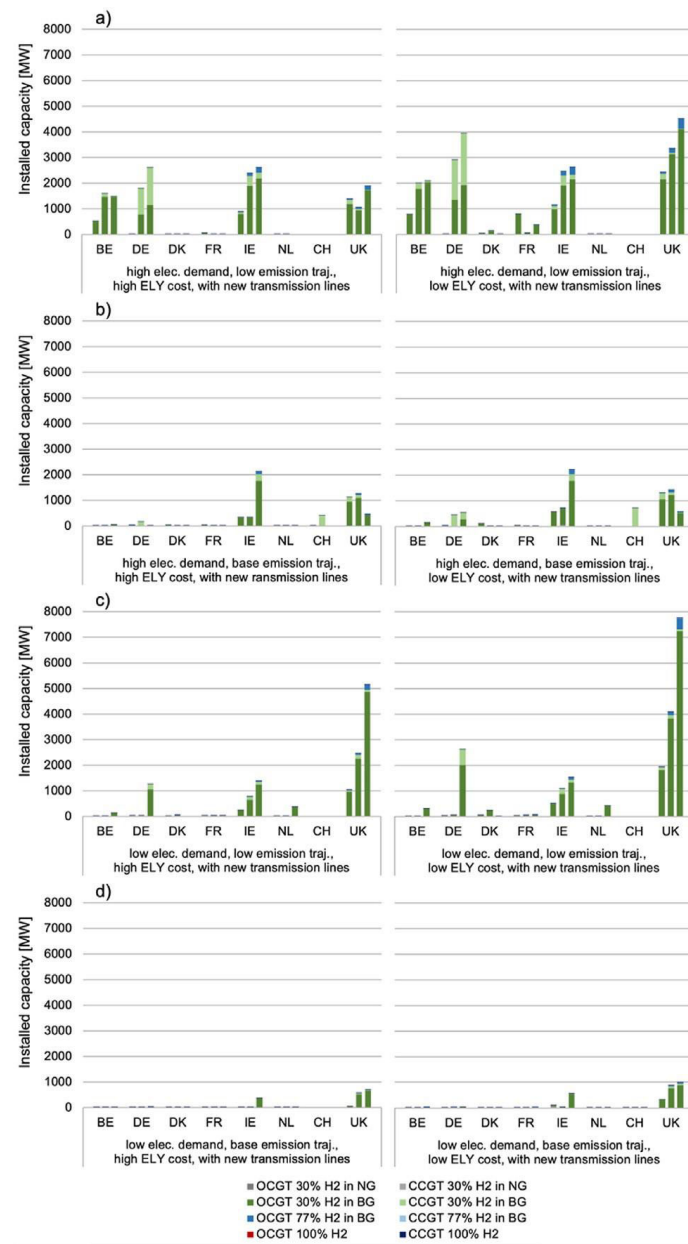


Figure 2: displays the installed capacity for new hydrogen-fueled gas turbines in Scenario 1 for the year 2040, across four different combinations of electricity demand and emissions trajectory. Panel (a) shows results for high electricity demand with a low emissions trajectory, panel (b) for high electricity demand with a base emissions trajectory, panel (c) for low electricity demand with a low emissions trajectory, and panel (d) for low electricity demand with a base emissions trajectory.

Each panel presents data for three different levels of assumed fuel costs for natural gas (NG) and biogas (BG). The middle column reflects the baseline fuel cost, while the left and right columns represent scenarios where the fuel cost is decreased or increased by 25%, respectively. Additionally, the difference between the two plots within each panel is based on the electrolyzer (ELY) cost, which is set to either "high" or "low."

Unlike the results for 2030, the investments in hydrogen gas turbines for the years 2040 and 2050 do not depend on constraints related to new transmission line capacity, as new transmission capacities are considered in these later years. For hydrogen gas turbines to become competitive in 2040 and 2050, a smaller increase in the cost of complementary

fuels is required. Specifically, the costs for natural gas (NG) and biogas (BG) are varied by $\pm 25\%$ relative to the baseline cost (middle column) for these years, compared to the 50% to 100% increase used for 2030.

V. DISCUSSION

The analysis of hydrogen-fueled gas turbines for the years 2030, 2040, and 2050 reveals important insights into their competitiveness within future energy systems, highlighting key factors influencing investment decisions and the broader implications for energy transition strategies. For 2030, the findings indicate that investments in hydrogen gas turbines are constrained by several factors. The significant limitations on new transmission line capacity and the high cost of electrolyzers pose substantial barriers. In this context, hydrogen gas turbines only become competitive when there is a stringent requirement for low emissions, high electricity demand, and when the costs of complementary fuels such as natural gas and biogas are markedly higher than the baseline. The large increase in fuel costs required for competitiveness underscores the high initial investment risks associated with hydrogen technology in the near term. The results also show that hydrogen gas turbines are predominantly used in open cycle and combined cycle configurations, where hydrogen is mixed with biogas. This suggests that while hydrogen can play a role in reducing emissions, its economic viability in 2030 is still limited by high costs and relatively modest levels of variable renewable energy (VRE) integration.

The scenarios for 2040 and 2050 demonstrate a more favorable outlook for hydrogen-fueled gas turbines. By these years, the limitations imposed by new transmission capacities are no longer a constraint, allowing for a more flexible integration of hydrogen technology into the energy system. The reduced cost of electrolyzers further enhances the competitiveness of hydrogen gas turbines. This reduction lowers the overall cost of time-shifting electricity generation, making hydrogen turbines a more attractive option for energy systems aiming to balance high electricity demand with low emissions. In these later years, the required increase in complementary fuel costs to make hydrogen turbines competitive is also less dramatic, with variations of $\pm 25\%$ relative to the baseline, compared to the 50% to 100% increases seen for 2030. This change reflects a maturation of technology and infrastructure, which reduces the economic burden associated with hydrogen energy.

The results for 2040 and 2050 indicate that the investments are less sensitive to the costs of complementary fuels and more dependent on factors such as emissions trajectories and electricity demand. The investment patterns show a shift towards new open cycle gas turbines (OCGT) with a blend of 30% hydrogen and biogas, pointing to a growing demand for peak power generation rather than extensive time-shifting. This suggests that while hydrogen gas turbines may become a viable option for meeting peak demands, their role in providing large-scale time-shifting capabilities might still be limited.

The evolving competitiveness of hydrogen-fueled gas turbines reflects broader trends in energy technology and policy. The decreasing cost of electrolyzers and the removal of transmission capacity constraints contribute to a more favorable investment climate for hydrogen technologies. However, the pace at which these technologies become economically viable will depend on continued advancements in hydrogen production and storage, as well as supportive policies that promote low-carbon energy solutions.

VI. CONCLUSION

The exploration of hydrogen-fueled gas turbines reveals a complex landscape shaped by technological, economic, and policy factors. For the year 2030, the competitiveness of hydrogen gas turbines is constrained by high electrolyzer costs and significant limitations on new transmission line capacity. Investments in hydrogen turbines under these conditions require substantial increases in the costs of complementary fuels such as natural gas and biogas. The results suggest that, while hydrogen can contribute to emission reductions, its economic viability in the near term is limited, particularly in contexts with moderate levels of variable renewable energy and significant cost barriers.

By 2040 and 2050, the outlook for hydrogen gas turbines becomes more favorable. The removal of constraints related to transmission capacity and the reduction in electrolyzer costs enhance the attractiveness of hydrogen as a fuel source. The smaller increase in complementary fuel costs required for competitiveness, along with advancements in technology and infrastructure, suggest that hydrogen turbines could play a more prominent role in energy systems with high electricity demand and stringent emissions targets. Investments shift towards configurations that use a blend of

hydrogen and biogas, indicating a growing role for hydrogen in meeting peak power needs while also benefiting from lower overall system costs.

The findings highlight that while hydrogen-fueled gas turbines face challenges in the short term, their potential for significant contributions to future energy systems is promising. Continued technological advancements, cost reductions, and supportive policy frameworks will be crucial in accelerating the adoption of hydrogen technology. As the energy landscape evolves, hydrogen gas turbines could become a key component in balancing the demands of high electricity consumption with the imperative to reduce carbon emissions, ultimately supporting a transition to a more sustainable and resilient energy system.

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