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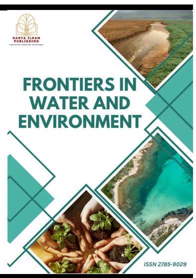

Hydrogen Gas Turbine for Low Carbon Future Energy Generation - A Review

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ABSTRACT

Low carbon energy generation is the major global agenda for the future, but traditional technologies are far from meeting the expectations. Hydrogen gas turbine (HGT) is a relatively modern technology that is slowly being adopted around the globe for energy generation. But every advancement comes with some challenges that need to be mitigated for its effective future use. Existing research does not provide useful implications from which current challenges faced by HGT use can be determined. The study was aimed at finding out the challenges and mitigation techniques for effective use of HGT in future low-carbon energy generation. Structures Literature Review (SLR) was adopted involving articles from 2013 to 2022. A total of 20 challenges are identified from existing literature, along with their priority from the perspective of mitigation. Further mitigation interventions are also presented for each of the identified challenges affecting the sustainable use of HGT for future energy generation. The study provides positive theoretical and practical implications for future researchers and professionals working on the development of HGT in sustainable energy generation

1. Introduction

As part of the worldwide effort to reduce greenhouse gas emissions and slow or prevent the advancement of global warming, decarbonization of the economy has been called for. Substitutes for fossil fuels that are both practical and affordable are required. Hydrogen, which can be synthesized from water using renewable energy sources like solar or wind power, has been discussed as a possible clean fuel of the future for quite some time [1,2]. Combining these variable renewable energy sources with hydrogen, which can be stored and converted into electricity on demand with no carbon emissions, might provide stability. However, we need safe and reliable methods of hydrogen storage and transportation if we're going to make the transition to a hydrogen-based economy [3,4]. Hydrogen may be utilized as a fuel in power plants after it is produced. Gas turbines are adaptable because hydrogen, which is utilized in many different types of manufacturing, may be employed as a fuel source. Steel mills, refineries, and petrochemical plants are all included in this category. Gas

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turbines may be created to burn a wide variety of fuels, including natural gas and other fossil fuels as shown in Figure 1, as well as eco-friendlier options later on [5,6].

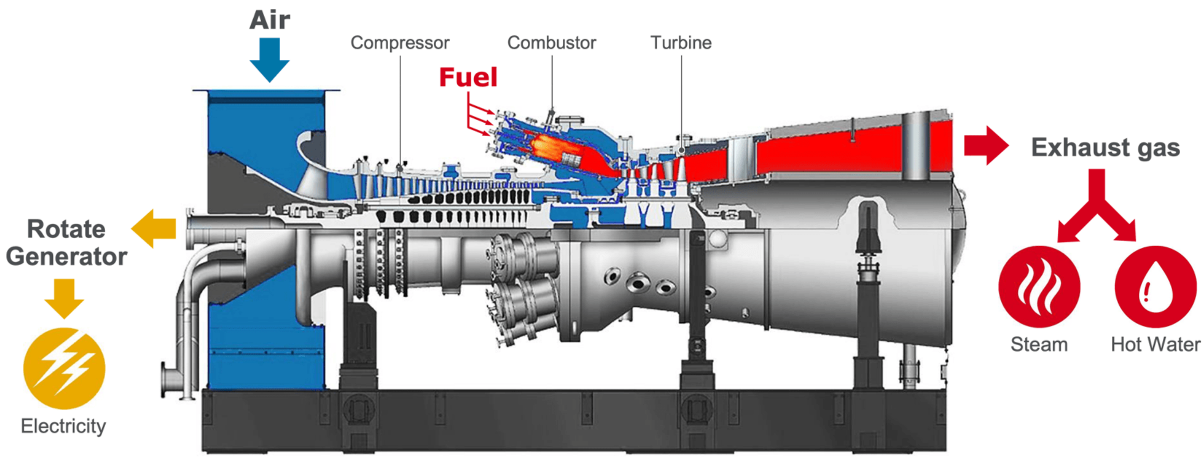

Fig. 1. Gas Turbine Operation [5]

Numerous experts claim that the advent of carbon reduction regulations throughout the world has boosted the efficacy of renewables, leading to an uptick in the number of corporations working on hydrogen-fueled gas turbines [7,8]. Experts agree that hydrogen has the greatest energy capacity of common fuels per weight, is odorless and nontoxic, and has several potential applications as a transporter of energy in sectors as varied as transportation, industry, and power generation [9,10]. There is a difficulty in making hydrogen gas turbines work without sacrificing efficiency, responsiveness, or environmental friendliness. If the hydrogen economy keeps growing over the next decade, gas turbines will be able to meet demand without sacrificing efficiency, responsiveness, or production [11,12].

Limited research is available that highlights the contemporary challenges of using HGT specifically for low-carbon future energy generation. In a practical context, there is a significant need for transitioning to modern technologies and fuels, but a lack of credible information hinders the ability of power generation industries to adopt new advancements. Further, there are always certain challenges associated with new interventions that are important to incorporate into their theoretical and practical implications.

Based on this rationale, the article is structured with the aim of reviewing the potential challenges of using HGT for low-carbon future energy generation. This study uses a Structured Literature Review (SLR) approach to provide a summarized view of HGT adoption challenges from the most recent studies in order to fill a research gap. The research questions are: RQ1: What challenges exist in the implementation of HGT for low-carbon future energy generation projects? and RQ2: What interventions can be adopted to handle challenges affecting the usage of HGT for low-carbon future energy generation projects? The implications of this study include assisting the power generation industry in projecting long-term use of HGT for low-carbon future energy generation.

2. Research Methodology

SLR is needed whenever there is a goal of doing a thorough review of the existing literature. Researchers say that the approach is very helpful for doing qualitative review research and gives good practical and theoretical implications. When peer-reviewed articles are part of a study, the most important thing is to include secondary information. Following this, SLR on possible challenges of using HGT for low carbon future energy generation projects is carried out. The analysis only looked at peer-reviewed articles from high-impact journals from January 2013 to December 2022. We used databases like Scopus, ScienceDirect, IEEE Xplore, MDPI, and Google Scholar to find articles that had been published. Keywords were used to find relevant articles, and the language was only set to English.

Figure 2 shows the flow of research, including how research articles are sorted and chosen. Thirty research articles were chosen, and according to SLR, each one was carefully looked over to meet the needs of RQ1 and RQ2. Comparisons were made between the results and the research questions in order to find out what the most important challenges and needed mitigation interventions for HGT usage in low carbon future energy generation projects. A critical discussion is held based on findings from existing literature, and final HGT usage challenges with prioritization and corresponding mitigation interventions are presented.

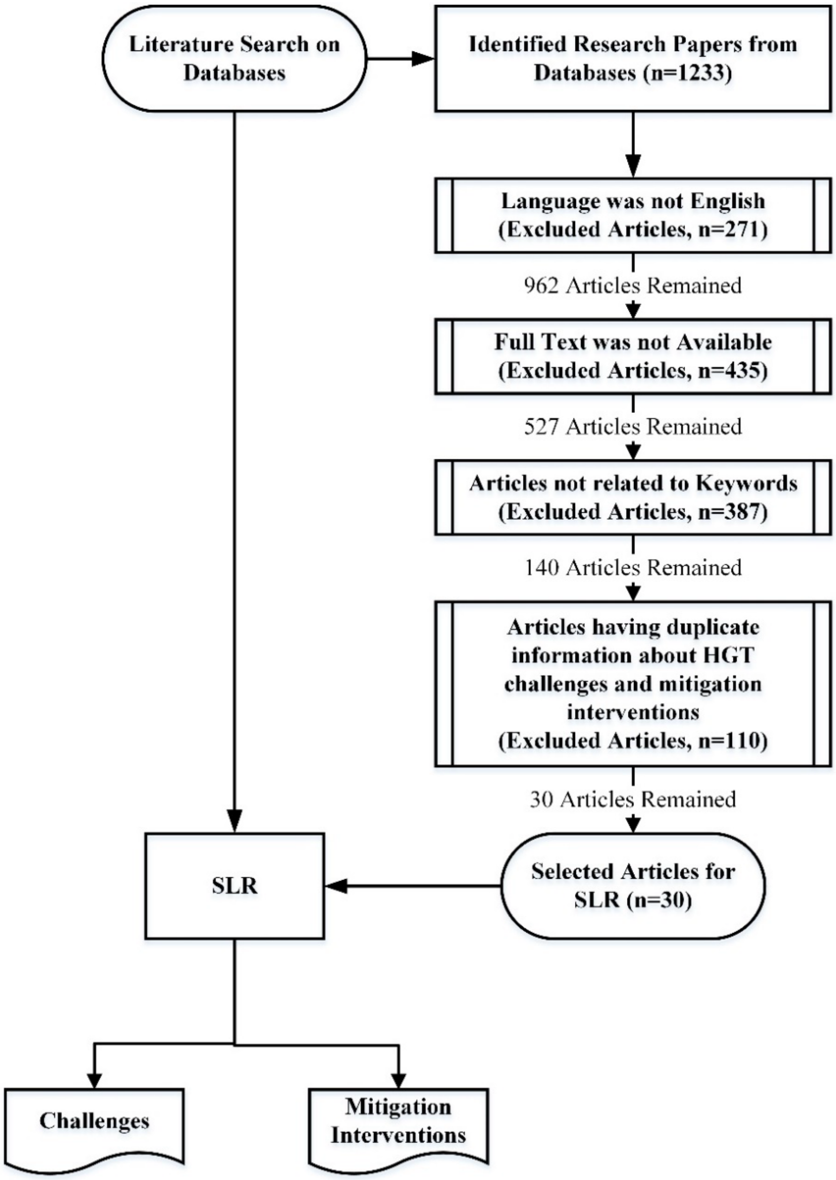

Fig. 2. Research methodology flowchart

3. Identification of Challenges

The first stage was focused on identification of HGT usage challenges from existing literature. All the selected articles were reviewed with an objective of effective identification of challenges.

Arguments of authors were evaluated for specific determination of significance of identified challenge. Each challenge was further reviewed from the cross-comparison perspective to exclude duplicates. Top 20 challenges hindering the sustainable use of HGT are presented in Table 1. Wide flammability range, low ignition energy and molecular properties, these are risk factors which are also the challenge for the combustion chamber in HGT as shown in Figure 3.

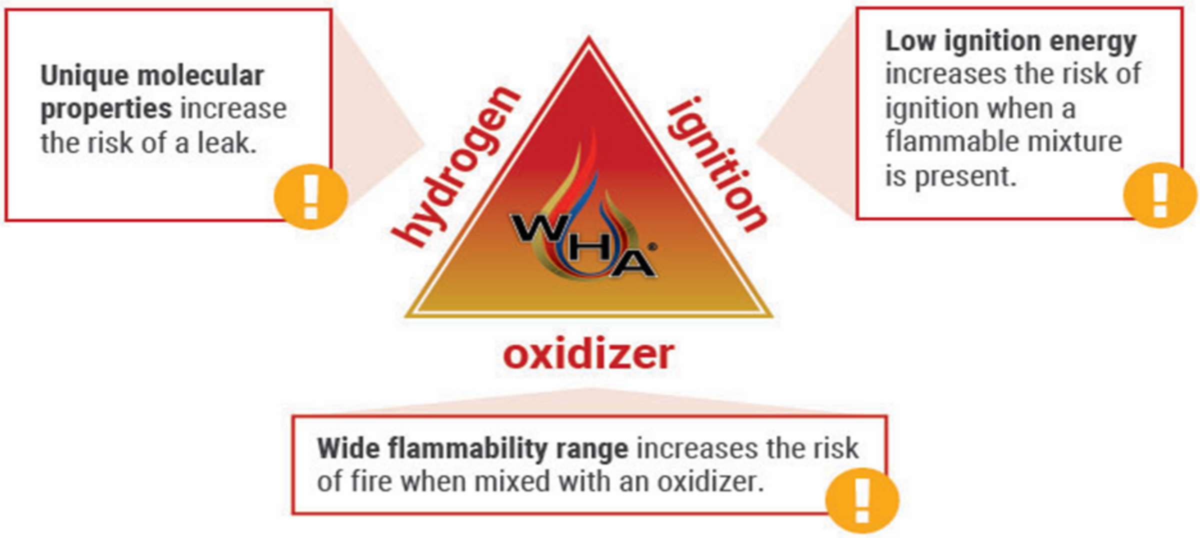

Fig. 3. Critical risk factors [13]

The occurrence of each of the considered challenge from overall research articles is presented in Figure 4. The occurrence frequency is also indicating significance of each of the challenge which authors have indicated in existing research. The found occurrence corresponding to significance of the challenges is indicated as, C1 “High risk of Fire” at 14%, C2 “High Handling Cost of Hydrogen” at 10%, C3 “High Cost of Generated Power” 9% C4 “High Fuel Production Cost” and C5 “Elemental Hydrogen is Scarce” at 8%, C6 “High Carbon Emissions in Hydrogen Production” 7%, C7 “Inefficient Fuel Supply Chain” and C8 “Require Extensive Modification in Turbine Design” at 6%, C9 “Storage Hazards” and C10 “Require Effective Blending with Other Fuels” at 5%, C11 “High Operating Temperature” at C12 “High Performance Materials Needed” at 4%, C13 “High Maintenance Cost of Turbine Parts” and C14 “Require Skilled Workers to Operate” at 3%, C15 “Ineffective Hydrogen Infrastructure Regulations”, and C16 “High Embodied Carbon of Hydrogen Turbine” at 2%, C17 “Lack of Sustainable Project Funding”, C18 “Monopoly of Fossil Fuel Industry”, C19 “Lack of Knowledge” and C20 “Lack of Innovation” at 1%. Overall, the authors have emphasized more on C1, C2, C3, and C4. The least significant challenges identified from analysis are C12, C13, C14, C15, C16, C17, C18, C19 and C20.

Table 1
HGT usage challenges

Code	HGT Usage Challenges	References
C1	High risk of Fire	[14,15]
C2	High Handling Cost of Hydrogen	[16,17]
C3	High Cost of Generated Power	[5,8]
C4	High Fuel Production Cost	[11,18]
C5	Elemental Hydrogen is Scarce	[6,19]
C6	High Carbon Emissions in Hydrogen Production	[12,20]
C7	Inefficient Fuel Supply Chain	[21,22]
C8	Require Extensive Modification in Turbine Design	[13,23]
C9	Storage Hazards	[24,25]
C10	Require Effective Blending with Other Fuels	[2,10]
C11	High Operating Temperature	[3,4]
C12	High Performance Materials Needed	[1,26]
C13	High Maintenance Cost of Turbine Parts	[27,28]
C14	Require Skilled Workers to Operate	[9,29]
C15	Ineffective Hydrogen Infrastructure Regulations	[7,30]
C16	High Embodied Carbon of Hydrogen Turbine	[2,27]
C17	Lack of Sustainable Project Funding	[4,29]
C18	Monopoly of Fossil Fuel Industry	[10,26]
C19	Lack of Knowledge	[7,8]
C20	Lack of Innovation	[6,15]

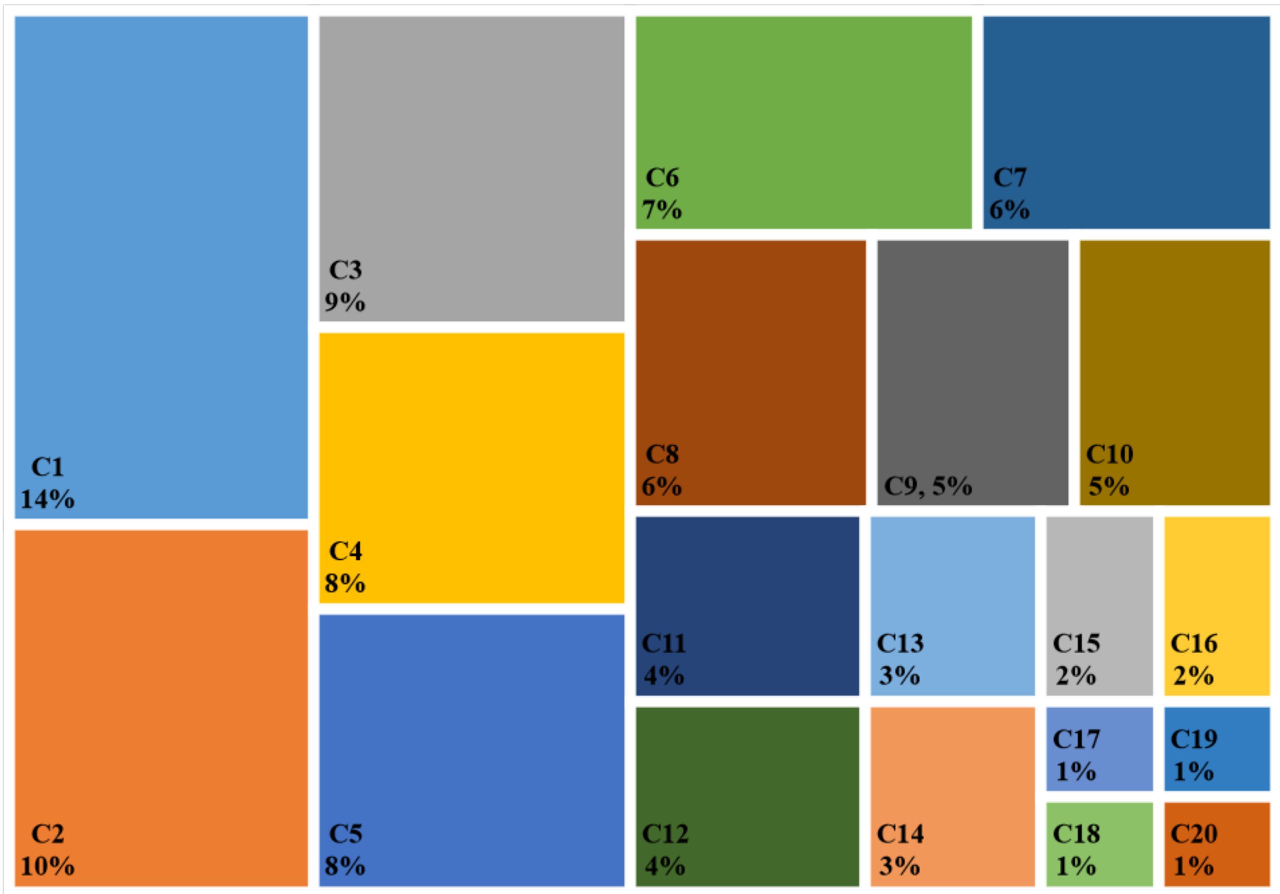

Fig. 4. Relative evidence of HGT challenges from research papers

4. Analysis and Discussion

4.1 High Risk of Fire

According to Pyo *et al.,* [15], there are significant benefits to using HGT, but the unfortunate challenge of high flammability cannot be ignored. It affects the implementation of HGT in the power sector, where the existing safety protocols are not at a level where they could handle the high risk of fire. The possible intervention that could be implemented is related to advancing ignition systems that can prevent fire accidents. Shih & Liu [14] also indicated that effective utilization of noncombustible materials can help to reduce the fire risk, but it is also not the permanent solution. Pyo *et al.,* [15] also shown that there is possible improvement in fire safety of HGT if proper technology is utilized in fire safety systems.

4.2 High Handling cost of Hydrogen

According to Sun *et al.,* [17], hydrogen is very difficult to handle in normal conditions, which carries a series of risks in terms of creating a big disaster in the power industries. Valera-Medina *et al.,* [16] has also shown that there is a need to utilize available technology, in which the latest leak detectors are important, while successful implementation can be accelerated by increasing the effectiveness of ignition source control. There are significant gaps in storage regulations that need to be increased to ensure proper handling of hydrogen as a fuel.

4.3 High Cost of Generated Power

According to Fawwaz Aalrebei *et al.,* [5], it is evident that there is a significant cost associated with it despite the benefits of HGT because the fuel is very expensive to produce. The generated power is expensive for the consumers, due to which Funke *et al.,* [8] has recommended maximizing the production capacity of hydrogen while also transitioning towards renewable energy resources. This is also significant indication showing improvement in hydrogen infrastructure is recommended that can ultimately improve neutralization of HGT for the future energy generation with low carbon emissions.

According to Devriese *et al.,* [4], there is a significant barrier in the procurement of sustainable project funding, which will likely affect the use of HGT in the power industry even in developed regions. The effective interest in hydrogen energy projects depends on a variety of factors that are not aligned from a business perspective with funding parties, and ultimately, it indicates the need for improvement in the funding process for hydrogen infrastructure. According to Shulga *et al.,* [29], the cost-benefit ratio is also low and needs to be increased while also developing effective investment appraisals.

4.4 High Fuel Production Cost

The fuel production cost of HGT is not decreasing according to Kotowicz *et al.,* [11], it is the reason due to which there is a need of utilization of renewable energy resources while also using alternate production methods. It is evident from Xiao & Valera-Medina [18], that the electrolysis process may not always be useful for fuel production and needs to be replaced by more advanced ones. There is a possible positive impact on the utilization of HGT for low-carbon energy production if their fuel cost is reduced. Possible interventions need to be implemented that may follow the local production goals and adopt renewable energy resources to make it possible for the power sector to decrease carbon emissions.

4.5 Elemental Hydrogen is Scarce

According to Ditaranto *et al.,* [6], it is very difficult to properly maintain the supply of fuel for HGT in the power sector, and this challenge is affecting the full usage of technology for power production. Welch [19] have also shown that there are benefits in utilizing the impure hydrogen, but it is not significant in terms of living the other methods of power production where turbines are used. One possible way of producing hydrogen in excess is to transition to a biological hydrogen production method while also investing in hydrogen capture technology.

4.6 High Carbon Emission in Hydrogen Production

According to Kosowski & Piwowarski [12], the production of hydrogen creates a significant impact on the environment due to carbon emissions, and there is a need to effectively reduce these emissions with the help of changes in the supply chain while also using hydrogen capture systems. Sharif *et al.,* [20] indicated there is an effective need of reducing the embroidered carbon which can ultimately help to reduce carbon emissions associated with hydrogen production methods. Future sustainable use can be increased only if it is possible for HGT to decrease the carbon emissions associated with them.

According to Bexten *et al.,* [2], the embodied carbon of HGT is high, which has a negative impact on sustainable power generation. It is also indicated that proper neutralization of materials may help to accelerate its use in power industries, while Lee & Lee [27] has also indicated the use of carbon capture systems along with heterogeneous materials as an effective solution. Further, the high embodied carbon may act as a major barrier to funding HGT projects, for which effective improvement will be needed. The effective development of power generation with the use of technology may help to reduce its emissions of carbon in the future.

According to Ilbas *et al.,* [10], the fossil fuel industry has always played monopoly when it comes to transitioning to other types of fuel in the power industry. Moradi Nafchi *et al.,* [26] has also indicated the need for negotiation with fossil fuel industry leaders along with an effective but slow transition to hydrogen fuel. Further, there is high possibility of joint ventures that can accelerate the implementation of HGT for future low-carbon energy generation. It is critically important to handle the challenge of monopoly of fossil fuel industry as it can affect the future development of hydrogen gas power generation turbines. That can lead to the effective development of the power industry while also being directly affected by inappropriate handling of hydrogen as a fuel.

4.7 Inefficient Fuel Supply Chain

The problem of low efficiency in fuel supplies is indicated by Öberg *et al.,* [21], where it is not possible for new power plants to establish HGT infrastructure as the fuel supply chain involves significant delays. Taamallah *et al.,* [22] indicated that one possible way to handle the problem of fuel supply is to extend the network while producing the fuel locally, which can ultimately support the sustainable supply chain transformation. Further, it is important for the industry to adopt effective protocols that must maintain good efficiency in the supply chain.

4.8 Require Extensive Modification in Turbine Design

According to Langston [13], it was found that the existing turbine infrastructure required significant modification if the modern HGT was implemented. Schastlivtsev & Nazarova [23] also indicated the significant need of reinventing the turbine design protocols for power generation that create barrier in adopting HGT. Similarly, effective utilization of composite materials that can help in supporting the turbine design and reducing the chances of failures. Further, it is indicated that reduction in weight and size will ultimately improve the challenge of turbine design modification. It is also important to consider the effective adoption of the latest technology, which can help modify the turbine design and provide great leverage in controlling the future outcomes of low-carbon energy production.

4.9 Storage Hazards

According to Seitz *et al.,* [25], there are significant storage hazards because the gas itself is difficult to handle. Stefan *et al.,* [24] have also shown significant evidence of different accidents that may happen during storage and ultimately cause minor or major injury to workers on power plants. Proper isolation of storage will be needed, while further automated flow control systems will be required in terms of handling the storage hazards. Stefan *et al.,* [24] have also indicated the adoption of artificial intelligence in future that will ultimately improve inventory management.

4.10 Require Effective Blending with Other Fuels

Bexten *et al.,* [2] has indicated the possible blending of hydrogen with other types of fuel for power generation in turbines. It is indicated by Ilbas *et al.,* [10], that there is a significant need for atmosphere in the fuel combination research, while further neutralization of ammonia is indicated as a replacement for hydrogen fuel for the successful use of a HGT. There is a need of improving the fuel injection and ignition systems which is critically related with handling variety of blends of hydrogen-based fuels. Following figure 5 shows the blended hydrogen fuel producing, storage and used in hydrogen gas turbines (HGT).

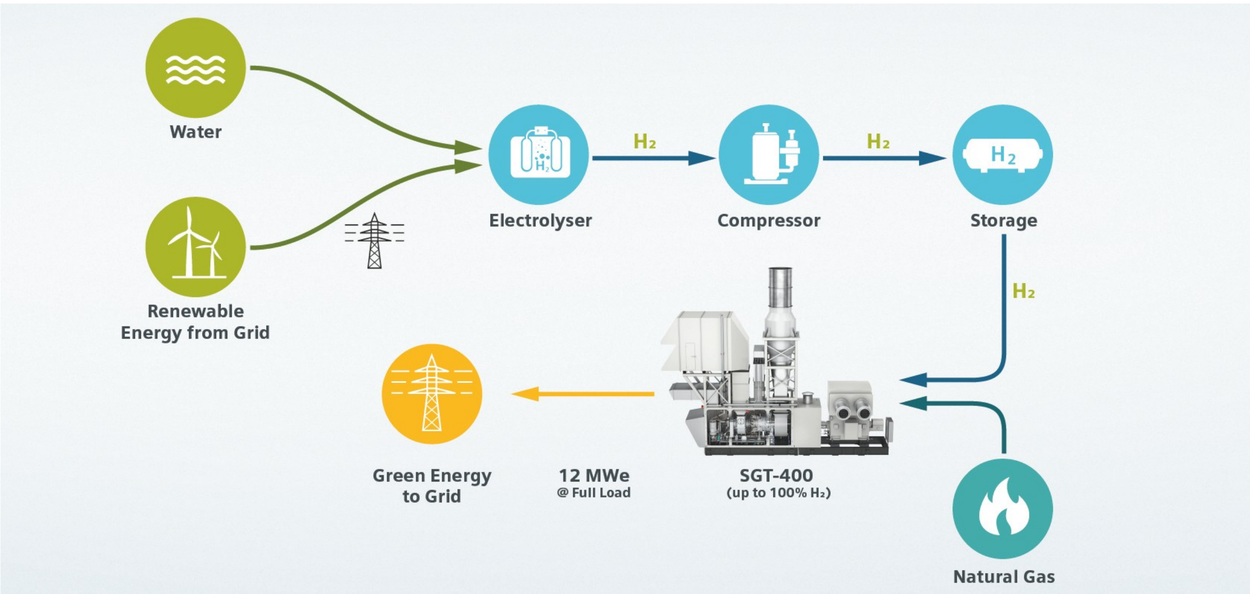

Fig. 5. Fuel blending in hydrogen turbine [26]

4.11 High Operating Temperature

Devriese *et al.,* [4] has indicated that there is a significant challenge in handling the operating temperature of a HGT because it is relatively higher than the normal ones, which ultimately requires more effective composite temperature-resistant materials and automated ignition control devices. Different problems can occur during the production of energy, due to which there is always a need for automated ignition control devices as well as active cooling systems for turbines that can effectively contribute to the effective use of HGT for sustainable power generation in the future. However, Bexten *et al.,* [3] also indicated that the problem may arise in the future because the characteristic properties of hydrogen are not going to change.

4.12 High Performance Materials Needed

Ammar & Alshammari [1] indicated there is a significant need for high-performance materials for the manufacturing and use of HGT in the power sector. The material research for turbine production is indicated as an effective intervention that will possibly help to adopt HGT. It is also indicated by Moradi Nafchi *et al.,* [26] that a possible adjustment of the HGT cycle will be needed that may help to control potential risk factors while providing full support for future power generation with HGT. It will be important that the high-performance materials need to be utilized to handle such risk factor as it can ultimately lead to effective development of power sector and expanding in the use of HGT.

4.13 High Maintenance Cost of Turbine Parts

Schiebahn *et al.,* [28] indicated there is significant rise in the cost of maintenance of turbine if the hydrogen is used as fuel. Authors has also indicated the significant need for modern technology when maintaining HGT because of the associated cost. For this, Lee & Lee [27] has recommended effectively reducing material damage by using advanced thermal monitoring and x-ray systems. Effective reduction of turbine assembly parts will be also needed if the power sector continues to use HGT.

4.14 Require Skilled Workers to Operate

HGT always requires more skill to operate because it is rather complex than a normal turbine, on which workers are mostly trained. Shulga *et al.,* [29] also indicated a significant gap in the safety training of the workers, which can be accelerated with the help of modern technology like virtual reality and augmented reality. Javadi *et al.,* [9] have also found significant evidence of improvement in skill of workers if proper simulations are used, and better regulatory environment is implemented when using HGT for sustainable power generation for the future.

According to Gazzani *et al.,* [7], it is further indicated that the lack of knowledge is in a critical in affecting the implementation of HGT for which effective improvement in feasibility studies is important. It is also indicated that media utilization may help to increase awareness about HGT in our also society while Funke *et al.,* [8] have also indicated extending the exploration of benefits that may attract more opportunities available in power sector for the use of HGT.

4.15 Ineffective Hydrogen Infrastructure Regulations

According to Weiland *et al.,* [30], the regulatory standards are not fully equipped to expand the consumption of HGT, which act as a barrier, and there is a need for government-level regulation.

Gazzani *et al.,* [7] also found significant evidence for forming standard consumption protocols that may help to effectively improve hydrogen infrastructure regulations. Proper safety protocols will also be needed in terms of forming a sustainable HGT power plant. There is also an effective need for improving the hydrogen infrastructure, which may help accelerate its use in modern industries. It is ultimately linked to the effective formation of industry regulations.

According to Ditaranto *et al.,* [6] at The Limited, innovation is being carried out when it comes to hydrogen infrastructure. It is acting as a major barrier to the use of HGT, while Pyo *et al.,* [15] has also indicated the possibility of future investment in green systems so that hydrogen production can be increased to meet the standards of the power sector involving HGT. The effective need for government support is also needed, which may help to improve innovation for hydrogen infrastructure, while reading is also needed as a possible method of handling the innovation challenge in the HGT power sector. The following Table 2 summarizes all mitigation interventions observed in case of each challenge observed through SLR.

Table 2
Mitigation intervention for HGT usage challenges

Code	Mitigation Interventions	References
C1	• Increasing fire safety • Using non-combustible materials • Advancing ignition systems	[14,15]
C2	• Following storage regulations • Using leak detectors • Effective ignition source control	[16,17]
C3	• Investing in hydrogen infrastructure • Using solar and wind power to generate hydrogen. • Increasing production capacity of hydrogen	[5,8]
C4	• Using alternate production methods then water electrolysis • Using renewable energy • Establishing local production	[11,18]
C5	• Using slightly impure hydrogen • Capturing excess hydrogen from industries • Biological hydrogen production	[6,19]
C6	• Reducing embodied carbon • Reduction of stages in hydrogen supply chain • Using carbon capture systems	[12,20]
C7	• Extension of hydrogen supply network • Supporting local production of fuel • Supporting sustainable supply chain transformation	[21,22]
C8	• Reinventing turbine design protocols for power generation • Using composite materials • Advancing research on turbine weight and size reduction	[13,23]
C9	• Effective inventory management with AI • Isolation of hydrogen storage in power plant • Using redundant automated flow control systems	[24,25]
C10	• Advancing in fuel combination research • Using ammonia as hydrogen fuel • Improving fuel injection and ignition system	[2,10]
C11	• Using composite temperature resistant materials in combustion chambers • Using automated ignition control devices • Active cooling system for turbine	[3,4]
C12	• Advancing the material research for turbine production • Reinventing the turbine assembly design	[1,26]

C13	• Adjustment of hydrogen gas turbine cycle • Reducing material damage with advanced thermal monitoring • Using automated X-ray systems for crack detection • Reducing turbine assembly parts	[27,28]
C14	• Safety training of workers with VR and AR • Fuel handling simulations • Regularizing training policies for workers	[9,29]
C15	• Government level regularization of hydrogen fuel • Formation of standard consumption protocols • Formation of safety protocols for each power plant	[7,30]
C16	• Using materials with low embodied carbon • Carbon dioxide capture systems • Using heterogeneous materials	[2,27]
C17	• Effective investment appraisal for hydrogen energy projects • Developing robust funding processes for hydrogen infrastructure • Improving cost-benefit ratio	[4,29]
C18	• Negotiations with fossil fuel industry leaders • Slow transitioning to hydrogen fuels in industry • Effective improvement of fuel infrastructure with joint ventures	[10,26]
C19	• Media utilization for public awareness • Further exploration of hydrogen turbine benefits • Conducting extensive feasibility studies	[7,8]
C20	• Investing in green systems for hydrogen production • Redesigning of gas-powered turbines. • Government support for innovative projects	[6,15]

The prioritization of HGT usage challenges is presented in Figure 6. All the 20 identified challenges are indicated in five level of priorities with one being the highest and five being the lowest. C1, C2, C3, C4, and C5 should be highly prioritized in terms of mitigation in power sector. C6, C7, C8, C9 and C10 cones at second priority level, C11, C12, C13, C14 and C15 comes at third level of priority and C16, C17, C18, C19 and C20 should be least prioritized in use of HGT for future sustainable power generation. The provided prioritization may help the power industry to increase the use of HGT with low carbon energy generation for the future.

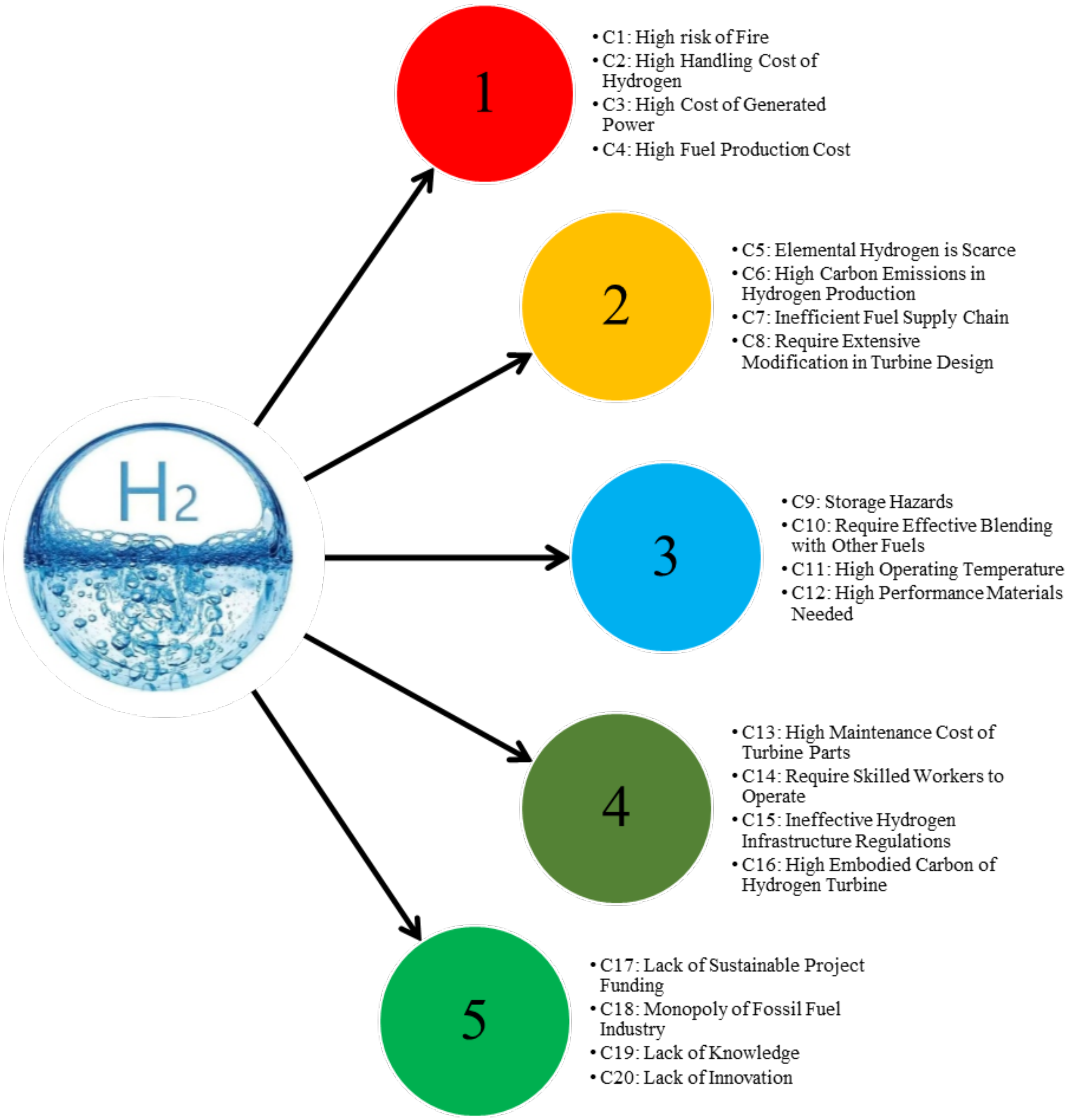

Fig. 6. Prioritization of HGT Challenges

5. Conclusion

For the sustainable use of HGT, it is important that the mitigation interventions are implemented to handle the challenges. The study was intended to evaluate the challenges affecting HGT use for future low-carbon energy generation and effective mitigation interventions from existing literature. The SLR methodology helped in the identification of twenty critical challenges affecting the use of HGT for future low-carbon energy generation, which answered RQ1. RQ2 was answered by the evaluation of mitigation interventions found in the literature and a prioritized view of challenges. High risk of fire, high handling cost of hydrogen, high cost of generated power, high fuel production cost, and elemental hydrogen being scarce are the high-priority challenges that should be focused on by the power generation industry for effective mitigation. Lack of sustainable project funding, the monopoly of the fossil fuel industry, a lack of knowledge, and a lack of innovation are low-priority challenges affecting the use of HGT for future low-carbon power generation. Theoretically, the study summarized the twenty most critical and contemporary challenges that future researchers should study for the better development of strategies for mitigation. Practically, the study helps professionals in the power sector improve the use of HGT for future low-carbon power generation.

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