iJRASET
International Journal For Research in
Applied Science and Engineering Technology

INTERNATIONAL JOURNAL FOR RESEARCH

IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 13 Issue: VI Month of publication: June 2025

DOI: https://doi.org/10.22214/ijraset.2025.72551

Towards Intelligent Combustion: A Bibliometric and Machine Learning Analysis of Hydrogen-Fueled Gas Turbines

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Abstract: Thermo-acoustic instability poses significant challenges to the safe and efficient operation of hydrogen-fueled gas turbines, particularly in industrial applications. This study conducts a comprehensive bibliometric analysis to explore research trends, identify gaps, and evaluate predictive modeling opportunities for thermo-acoustic instability in hydrogen combustion systems. Using Scopus and Web of Science data analyzed with Bibliometrix (R-package), the study maps the thematic evolution of key research areas. The findings reveal extensive work on performance optimization, flow dynamics, and combustion propagation, yet limited attention to hydrogen-specific thermo-acoustic instability. Additionally, while numerical simulations and active control mechanisms are well-developed, real-time predictive modeling using machine learning (ML) remains underexplored. To bridge these gaps, this study proposes a hybrid AI-CFD framework incorporating neural networks for enhanced instability prediction and control. The insights gained contribute to advancing hydrogen combustion technologies, enabling safer and more efficient gas turbine operations.
Keywords: Hydrogen, Computational fluid dynamics (CFD), Combustion , Thermo-acoustic instability, Machine Learning (ML)

I. INTRODUCTION

The world energy industry is going through a transformative change, spurred on by the imperative to counter climate change and lower greenhouse gas emissions [1, 2]. As countries make efforts toward meeting ambitious decarbonization goals, hydrogen has come to the fore as a key player on the future energy stage [3]. With its superior energy content and carbon-zero combustion properties, hydrogen is becoming increasingly seen as a competitive substitute for fossil fuels, especially for uses like power generation, road transport, and industrial applications [4]. Yet, its adoption within existing infrastructure poses certain technical limitations, most notably thermoacoustic instability—a process by which variations of heat release couple with acoustic oscillations and generate unstable combustion. This instability must be countered to ensure secure and efficient operation of combustion engines and gas turbines run on hydrogen. Conventional numerical methods such as Computational Fluid Dynamics (CFD), Large-Eddy Simulation (LES), and Direct Numerical Simulation (DNS) have been largely applied for modeling combustion behavior and instability prediction. But these are computationally intensive and hence pose limitations for applications on a real-time scale.

To fill this gap, machine learning (ML) methodologies—notably neural networks and predictive modeling—have come to prominence as means for instability detection, performance improvement, and active control. Recent developments in Convolutional Neural Networks (CNNs), Long Short-Term Memory (LSTMs), and hybrid AI-CFD models have proven extremely beneficial for modeling complex nonlinear combustion behavior and reducing computational expense. Physics-Informed Neural Networks (PINNs) are also being utilized to embed domain-specific know-how within ML models, with improvements to precision and interpretability.

In light of the interdisciplinary and complex topic of hydrogen combustion research, bibliometric analysis provides an evidence-based means of depicting the changing research terrain. Unlike qualitative reviews, bibliometric approaches can examine large sets of data, detect pervasive research themes, and monitor developing trends. This research utilizes Bibliometrix (R-package) and various visualization software—such as bubble charts, tree maps, word clouds, network visualizations, and timeline charts—to investigate the research terrain of hydrogen combustion, particularly relating to thermoacoustic instability and applications of machine learning.

The main aims of this research are:

1) To recognize leading research trends and developing directions for hydrogen combustion, especially regarding thermoacoustic instability and computational modeling.
2) To study how machine learning can forecast and prevent combustion instabilities, with a focus on coupling ML with CFD models.
3) To create a comparative bibliometric study to indicate research gaps, interdisciplinary relationships, and directions for future research.

By working towards these goals, this research hopes to create a data-driven foundation for future research on hydrogen combustion, informing academia, industry, and governments how to drive hydrogen energy innovations.

II. LITERATURE REVIEW

A. Bibliometric Analysis: Concepts and Applications

Bibliometric analysis is a quantitative technique with tremendous strength utilized for mapping research terrain, monitoring developing trends, and determining areas of research gap. In contrast to qualitative analyses based on literature reviews, bibliometric methods employ citation analysis, networks of co-occurring keywords, and patterns of collaborative research to give objective large-scale insights into scientific developments.

Bibliometric analysis has been proven to be an effective tool in various fields like energy studies, computational modeling, and sustainability research, enabling scholars to measure research influence and monitor interdisciplinary relationships. Under conditions of hydrogen combustion, bibliometric study identifies crucial themes like combustion dynamics, instability forecasting, computational modeling, and incorporation of machine learning techniques. This research utilizes Bibliometrix (R-package) and other visualization tools like bubble charts, tree maps, word clouds, and networks to examine thermoacoustic instability suppression research evolution and AI-driven predictive modeling.

B. Applications of Machine Learning to Predict Hydrogen Combustion Instability

Increased complexity of hydrogen combustion dynamics, with a specific challenge posed by thermoacoustic instability, has resulted in investigations involving machine learning methods for predictive modeling and on-line instability control. Classical computational methods like Large-Eddy Simulation and Direct Numerical Simulation are high-fidelity but computationally time-consuming and hence less desirable for on-line instability control. Therefore, ML-informed methods are being formulated for developing fast, scalable, and adaptive models of instability prediction.

Between data-driven and learning models such as neural networks (NNs), anomaly detection models, and adaptive algorithms, neural networks are most appropriate for hydrogen-fired gas turbines due to their ability to effectively detect complex, nonlinear behavior, handle changing operating conditions, fuse multi-sensor data, and function in real time [5] [6]. Their adaptability, resilience, and data learning make them a better fit for handling the special difficulties involved in hydrogen combustion and for reliable and anticipatory instability detection [7].

C. Analysis Of Recent Publications On Neural Networks for Instability Prediction

Neural networks have also become potent means of detecting precursors to instability within combustion systems. Numerous recent publications have investigated different neural architectures like artificial neural networks (ANNs), deep neural networks (DNNs), and convolutional neural networks (CNNs), and more recent and advanced methods like generative adversarial networks (GANs), and physics-informed neural networks (PINNs) and have shown considerable advancements in the deployment of neural networks to solve problems concerning combustion instability predictions, detections, and control.

Wang et al. applied Artificial Neural Networks (ANNs) to forecast unstable combustion states and identify leading chemical kietics, and proposed integrating neural networks with state-of-the-art Computational Fluid Dynamics (CFD) to improve prediction precision on MILD combustion systems [8]. Mondal et al. applied Deep Neural Networks (DNNs) for predicting thermoacoustic instabilities, recommending the refinement of deep learning models with different architectures and hyperparameters, as well as the exploration of real-time monitoring systems [9]. Gaudron and Morgans combined physics-based acoustic network models with deep learning to predict thermoacoustic stability, emphasizing the need for improved accuracy and efficiency in these models [10].

In the context of turbulent combustion simulations, Zhang et al. employed ANNs to accelerate large-eddy simulations (LES) of swirling premixed flames, proposing further investigation into the application of machine learning techniques for both premixed and non-premixed flames [11].

An et al. developed a Deep Convolutional Neural Network (CNN) based on the U-Net architecture for hydrogen-fueled turbulent combustion, highlighting the potential for integrating deep learning frameworks with real-time monitoring and control systems in gas turbines [12]. Gangopadhyay et al. used 2D CNNs to detect combustion instabilities, suggesting the integration of physics-aware neural networks for improved accuracy and the optimization of neural network PID controllers for better control efficiency [13].

For early detection of combustion instability precursors, Cellier et al. combined CNNs with Recurrent Neural Networks (RNNs), recommending the exploration of alternative machine learning techniques such as reinforcement learning or unsupervised learning [14] . Lyu et al. developed an LSTM-CNN hybrid model for fast detection of combustion instabilities, proposing the integration of multi-modal sensor data for real-time applications and the exploration of deeper CNN architectures [15].

Physics-informed approaches have also gained traction. Mariappan et al. applied Physics-Informed Neural Networks (PINNs) to learn thermoacoustic interactions in combustors, suggesting the expansion of the method to more combustor designs and its integration with real-time monitoring for adaptive control systems [16]. Son and Lee used PINNs to identify governing parameters in noisy thermoacoustic systems, emphasizing the need for improved noise-handling techniques and experimental validation [17].

Generative models have shown promise as well. Grenga et al. developed a Generative Adversarial Network (GAN)-based model for premixed turbulence-combustion regimes, proposing the integration of GANs with traditional simulations for more comprehensive models [18]. Xu et al. employed Wasserstein GANs for early detection of thermoacoustic instability in solid rocket motors, suggesting the exploration of AI techniques for enhanced detection across various industrial settings [19].

Other notable contributions include Lyu et al., who used ANNs for precursor detection of thermoacoustic instability, recommending the expansion of the methodology to other combustion systems and the integration of ANN-based detection with real-time monitoring systems [20]. Sengupta et al. applied a Bayesian Neural Network Model to forecast thermoacoustic instabilities in liquid propellant rocket engines, proposing further refinement of Bayesian approaches for small datasets and strategies to handle sensor failure events [21]. Bhattacharya et al. utilized Hidden Markov Models (HMMs) and Symbolic Time Series Analysis (STSA) for data-driven detection and early prediction of thermoacoustic instability, suggesting the integration of detection methods with active control strategies for real-time system adjustments [22]. Cellier explored deep learning techniques for detecting instability and blow-off/flashback precursors in aeronautical engines, recommending the refinement of deep learning models and the incorporation of multi-modal data for real-time applications [23].

Morgans and Yang investigated direct and hybrid computational approaches for thermoacoustic instability in combustors, emphasizing the need for advanced computational tools combining direct and hybrid approaches [24]. Finally, Kim and Kim developed a network-based thermoacoustic model for gas turbine combustors, proposing the exploration of advanced modeling techniques like 3D simulations and the study of alternative fuels' impact on thermoacoustic instability [25].

In summary, the brief review of different studies on the application of neural networks provides a robust foundation for understanding current progress and challenges in neural network applications for combustion instability. It also highlights ample scope for further exploration, particularly in enhancing prediction accuracy, computational efficiency, and practical implementation. Despite significant advancements in the study of thermo-acoustic instabilities and the application of machine learning techniques for their detection, several critical gaps remain as summarised in table 1 from an analysis of the studies .

Beyond predictive modeling, ML is being increasingly applied to optimize combustion parameters and actively control instabilities. Reinforcement Learning (RL) algorithms have been explored for adaptive fuel injection control, allowing gas turbines to autonomously adjust injection rates and air-fuel mixing to suppress instability. Similarly, Bayesian Optimization has been used to refine turbulence models, improving combustion efficiency while reducing emissions. These AI-driven control strategies are being integrated with sensor networks, enabling self-learning combustion systems capable of dynamic instability mitigation under varying operating conditions.

D. Research Gap Analysis and Future research directions .

Most of the studies reviewed above focus on generic or industrial combustion systems but do not specifically target hydrogen-fueled gas turbines, which present unique challenges due to high reactivity, flame speed, and propensity for instabilities [19] [12]. There is a lack of specialized neural network architectures tailored for the dynamics of hydrogen combustion, which involve higher thermo-acoustic sensitivity compared to conventional fuels. Although studies such as [19] and [15] explore early detection mechanisms, these are predominantly focused on generic instabilities or other combustion systems (e.g., solid rocket motors, propane-air mixtures). Additionally, Comparative studies evaluating different neural network architectures for hydrogen combustion instability detection are limited, the integration of high-fidelity CFD data with ML models remains an area requiring further exploration. Table 1 summarises the research gaps from the literature review analysis.

Addressing these gaps will contribute to the development of more reliable, efficient, and scalable hydrogen combustion technologies, fostering their adoption in clean energy applications. Neural networks and machine learning techniques have the potential to revolutionize combustion science and engineering, leading to more stable and efficient combustion systems. Future research should focus on Enhancing real-time instability prediction models using deep learning architectures. Developing hybrid AI-CFD approaches to improve computational efficiency. Integrating ML-based control strategies for adaptive fuel injection and dynamic stability control. Expanding research on hydrogen combustion-specific ML models to address unique instability challenges. By integrating AI with traditional combustion modeling techniques, researchers can develop scalable, data-driven solutions for safer and more efficient hydrogen combustion systems. This literature review highlights the increasing role of machine learning in hydrogen combustion research, particularly in thermoacoustic instability prediction, CFD acceleration, and real-time control.

Table 1. Summary of the research gaps

Research Gap	Description	Literature
Lack of Focus on Hydrogen-Fueled Systems	Most studies focus on generic combustion systems (e.g., propane-air, natural gas) but do not specifically target hydrogen-fueled gas turbines.	Xu et al. and An et al. explored early detection but not for hydrogen combustion.
Limited Comparative Analysis of NN Architectures	Insufficient comparison of NN architectures (e.g., ANN, CNN, RNN, DNN) for TAI detection in hydrogen combustion systems.	Cellier et al. and Lyu et al. used hybrid models but did not compare architectures.
Insufficient Integration of High-Fidelity CFD Data	Many studies rely on experimental or synthetic data, lacking the high-fidelity CFD data needed for accurate modeling of hydrogen combustion dynamics.	Wang et al. emphasized CFD-NN integration but few studies implemented it for hydrogen combustion.
Limited Exploration of Physics-Informed Neural Networks (PINNs)	PINNs integrate physical laws into NN training but are underexplored for hydrogen combustion systems.	Mariappan et al. and Son and Lee used PINNs but not for hydrogen combustion.
Limited Use of Generative Adversarial Networks (GANs)	GANs have been explored for data augmentation and instability prediction but are not widely applied to hydrogen combustion systems.	Grenga et al. and Xu et al. explored GANs but not for hydrogen combustion.
Lack of Hybrid Models Combining CFD and NNs	Few studies develop hybrid models that combine CFD simulations with neural network architectures for TAI detection in hydrogen combustion.	Wildemans et al. suggested hybrid models but did not implement them for hydrogen combustion.
Limited Exploration of Advanced Architectures	Few studies explore advanced NN architectures (e.g., Transformer models,Graph Neural Networks (GNNs)) for TAI detection in hydrogen combustion systems.	Most studies focus on standard architectures (e.g., ANN, CNN, RNN),with limited exploration of newer models.
Insufficient Exploration of Multi-Modal Data Integra-tion	Few studies integrate multi-modal data (e.g., pressure,temperature, velocity) for TAI detection in hydrogen combustion systems.	Lyu et al. used LSTM-CNN but did not fully leverage multi-modal data for hydrogen combustion.

III. METHODOLOGY

A. *Data Collection Strategy*

The bibliometric analysis for this study was conducted using datasets retrieved from two major scientific databases: Scopus and the Web of Science (WoS). These databases provide comprehensive coverage of peer-reviewed journal articles, conference proceedings, and technical reports in hydrogen combustion research. The dataset collection process was performed on December 2, 2024, ensuring that the dataset reflects the most recent advancements in the field. A systematic search was performed using the following query string: "thermo-acoustic instability" OR "hydrogen combustion" OR "CFD" OR "neural networks" .

This query was designed to capture key themes related to thermoacoustic instability, computational modeling techniques, and emerging machine learning applications in hydrogen combustion.

The dataset as expressed in figure 1 includes 209 documents drawn from 84 sources, consisting of journal articles (197), early access papers (3), proceedings papers (1), and review articles (8). The inclusion of 690 Keywords Plus (ID) and 734 Author Keywords (DE) indicates a diverse range of research themes covered in this study.

ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 13 Issue VI June 2025- Available at www.ijraset.com

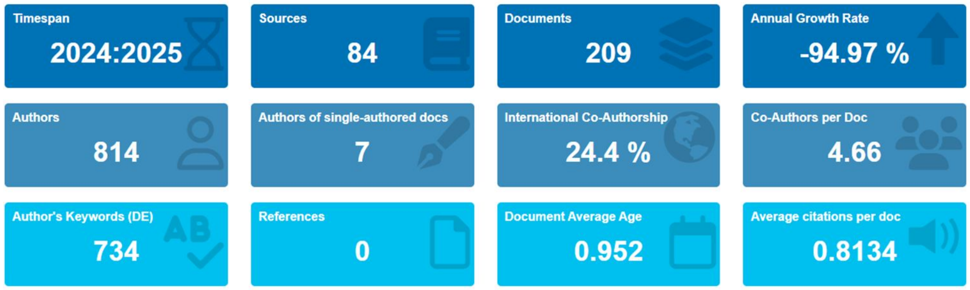

Figure 1. Bibliometric Insights into Hydrogen Combustion and Thermoacoustic Instability Research (2024-2025).

B. Bibliometric Analysis Approach

To systematically analyze research trends, Bibliometrix (R-package) was employed for bibliometric analysis. Bibliometrix provides tools for trend identification, citation analysis, co-authorship networks, keyword co-occurrence mapping, and research impact evaluation. The bibliometric workflow consisted of data cleaning, preprocessing, and visualization using a combination of bibliometrix R-package (for keyword analysis, citation mapping, and thematic evolution), network visualization tools (for co-occurrence and interdisciplinary research connections), . Before analysis, the dataset was cleaned and preprocessed to remove duplicate records, normalize author names, and unify keyword variations to ensure consistency in results.

C. Visualization Techniques for Comparative Analysis.

To provide a comprehensive overview of research trends, multiple visualization techniques were employed. These techniques enabled an in-depth understanding of dominant research areas, interdisciplinary collaborations, and emerging trends in AI-driven hydrogen combustion research.

1) Keyword Frequency Analysis Using Bubble Charts.

The bubble chart (figure 2) presents the frequency of key terms appearing in research related to thermoacoustic instability, combustion, and hydrogen combustion in gas turbines. The x-axis represents the number of occurrences of each keyword, while the y-axis lists the top keywords. The size of the bubbles indicates the relative frequency of each term, with larger bubbles representing higher occurrences. The chart highlights the exact count of keyword occurrences. "Combustion" appears 32 times, making it the most frequently used term, suggesting its fundamental role in the research domain. "Performance" and "propagation" both appear 18 times, indicating a strong focus on efficiency and flame propagation in combustion studies. Other crucial terms like "model" appear 16 times , "emissions" (15 times) , "hydrogen" (15 times), and "dynamics" (14 times) highlight the importance of emissions reduction, hydrogen fuel applications, and the dynamic behavior of combustion systems. Instability-related terms such as "instability" (14 times) and "instabilities" (12 times) further emphasize the focus on predicting and mitigating thermoacoustic instability in gas turbines.

Figure 2 provides insights into the primary research themes and priorities in combustion-based instability studies, particularly within the context of hydrogen fuel and emissions performance.

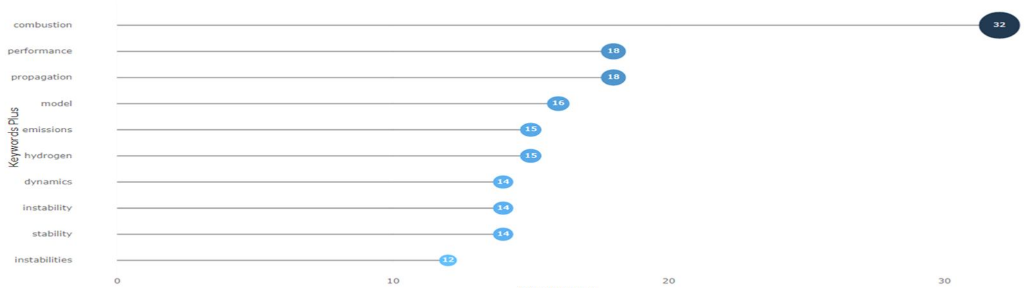

Figure 2. Keyword frequency analysis in thermoacoustic instability research

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
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2) Hierarchical Representation Using Tree Maps

Tree maps were employed to categorize and structure research topics hierarchically. The treemap below (figure 3) visualizes the frequency of occurrence of different research terms in the dataset . Each block represents a term, with its size proportional to its frequency. Color variations differentiate terms but do not indicate specific categories. The percentages (%) in each block show the term's relative occurrence in the dataset.

"Combustion" (32 occurrences, 7%) is the most frequently mentioned term, indicating that the field is heavily focused on combustion-related studies. "Performance" and "propagation" (18 occurrences, 4% each) also have significant mentions, suggesting research on how combustion processes propagate and their effectiveness. "Model" (16 occurrences, 4%) suggests a focus on computational or predictive modeling.

"Emissions" (15 occurrences, 3%) and "Hydrogen" (15 occurrences, 3%) indicate interest in the environmental impact of combustion and the role of hydrogen. "Instability," "stability," and "dynamics" (14 occurrences each, 3%) highlight research into combustion stability and turbulence."Oxidation," "fuel," and "instabilities" (12 occurrences, 3%) suggest a focus on chemical reactions in combustion.

Traditional combustion research is still dominant, but hydrogen-related studies are emerging. Instability, dynamics, and emissions are key areas of concern, indicating efforts to improve combustion efficiency and reduce environmental impact.

3) Conceptual Importance via Word Clouds

The word cloud below (figure 4) visually represents the most frequent terms in a dataset, where larger words indicate higher occurrence and importance. This method provides a quick snapshot of emerging research priorities, reinforcing the relevance of machine learning and AI-based optimization in hydrogen combustion. "Combustion" (largest word) Suggests that research is primarily focused on combustion-related phenomena. "Propagation," "Performance," "Emissions," "Instability," "Hydrogen" are crucial themes, appearing frequently in discussions. "Hydrogen," "Fuel Cell," "Hydrogen Fuels" indicate a growing focus on hydrogen-based energy solutions. Their smaller size compared to "Combustion" suggests that hydrogen research is emerging but not yet dominant. "Instability," "Oscillations," "Pressure," "Ignition," "Flames" highlight concerns related to combustion efficiency and stability. "Large-Eddy Simulation (LES)," "Direct Numerical Simulation" indicate the use of advanced computational modeling techniques.

Figure 4. Key Research Trends in Combustion and Hydrogen Energy: A Word Cloud Analysis

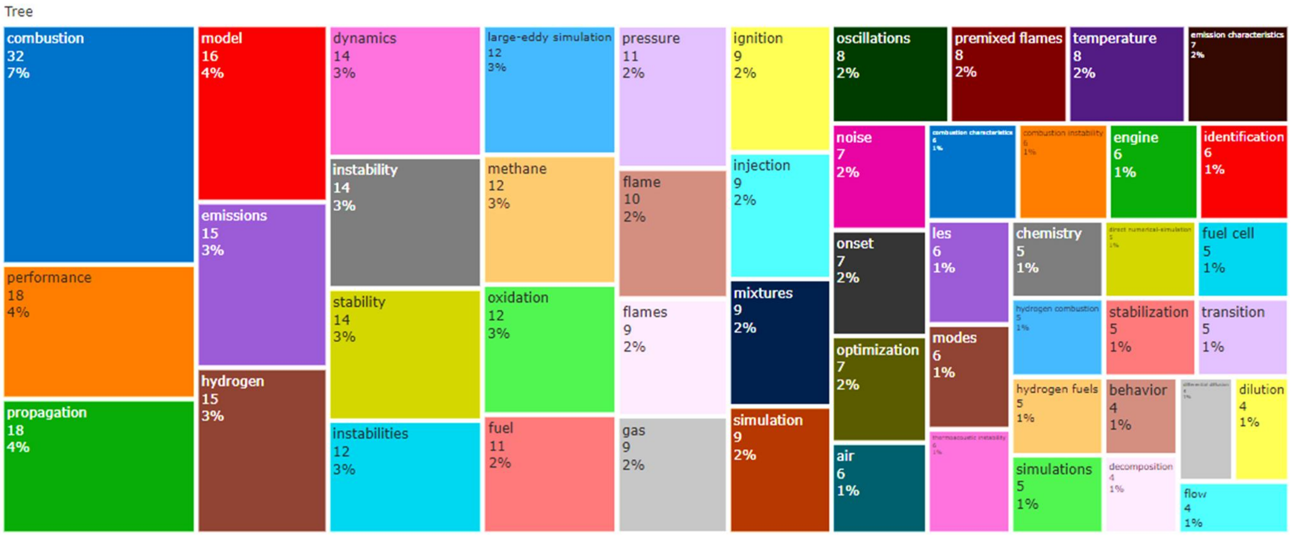

Figure 3. Research Term Distribution in Hydrogen and Combustion Studies: A Treemap Visualization

"Emissions," "Oxidation," "Emission Characteristics" emphasize the need for reducing pollutants in combustion. "Optimization," "Simulation," "Stabilization" suggest a focus on improving combustion efficiency and performance.

The Word Cloud suggests a transition phase in research, where combustion-related challenges are still dominant, but hydrogen-based solutions are gaining traction. "Combustion" (largest word) Suggests that research is primarily focused on combustion-related phenomena. "Propagation," "Performance," "Emissions," "Instability," "Hydrogen" are crucial themes, appearing frequently in discussions. "Hydrogen," "Fuel Cell," "Hydrogen Fuels" indicate a growing focus on hydrogen-based energy solutions. Their smaller size compared to "Combustion" suggests that hydrogen research is emerging but not yet dominant. "Instability," "Oscillations," "Pressure," "Ignition," "Flames" highlight concerns related to combustion efficiency and stability. "Large-Eddy Simulation (LES)," "Direct Numerical Simulation" indicate the use of advanced computational modeling techniques. "Emissions," "Oxidation," "Emission Characteristics" emphasize the need for reducing pollutants in combustion. "Optimization," "Simulation," "Stabilization" suggest a focus on improving combustion efficiency and performance. The word cloud suggests a transition phase in research, where combustion-related challenges are still dominant, but hydrogen-based solutions are gaining traction

4) Temporal Trends Using Bubble Timeline Charts

A bubble timeline chart was used to track the evolution of research themes over time. The chart (figure 5) illustrates the cumulative occurrences of various technical terms over time spanning from 2024 to 2025 . The x-axis represents the year, while the y-axis measures the cumulative number of times each term appears in the dataset. Different colored lines correspond to specific terms, which are listed in the legend at the bottom. From figure 5, "combustion" is the most frequently occurring term and continues to show an increasing trend over time, indicating its central role in research on hydrogen combustion and thermo-acoustic instability. Other key terms such as "hydrogen," "instability," and "dynamics" also show a steady increase, suggesting a growing interest in these aspects within the field. "Emissions," "model," and "performance" exhibit a more gradual rise, indicating their relevance but relatively stable focus. "Propagation" and "stability" remain significant but do not show dramatic changes in cumulative occurrences, reflecting their ongoing importance without substantial shifts in research focus.

The chart suggests a steady rise in research activity related to hydrogen combustion and its associated challenges, particularly in combustion dynamics and stability. The increasing trend in "instability" and "hydrogen" implies a heightened interest in mitigating combustion instability in hydrogen-fueled gas turbines, aligning with advancements in clean energy technologies. The relevance of "model" indicates the continued use of computational and machine learning-based approaches to predict and manage combustion instability.

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 13 Issue VI June 2025- Available at www.ijraset.com

5) Network Visualization for Research Linkages

The network visualization (figure 6) illustrates the co-occurrence of key research topics within the field of combustion science. Nodes represent research keywords, and edges indicate the co-occurrence of these terms within the same research papers or articles. The size of each node corresponds to the frequency of occurrence, while the thickness of the edges signifies the strength of the co-occurrence relationship. Different colors represent thematic clusters, suggesting distinct subfields or research directions within combustion science.

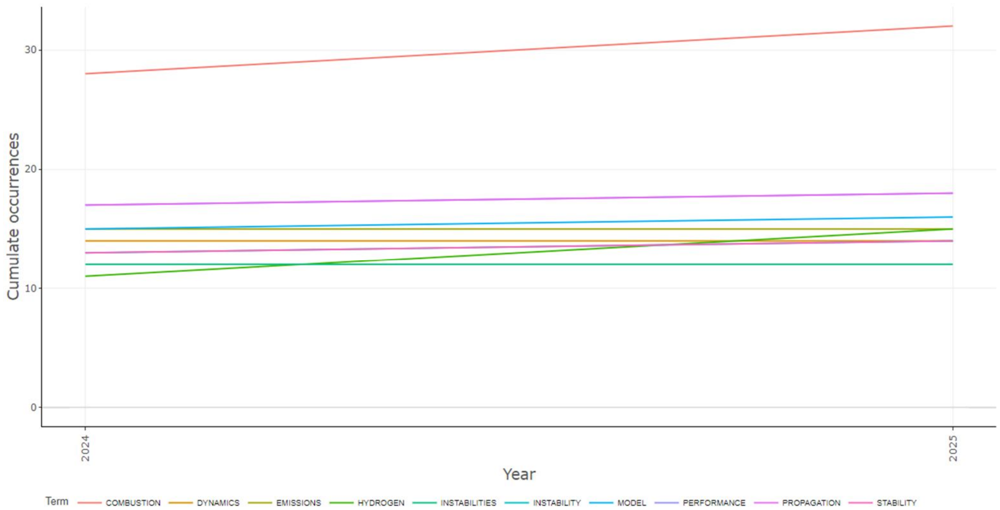

Figure 5. Trends in research terminology related to hydrogen combustion and thermo-acoustic instability (2024-2025)

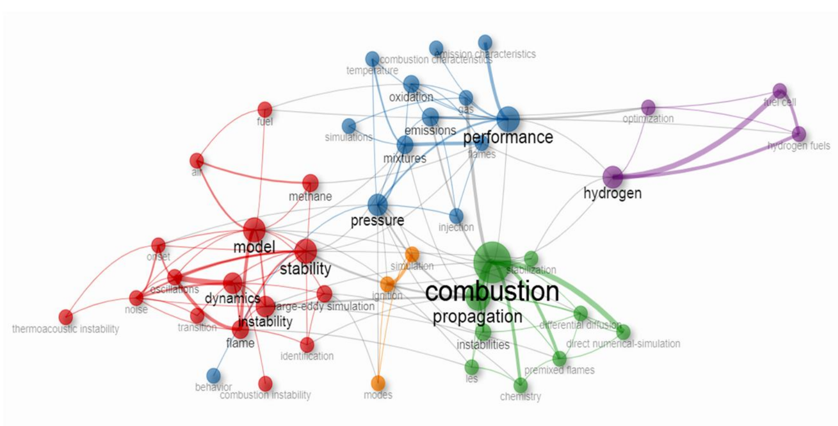

Figure 6. Research topic co-occurrence network in combustion science

The Green Cluster (Combustion and Propagation) is the core research focus, emphasizing flame dynamics, instabilities, and stabilization through high-fidelity simulations (DNS, LES) and species transport studies. The Red Cluster (Instability and Dynamics) explores thermoacoustic instability, oscillations, and predictive modeling, particularly for gas turbines and rocket engines, highlighting efforts to control dynamic combustion behaviors. The Blue Cluster (Performance and Emissions) focuses on combustion efficiency and emissions reduction (NOx, CO, soot), addressing regulatory challenges through fuel mixture optimization. The Purple Cluster (Hydrogen and Fuel Cells) represents the growing role of hydrogen in clean energy, emphasizing fuel cell performance and hydrogen combustion stabilization amid decarbonization efforts. The Orange Cluster (Ignition and Pressure Dynamics) investigates ignition processes, pressure wave interactions, and instability modes, using computational tools for engine start-up stability.

Cross-cluster linkages show strong connections between combustion and stability (Green & Red), performance and emissions (Blue & Green), and hydrogen utilization (Purple & Green), underscoring the interdisciplinary nature of hydrogen combustion research.

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D. Strengths and Limitations of Bibliometric Visualization.

While bibliometric analysis provides a data-driven, objective overview of research trends, it has certain limitations. The accuracy of the analysis is dependent on the quality and completeness of metadata from Scopus and WoS, Studies published in non-english languages or unindexed conference proceedings may not be fully represented, computational bias in ml-driven topic detection, and some highly specific research contributions may not appear in keyword frequency-based analyses.

Table 2 below provides a clear and concise comparison of the strengths and limitations of bibliometric visualization techniques, helping researchers understand their utility and potential challenges

Table 2. Strengths and limitations of bibliometric visualization techniques [26-32].

Aspect	Strengths	Limitations
Clarity and Interpretability	- Provides a clear and intuitive representation of complex data. - Makes it easier to identify patterns and trends.	- Interpretation can be subjective, especially with ambiguous or complex data.
Comparative Analysis	- Enables researchers to compare multiple datasets or time periods. - Offers a dynamic perspective on research evolution.	- May require high-quality data to ensure accurate comparisons.
Interdisciplinary Insights	- Reveals interconnectedness of research themes. - Highlights opportunities for interdisciplinary collaboration.	- Interdisciplinary connections may be overlooked if data is not comprehensive.
Data Quality	- Effective when data is complete and consistent. - Relies on accurate metadata for meaningful insights.	- Inaccurate or incomplete data can lead to misleading visualizations.
Scalability	- Works well for small to medium-sized datasets. - Provides detailed insights for focused research areas.	- Clutter and complexity increase with large datasets, making interpretation difficult. - Network diagrams may become unreadable with too many nodes and edges.

While bibliometric visualization has certain limitations, its strengths in clarity, comparative analysis, and interdisciplinary insights make it an indispensable tool for advancing scientific knowledge. Future research should focus on integrating machine learning, developing interactive visualization tools, and exploring cross-domain applications to further enhance the utility of bibliometric analysis.

IV. RESULTS AND DISCUSSION

The comparative analysis of the visualizations presented in Section III reveals several consistent patterns and trends in hydrogen combustion research. These patterns provide valuable insights into the dominant themes, emerging areas of interest, and the interconnectedness of key research topics. By examining the results from the Bubble Chart, Tree Map, Word Cloud, Bubble Timeline Chart, and Network Visualization, we can identify the most frequent keywords, their correlations, and the overarching research priorities in the field of hydrogen combustion.

A. Most Frequent Keywords and Dominant Research Themes

Across all visualizations, "combustion" emerges as the most dominant keyword, appearing 32 times in the dataset. This aligns with the findings from the bubble chart (figure 2) and tree map (figure 3), where "combustion" is the largest and most frequently occurring term. The centrality of "combustion" in the research landscape underscores its fundamental role in hydrogen combustion studies, particularly in understanding the dynamics of flame propagation, stability, and efficiency.

The word cloud (figure 4) further reinforces this observation, with "combustion" being the largest and most prominent term, indicating its pervasive presence in the literature.Other highly recurring keywords include "performance," "propagation," "hydrogen," "model," "emissions," "stability," and "instabilities."

These terms appear consistently across the visualizations, suggesting that research efforts are heavily focused on optimizing combustion performance, understanding flame propagation, and addressing stability issues, particularly in the context of hydrogen as a fuel. For instance, the tree map (figure 3) highlights the significance of "performance" and "propagation," each appearing 18 times, which reflects the emphasis on improving combustion efficiency and understanding how flames propagate in hydrogen-fueled systems. Similarly, the bubble timeline chart (figure 5) shows a steady increase in the occurrence of terms like "hydrogen," "instability," and "dynamics," indicating a growing interest in these areas over time.

B. Keyword Correlations and Research Linkages

The network visualization (figure 6) provides a deeper understanding of the relationships between these keywords by illustrating their co-occurrence within the same research papers. The visualization reveals strong correlations between "hydrogen" and "combustion", "instability" and "performance", reflecting the growing interest in hydrogen as a clean energy carrier and the challenges associated with its combustion. The close linkage between "hydrogen" and "instability" is particularly noteworthy, as it highlights the critical issue of thermo-acoustic instability in hydrogen-fueled gas turbines, a recurring theme across the visualizations. Another significant correlation is observed between "large-eddy simulation (LES)" and "combustion dynamics." The frequent appearance of "LES" in the word cloud (figure 4) and its strong connection to "combustion" and "dynamics" in the network visualization (figure 6) underscores the importance of advanced computational modeling techniques in predicting and mitigating combustion instabilities. This trend is further supported by the bubble timeline chart (figure 5), which shows a gradual rise in the use of terms like "model" and "simulation," indicating the increasing reliance on computational tools to address complex combustion phenomena.The terms "instabilities" and "oscillations" are also closely associated, as seen in the network visualization (figure 6). This correlation reinforces the importance of thermo-acoustic instability studies, which are critical for ensuring the safe and efficient operation of hydrogen-fueled combustion systems. The presence of these terms in the word cloud (figure 4) and their steady increase in the bubble timeline chart (figure 5) suggest that research on combustion instabilities remains a key priority, particularly in the context of hydrogen combustion.

C. Interconnectedness of Research Themes

The visualizations also reveal the interconnectedness of various research themes within hydrogen combustion. For example, the green cluster in the network visualization (figure 6), which focuses on "combustion" and "propagation," is strongly linked to the red cluster centered on "instability" and "dynamics." This interconnection highlights the close relationship between understanding combustion dynamics and addressing stability issues, particularly in hydrogen-fueled systems. Similarly, the blue cluster, which emphasizes "performance" and "emissions," is connected to both the green and red clusters, reflecting the integrated nature of performance optimization and emission reduction strategies.The purple cluster, which represents "hydrogen" and "fuel cells," also shows connections to the green cluster, indicating research efforts to understand hydrogen combustion characteristics and stabilization mechanisms. This interconnectedness underscores the multidisciplinary nature of hydrogen combustion research, where advancements in one area often have implications for others.

D. Summary of Key Findings

In summary, the comparative analysis of the visualizations reveals several key findings. "Combustion" is the dominant research theme, with a strong focus on performance, stability, and propagation. "Hydrogen" is closely linked to "combustion," "instability," and "performance," reflecting its growing importance as a clean energy carrier. Advanced computational techniques, particularly Large-Eddy Simulation (LES), play a crucial role in predicting and mitigating combustion instabilities. Emerging trends include a shift toward sustainable energy solutions, such as hydrogen fuel cells, and the use of machine learning for predictive modeling. The interconnectedness of research themes highlights the multidisciplinary nature of hydrogen combustion research, with strong linkages between combustion dynamics, stability, performance, and emissions. These findings provide a comprehensive understanding of the current state of hydrogen combustion research, offering valuable insights for future work in this critical area. The patterns and trends identified in this analysis underscore the need for continued interdisciplinary collaboration and the integration of advanced computational tools to address the complex challenges of hydrogen combustion.The comparative analysis of keyword trends across various visualizations reveals several consistent patterns. Firstly, there is a noticeable increase in research interest surrounding hydrogen combustion technologies, particularly in the context of reducing carbon emissions. Keywords such as 'hydrogen', 'combustion', and 'decarbonization' show upward trends, reflecting the global push towards cleaner energy solutions.Another prominent pattern is the growing focus on thermo-acoustic instability and its mitigation strategies. The data indicates a sustained interest in modeling and predicting combustion instabilities, with 'thermo-acoustic instability', 'acoustic waves', and 'pressure oscillations' being recurrent terms. This aligns with the critical safety and operational challenges posed by hydrogen combustion in gas turbines.Overall, the visualizations collectively illustrate a convergence of research efforts aimed at integrating hydrogen as a fuel while addressing associated instability challenges through advanced analytical techniques. These patterns provide valuable insights into the evolving priorities within the energy and combustion research communities.Table 6 provides a concise overview of the main insights derived from the bibliometric analysis in the field of hydrogen combustion. Overall, it provides a clear snapshot of the current state and future directions of hydrogen combustion research, emphasizing its importance in the broader context of sustainable energy development

Table 3. Summary of Key Findings in Hydrogen Combustion Research

Category	Key Findings
Dominant Keyword	"Combustion" is the most frequent keyword across all visualizations, indicating its central role in hydrogen combustion research.
Emerging Trends	Growing interest in "hydrogen," "fuel cells," and "emission reduction" reflects a shift toward sustainable energy solutions.
Computational Modeling	Terms like "Large-Eddy Simulation (LES)" and "model" highlight the importance of advanced computational techniques in predicting and mitigating combustion instabilities.
Interconnected Themes	Strong correlations between "combustion," "instability," and "performance" underscore the multidisciplinary nature of hydrogen combustion research.
Temporal Trends	Steady increase in research activity related to hydrogen combustion, with a focus on combustion dynamics, stability, and performance optimization.

The bibliometric analysis confirms an increasing intersection between hydrogen combustion research and machine learning applications. The key keywords like "instability," "oscillations," "flame dynamics," and "pressure waves" frequently appear across different visualization tools indicating a focus on predicting and mitigating combustion instability, a primary challenge in hydrogen-fueled gas turbines. Neural networks (NNs), particularly LSTMs, CNNs, and hybrid models, are increasingly being explored to model the nonlinear behavior of combustion instability in real-time. Thematic mapping and network visualizations show that traditional CFD-based approaches (LES, DNS) remain dominant but are increasingly complemented by AI-driven solutions for real-time instability prediction and control. A growing number of studies integrate machine learning (ML) techniques to model nonlinear combustion behavior more efficiently. The analysis highlights the increasing role of Artificial Neural Networks (ANNs), including LSTMs, CNNs, and hybrid models, for real-time instability prediction. While traditional Computational Fluid Dynamics (CFD) methods such as Large-Eddy Simulation (LES) and Direct Numerical Simulation (DNS) remain widely used, their high computational costs have led to the development of ML-based surrogate models (DNNs, PINNs, and GANs) to enhance predictive accuracy while reducing computational demands. Additionally, Bayesian Neural Networks and Reinforcement Learning are emerging as effective tools for performance optimization, flame stabilization, and emissions reduction in hydrogen-fueled turbines. Thematic mapping and network visualization further confirm a growing research shift toward AI-powered predictive modeling and sensor-driven real-time instability detection. These insights suggest that future advancements should focus on hybrid AI-CFD models and real-time sensor-based learning systems to improve hydrogen combustion stability. These findings suggest that hydrogen combustion research is undergoing a transition from physics-based models to AI-assisted predictive analytics, where machine learning techniques enhance accuracy, computational efficiency, and real-time control capabilities. This trend underscores the need for further hybrid AI-CFD models, real-time ML deployment, and interdisciplinary collaboration to address hydrogen's unique combustion challenges.Furthermore, the thematic map below (figure 7) generated from the same dataset using bibliometric analysis as explained in section 3 which illustrates the discussed key research themes in hydrogen combustion based on keyword co-occurrence analysis explains the research gaps in hydrogen combustion research which aligns with the findings of the analysis above.

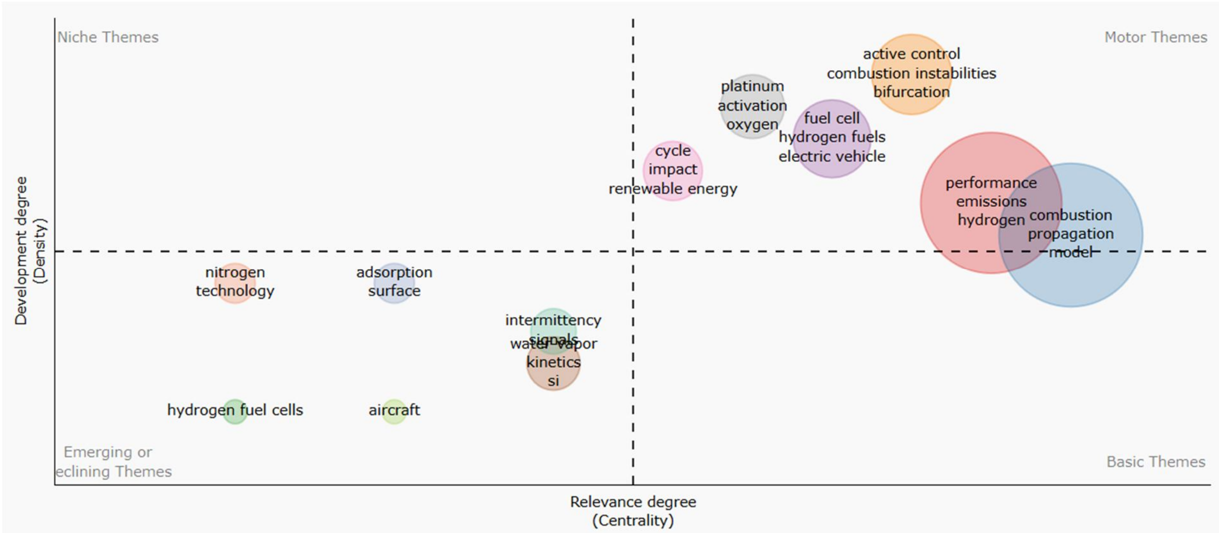

Figure 7. Thematic Map of Research Trends in Thermo-Acoustic Instabilities and Hydrogen Combustion: Centrality vs. Development

The thematic map (figure 7) categorizes research themes based on their relevance and development. From the thematic map provided, the research gaps can be identified by analyzing the position and clustering of the themes based on their relevance (centrality) and development (density). Bottom Left Quadrant which signifies emerging or declining themes like hydrogen fuel cells and aircrafts indicates that there is a limited focus on applying hydrogen fuel cells or their interaction with thermo-acoustic instability, especially in aviation contexts. Niche Themes (Top Left Quadrant) indicate high development in nitrogen technology and adsorption surface but limited centrality. According to the top left Quadrant , these are specialized areas with potential applications but limited integration into broader topics like hydrogen combustion and thermo-acoustic instability.
Basic Themes (Bottom Right Quadrant) are dominant themes such as combustion propagation, methane, fuel cell performance, and emissions optimization which are central but not highly developed. From this theme, research could focus on transitioning from methane to hydrogen combustion systems while addressing thermo-acoustic instability and emissions challenges.
Motor Themes (Top Right Quadrant) are themes like combustion instabilities, active control, and bifurcation which are well-developed and highly central, indicating they are driving research in the field but according to the map, while these themes are mature, there is a need for practical and scalable solutions, such as advanced machine learning models for active control of instabilities in hydrogen combustion systems. The thematic map provides visual evidence to support the findings, such as the dominance of combustion dynamics and the growing interest in hydrogen fuel cells. It also reinforces conclusion that advanced computational techniques (e.g., LES, DNS) and machine learning are critical for addressing combustion challenges. In conclusion from the thematic map, foundational areas like combustion propagation and emission control require deeper exploration to address challenges specific to hydrogen-fueled systems and advanced control strategies and machine learning methods for real-time instability prediction and mitigation remain underdeveloped.

V. CONCLUSION AND FUTURE RESEARCH RECOMMENDATIONS

The comparative analysis of keyword trends in hydrogen combustion research, conducted through a variety of bibliometric visualization tools, has provided a comprehensive overview of the current research landscape. This study has identified dominant themes, emerging trends, and the interconnectedness of key research topics, offering valuable insights into the evolving priorities and challenges in the field. The findings underscore the critical role of hydrogen as a clean energy carrier and highlight the need for continued innovation and interdisciplinary collaboration to address the technical challenges associated with hydrogen combustion.
Additionally, the bibliometric analysis in Section III serves as a quantitative validation of the literature review in Section II, particularly regarding the role of machine learning in thermoacoustic instability prediction. The keyword frequency trends and network visualizations confirm the increasing research focus on deep learning, hybrid AI-CFD models, and predictive analytics, aligning with the discussion in Section II.

Furthermore, the research gap analysis highlights unresolved challenges, such as the need for specialized neural network architectures and the integration of high-fidelity CFD data, reinforcing the importance of the literature review's findings.

By bridging qualitative insights from the literature review with quantitative trends from bibliometric analysis, this study provides a comprehensive, data-driven roadmap for future research in hydrogen combustion. Moving forward, continued exploration of machine learning techniques, hybrid modeling approaches, and advanced instability control strategies will be essential for accelerating the development of hydrogen-based energy solutions.

Based on the dominant themes, emerging trends, and research gaps identified by the literature view and the bibliometrics analysis , the following recommendations are proposed to guide researchers, policymakers, and industry stakeholders in advancing hydrogen combustion technologies and addressing the associated challenges:

Enhance Computational Modeling Capabilities

The continued development and application of advanced computational tools, such as LES and DNS, are essential for addressing the complex dynamics of hydrogen combustion. Future research should focus on improving the accuracy and scalability of these models, particularly for large-scale industrial applications.

Foster Interdisciplinary Collaboration:

The multidisciplinary nature of hydrogen combustion research necessitates collaboration across fields such as mechanical engineering, chemical engineering, computational fluid dynamics, and machine learning. Interdisciplinary research efforts can lead to innovative solutions for mitigating combustion instabilities and optimizing system performance.

Explore Hybrid Energy Systems:

The integration of hydrogen fuel cells with combustion-based systems represents a promising avenue for achieving sustainable energy solutions. Future research should investigate the design and optimization of hybrid systems that leverage the strengths of both technologies. The recommendations outlined above provide a strategic framework for advancing hydrogen combustion research and addressing the critical challenges associated with its implementation. By prioritizing combustion stability, leveraging advanced computational tools, fostering interdisciplinary collaboration, and exploring innovative combustion techniques, researchers can contribute to the development of sustainable and efficient hydrogen-based energy systems. These efforts will not only support the global transition to clean energy but also pave the way for the widespread adoption of hydrogen as a key component of the future energy landscape.

VI. ACKNOWLEDGMENTS

The authors would like to extend their sincere appreciation to Niger Delta University, Universiti Teknologi Malaysia and the Petroleum Technology Development Fund (PTDF) for their generous backing of this research endeavor.

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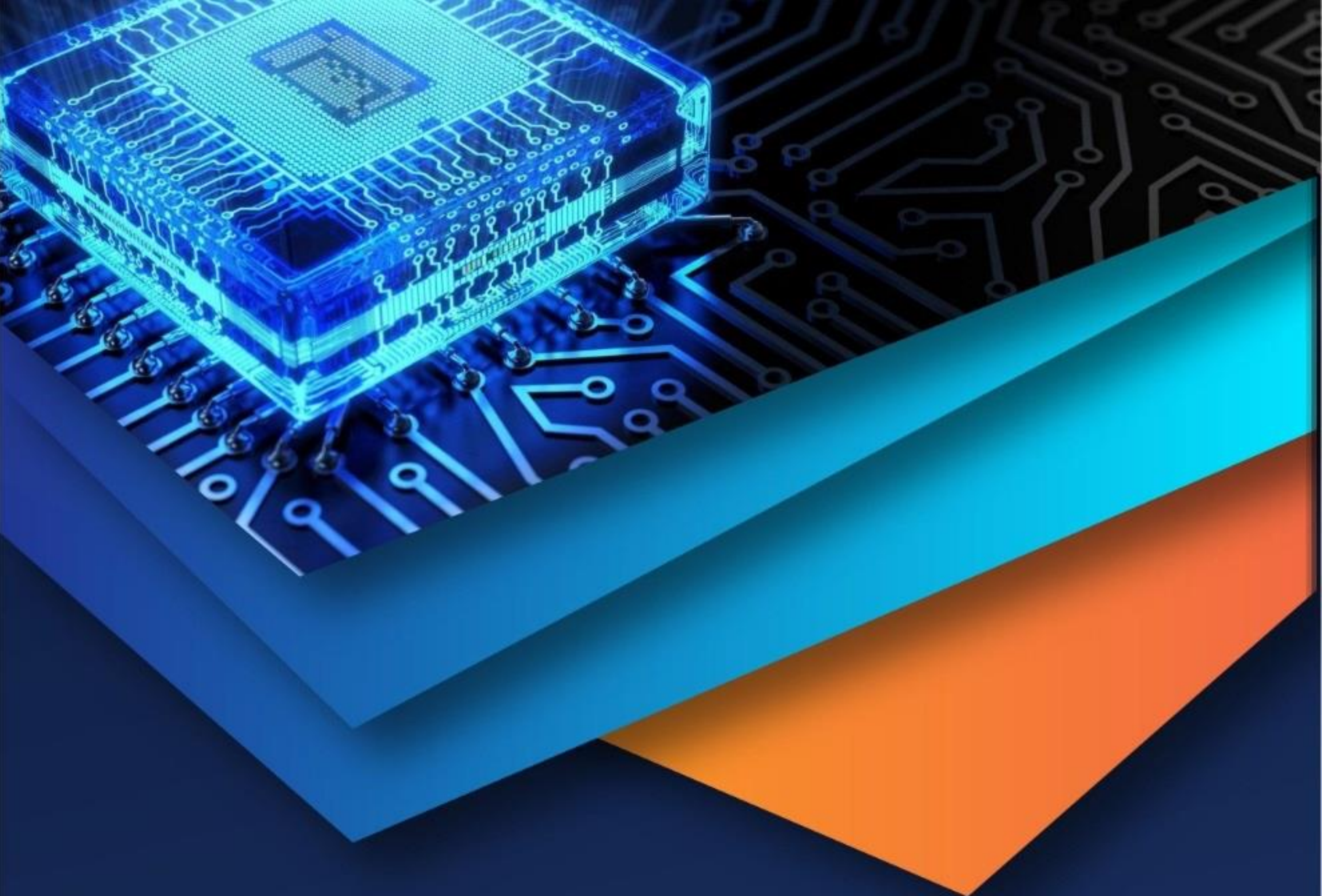

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