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ENHANCING SUSTAINABILITY IN GAS TURBINE ENERGY GENERATION BASED ON INNOVATIVE PRACTICES AND TECHNOLOGIES

Guillermo David Arias Castillo
General Electric Power Services
Risk Modeling Analyst
Mexico, City, MEXICO
gdavidarias07@gmail.com

Abstract

Gas turbines, normally referred to as I.C. engines, are a specialised type which is used widely in energy sectors and industries because of their high efficiency, reliability and flexibility. Running on Brayton cycle, these turbines constantly compress air-fuel mixture and then burn it to produce high-temperature gases that turn the turbine blades. These include a high power-to-weight ratio, quick starting ability and the capability to quickly meet peak electricity demand and, therefore, are invaluable in electricity generation, aviation and industrial processes. However, gas turbines based on fossil fuel have limitations such as the emission of greenhouse gases and poor efficiency at off-design conditions. These challenges are solved by recent improvements that include DLN systems, TBCs, – new manufacturing techniques such as AM, and the use of cleaner fuels such as hydrogen and biofuels. Combined cycle systems and waste heat recovery further enhance efficiency and reduce emissions. As the energy sector shifts towards net-zero goals, sustainable gas turbine technologies, supported by regulatory frameworks and digital advancements, are critical to achieving cleaner energy production while meeting global energy demands.

***Keywords:** Gas turbine technology, Sustainability in energy production, Combined Cycle Gas Turbines (CCGT), Brayton cycle, Greenhouse gas emissions.*

I. INTRODUCTION

Mechanical power is generated by running a gas turbine, which is a type of internal combustion engine. This engine uses hot gases produced by burning an air-fuel combination to generate this power [1]. Combustion happens continually in gas turbines, although it happens occasionally in reciprocating internal combustion engines. Electricity generation, aircraft propulsion, and a host of industrial uses (including petrochemical facilities and refineries) rely on gas turbines [2]. A gas turbine's high power-to-weight and power-to-volume ratios make it an attractive propulsion system for aviation and vehicle applications. In addition, gas turbines have a better cycle efficiency than reciprocating engines under specific operating circumstances [3]. Gas turbines have historically been often used in the energy generating sector when quick start up and shutdown on demand were necessary [4]. Gas turbines have long been the go-to power plant technology for the majority of nations. During the early days, its primary usage was to generate power during the peak electricity demand time. Due to their rapid starting and stopping capabilities, gas turbines are perfect for applications where they can be brought into service as needed to satisfy peak energy demand [5]. However, many nations use large conventional gas turbines as base load units

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because natural gas is more affordable than distilled fuels, while smaller ones are used to fill any gaps in the available electricity supplies during emergencies or periods of peak electricity demand [6]. These systems are particularly inefficient when operating in an open or simple cycle, which results in relatively high unit costs for the power generated.

Gas turbine energy generation is a widely used method of power production that harnesses the energy from burning natural gas or other fuels to drive a turbine connected to a generator. This technology is valued for its efficiency, flexibility, and relatively low emissions compared to other fossil-fuel-based systems [7]. The Brayton cycle is the mechanical principle that drives gas turbines. It entails compressing air, mixing it with fuel, and then lighting it to create high-pressure, high-temperature exhaust gases. The mechanical energy that is produced is then transformed into electrical energy. Gas turbines are commonly used in power plants for both base load and peak load electricity generation, as well as in combined cycle configurations where waste heat is utilised to drive a steam turbine, further enhancing efficiency. Their ability to start up quickly makes them ideal for balancing renewable energy sources like wind and solar in modern energy grids.

The paper is structured as follows: Section I introduces the significance of gas turbine energy generation in modern power systems. Section II provides an overview of gas turbine technology, including its components and operational principles. Section III addresses challenges in achieving sustainability in gas turbine systems, while Section IV explores innovative practices to enhance their sustainability. Section V reviews relevant literature, highlighting current advancements and research gaps. In Section VI, the article comes to a close by outlining important points and suggestions for further research into sustainable gas turbine energy production.

II. OVERVIEW OF GAS TURBINE TECHNOLOGY

Engines, the heart of mechanical systems, convert energy into mechanical work and are broadly classified into internal combustion (IC) and external combustion (EC) engines. The great efficiency and power-to-weight ratio of IC engines make them ideal for a variety of applications, including gas turbines, compression-ignition (CI) engines powered by diesel, and spark-ignition (SI) engines powered by petrol [8]. SI and CI engines operate on thermodynamic cycles like the Otto and Diesel cycles, converting chemical energy into mechanical energy using components like pistons, crankshafts, and camshafts. Gas turbines, governed by the Brayton cycle, compress air, mix it with fuel, ignite it, and expand the resulting high-energy gases to drive turbines, making them reliable for large-scale power generation and aviation [9]. Their operation involves stages of air suction, compression, controlled combustion, energy expansion, and exhaust, with spent gases often used in combined cycle systems to enhance efficiency [10]. With fewer moving parts and the ability to efficiently convert large amounts of fuel energy [11], gas turbines are integral to modern power systems [12], with continuous advancements expected to further enhance their efficiency and environmental performance.

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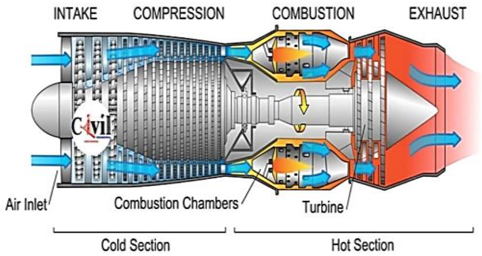


A sketch of gas turbine [13].

Gas turbine technology has evolved into a crucial component of modern energy production and industrial processes, characterised by high efficiency, reliability, and versatility. This section provides a comprehensive overview by examining its evolution, key components, and applications.

A. Evolution of Gas Turbine Systems

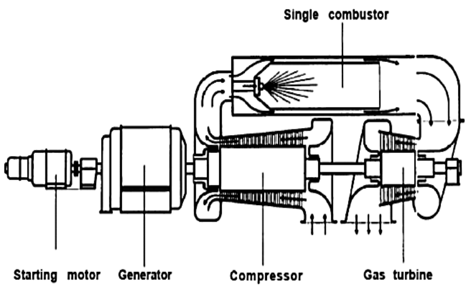
The evolution of gas turbine systems spans over two centuries, reflecting continuous advancements in technology, materials, and efficiency. Here, the focus is on the conceptual developments that characterised the progress of the gas turbine.

B. Historical Milestones:

- Aegidius Elling created the initial gas turbine in 1903; the output was 8 KW and then turned to 33 kW [14].
- Closed cycle gas turbines became tangible, with the first generation produced in 1935. The first industrial gas turbine, achieving 18% efficiency by 1939, was only good enough to be installed in Neuchatel, Switzerland [15].
- Since 1970, significant steps have been made in turbine efficiency and temperature control, including the use of helium as working fluid using successfully applied Combined Cycle Gas Turbines (CCGTs) [16].

C. Modern Advances:

- Technologies like Dry Low NOx (DLN) combustion systems reduce emissions [17].
- Material innovations (e.g., Thermal Barrier Coatings, TBC) and advanced cooling systems enable turbines to withstand ultra-high temperatures [18].
- Integration of smart sensors and digital monitoring enhances reliability and operational lifespan.



The first ever built industrial GT set with a single combustor

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A basic gas turbine system's constituent parts. Gas turbines, starting motors, generators, compressors, and a single combustor are all part of it, and it shows how the fuel and air move together to generate power.

I. History of gas turbine [5].

1791	John Barber of the UK submitted the first gas turbine patent.
1904	The Berlin-based inventor Franz Stolze tried and failed with a gas turbine endeavour.
1906	Armengaud Lemale in France developed a gas turbine with a centrifugal compressor, but it did not generate useful power.
1910	Holzwarth created the first 150 kW gas turbine with combustion capabilities (constant volume combustion).
1923	Diesel engines were the initial targets of the exhaust gas turbocharger development.
1935	The pioneering closed-cycle gas turbine was actually patented in Switzerland by Keller and Ackeret.
1939	The first gas turbine to generate electricity was created by the Brown Boveri Company of Neuchatel, Switzerland.
1962	The initial closed-cycle gas turbine for air liquefaction was created by American James La Fleur using helium.
1972	Escher Wyss of Vienna constructed the largest and last air closed-cycle gas turbine.

D. Key Components of Gas Turbines

Compressor:

- Compresses air through multiple stages of blades and vanes to increase pressure efficiently.

Features like Control Diffusion Airfoils (CDA) and bleed valves ensure smooth airflow and operational stability.

Combustor:

- Responsible for mixing compressed air with fuel and igniting it to generate high-temperature gases.
- Advanced materials like Mitsubishi Gas Turbine Alloy (MGA) improve durability under severe thermal stress.
- Technologies such as steam cooling and optimised flame temperatures manage emissions and combustion stability. Figure 3 shows the gas turbine combustor parts.

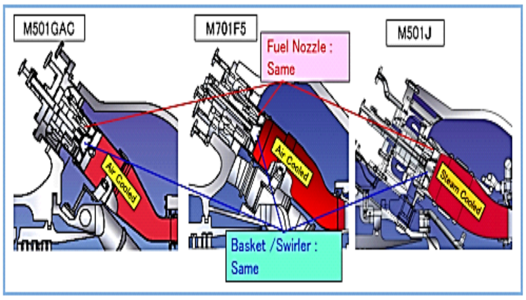

Figure 7 Common combustors parts among "GAC", "J" and "F5"

Common combustors parts among 'GAC', 'J' and 'F5'

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Turbine:

- Converts energy from high-pressure gases into mechanical work.
- Innovations like high-efficiency film cooling and advanced TBCs enhance performance and reduce cooling air requirements.
- Modern designs incorporate multi-stage turbines with precision cooling for higher durability. Figure 4 shows the gas turbine Turbine blade technologies.

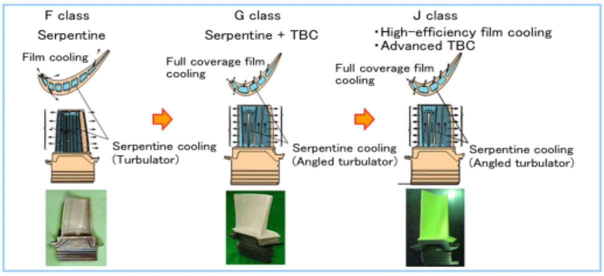

Figure 8 Turbine blade technologies for each frame

Turbine blade technologies for each frame.

E. Working Principles

- Gas turbines operate on the Brayton cycle, which includes compression, combustion, expansion, and exhaust.
- High-pressure and high-temperature working gas drives the turbine blades, converting thermal energy into rotational energy.
- Combustion chambers feature a pressure drop of 3–5% to optimise the heat transfer process [19].
- Advanced heat exchanger designs ensure minimal pressure drops and efficient energy utilisation.

F. Notable Trends and Innovations

- **Efficiency Improvements**: Gas turbine inlet temperatures have increased significantly, with breakthroughs like the M701J achieving a 1,600°C class[20].
- **Environmental Performance**: DLN systems and material innovations focus on reducing emissions and improving fuel efficiency.
- **Digital Advancements**: Integration of smart systems for real-time monitoring optimises turbine operation and extends service life.

III. CHALLENGES IN SUSTAINABLE GAS TURBINE ENERGY GENERATION

Gas turbines have become an integral part of energy generation systems, particularly in the context of sustainable energy solutions. Although once primarily driven by natural gas, their contribution to maintaining the stability of the grid and supplementing power during hours of increased demand is still substantial [21]. However, there is an issue of sustainability in the emission of carbon dioxide, other pollution resulting from burning Fossil Fuels. To this end, current research is being conducted aimed at potential ways of cutting emissions and improving efficiency, for instance, with the use of carbon capture technologies or the change of the fuel type to hydrogen [22].

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Change process in the gaseous turbine fuel energy production to more sustainable technologies needs policy and innovation intervention [23]. Other potential measures currently under assessment to enhance the efficiency of gas turbines include the use of renewable energy and a more efficient design of combined-cycle gas turbine systems. These advancements seek to reduce the amount of pollution produced and rank gas turbines as a less pollutive energy player in the global scenario [1].

The process of changing to green energy production through gas turbines has some operative challenges in environmental, technology, and cost perspectives.

A. Environmental Concerns:

- **Greenhouse Gas Emissions**: Nonetheless, gas turbines are still densely used fossil fuel, and therefore cause substantial CO_2 emissions.
- **Air Pollutants:** Sulphur also affects combustion and increases emissions of NOx which pollutes the air and requires technologies such as the Dry Low NOx (DLN) system to reduce them.

B. Technological Limitations:

- **Fuel Adaptation:** Technologic combination with renewable fuels like hydrogen or biofuels proves problematic because of variations in fuel burning characteristics and fuel availability.
- **Efficiency at Part-Load Operation**: Gas turbines have lower efficiency and greater emissions when they do not work at full power therefore posing challenges as renewable integration into grid.
- **Material Constraints**: The demand for higher turbine inlet temperatures for efficiency improvements stresses material durability and cooling technologies.

C. Economic and Policy Barriers:

- **High Initial Investment:** The cost of developing and deploying advanced gas turbine technologies, such as combined cycle systems or hydrogen-ready turbines, remains prohibitive for many projects.
- **Fuel Supply Costs**: The viability of utilising cleaner fuels such as hydrogen or Synthetic Natural Gas, which can well be expensive and not readily available, influences adoption.
- **Regulatory Compliance**: To meet high demands for emission reductions, expensive retrofitting and innovations must be made to vehicles and engines, creating costs.

D. Integration with Renewable Energy:

- **Intermittency Issues:** Renewables such as wind and solar may be erratic, causing stress on gas turbines when expected to back them up and ramp up or down immediately.
- **Grid Stability**: To achieve grid frequency and voltage with renewable integration all while ensuring high turbine efficiency becomes a multifaceted task [24].

IV. INNOVATIVE PRACTICES IN SUSTAINABILITY OF GAS TURBINE

The main areas of interest of sustainability of gas turbines are directed towards increasing the environmental efficiency of the concerned turbines, or in other words, the capacity to convert cleaner energy forms. Several strategies are as follows: emissions reduction, provision of fuel flexibility, and improvement of operational efficiency. Another focus is the research of hydrogen

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and bio-fuels application in combustion systems of gas turbines so that the use of raw-gas turbines with fewer amount of CO2 emissions is possible. Such projects like the initiative of the use of hydrogen in a gas turbine show that society can operate sustainably.

Also, increasing operational flexibility makes turbines respond effectively to the fluctuating energy requirements, a relevant aspect in today's re-energised systems. Additional digital advancements and materials, like enhanced sensors and new efficient combustion material, also support these goals by increasing efficiency and prolonging the life of the turbines. As the world moves in the direction of achieving zero emission levels in energy utilisation, the gas turbine industry has developed these innovations to remain relevant and environmentally friendly [25].

Emerging technology in gas Turbine industries has brought new improvements that have focused on some aspects of sustainability, such as efficiency, emission, and integration of renewable resources. These practices address environmental, economic, and operational challenges, paving the way for cleaner energy production.

A. Advanced Materials and Manufacturing

The gas turbine input temperature is rising at a pace that is significantly higher than the maximum limit of superalloys. The quick rise in intake temperature has been controlled by enhancing cooling and coating protocols. The enhanced TBC, developed as part of the national project, has been used by the newest 1600°C-class Type J gas turbines. The following are the technical specifications and layout of the materials used in advanced TBC. Gas turbines can now function at higher temperatures with greater thermal efficiency and longer lifespans due to nickel-based superalloys and thermal barrier coatings (TBCs).

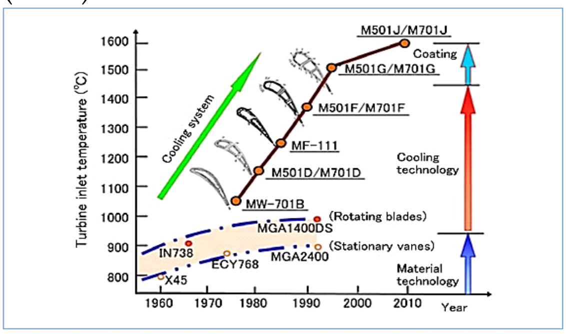

Figure 1 Increase in the turbine inlet temperature and transition of applied materials and technologies

Increase in the turbine inlet temperature and transition of applied materials and technologies.

Additive manufacturing, depicted in Figure 5 (3D printing), enables complex component designs, reducing weight and increasing performance. Benefits are:

- **Greater Efficiency:** The efficiency of a turbine's airflow and combustion are directly proportional to its structural precision. Results are improved with intricate geometry and overly complicated channels.
- **Shorter Lead Times:** Titanium components that were formerly manufactured over the course of weeks or months may now be completed in only one day using modern technology [26].
- **Material Savings:** Material waste is a common result of traditional industrial methods. In contrast, additive manufacturing only makes use of materials when absolutely necessary.

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B. Waste Heat Recovery and Combined Cycle Systems

Power plants often have their exhaust heat recovered using a complicated mechanism called a HRSG. Evaporator, super heater, economiser, and steam drum are a few of the massive components that make up the heat recovery system [27]. Figure 6 shows the layout of a HRSG. The super heater is positioned in the gas with the highest temperature just before the evaporator, while the economiser is positioned in the gas with the lowest temperature just after the evaporator. In most cases, HRSGs have a three-pressure system: high, reheat (or intermediate), and low. The system can also recover waste heat from manufacturing process exhaust and use it to generate steam, which can be utilised for process heating in the factory or to power a steam turbine. It has been reported that a system efficiency of 75-85% can be achieved with the use of HRSG for steam production.

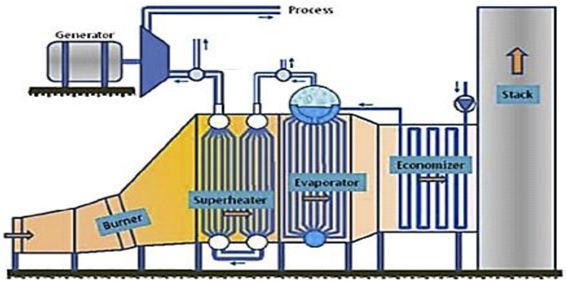

Fig. 17. Heat Recovery Steam Generator (HRSG) [83].

Heat recovery stream generator (HRSG).

Multi-stage turbines with advanced heat exchangers minimise heat loss and maximise energy recovery [28].

C. Fuel Innovation and Alternative Fuels:

- Adoption of hydrogen and biofuels reduces reliance on fossil fuels, lowering CO_2 and NOx emissions.
- Fuel-flexible combustion systems enable turbines to operate on a mix of natural gas and renewable fuels.

D. Low Emission Combustion Technologies:

Modern gas turbines are much more efficient and have a much smaller effect on the environment thanks to developments in combustion technology, which is fundamental to their operation.

- **Low-NOx Combustion:** Enhanced combustion methods, like lean-premixed combustion, lessen the emissions of nitrogen oxides (NOx), which are dangerous pollutants, by promoting a cleaner and more thorough combustion.
- **Lean-Burn Combustion:** As a result of improved fuel-air mixing brought about by lean-burn combustion, combustion is more efficient and steady, leading to lower emissions and generally higher fuel economy.
- **Alternative Fuels:** A cleaner alternative that produces only water vapour as a byproduct is hydrogen, which offers a clean alternative. Creating turbines that can operate on a variety of fuels, including biofuels and hydrogen, advances fuel flexibility and sustainability.

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E. Integration with Renewable Energy Systems

- Hybrid systems: Power generating systems may be made more resilient and flexible by combining gas turbines with other energy sources, such as renewable energy, solar power, batteries, or generators.
- Gas turbines are used as quick-start backup power, supporting the transition to a cleaner energy grid[29]

V. LITERATURE REVIEW

Table II provides a brief description of the examined research and this section gives a literature assessment on gas turbine energy generation.

In, Gabbar et al. (2014), investigates several scenarios for generating power using gas and renewable energy sources in order to construct a micro energy grid (MEG) that can withstand extreme conditions. A state-of-the-art algorithm is then used to assess each of the possible outcomes and choose the best one based on a number of key performance indicators (KPIs). These KPIs will take into account factors like cost, power quality, dependability, and environmental friendliness [30].

In, De Angelis and Grasselli (2015) the purpose of this study is to present a revised PUE metric for CCHP architectures that are powered by natural gas or biogas, with the latter offering the potential for very reliable systems that might be configured with local gas storage. The goal is to build on a data centre benchmark. In fact, data centre designers do not have a lot of resources at their disposal to assess the cost, sustainability, and reliability of data centre infrastructures like CCHP, which has the ability to reduce air pollution and carbon emissions while significantly increasing source energy efficiency [31].

In this study, Alexander et al. (2016) thought about the thermo-technology of roasting siderite ore with a GTP cycle that converts carbon dioxide. A strategy for roasting ore that uses less energy has been devised. Learn about the scheme's practicality and execution in processing siderite ore while keeping an eye on the fundamental energy concerns [32].

In, Hu et al. (2017) They have developed the probabilistic energy flow model of the IEGES, which incorporates wind power. In the IEGES, P2G technology can promote the consumption of wind power from grid by conversing it to natural gas stored in the gas network. So, P2G technology reduces the impact of wind power integration on power system security [33].

In, De Melo et al. (2017) by integrating the SOFC with a MGT, hybrid systems that employ cogeneration are able to produce more electricity from the same fuel input. Cogeneration is an intriguing option for producing electricity, whether in small quantities (a few kilowatts) for homes and businesses or large quantities (megawatts) for power plants or factories. Integrating an MGT to use the exhaust gases of the SOFC increases efficiency, according to the study provided here[34].
In, Chen et al. (2018) is to investigate how well a regression-based AI algorithm, specifically SVR, can forecast the amount of SO2 emissions in the air near a CCGT power plant by integrating with various big data sets. The meteorological data, data on terrain and land use, data on historical

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emissions, and characteristics of power plants, especially those pertaining to point source emitters, are examples of the diverse data sources that have been utilised to train and build SVR's expertise [35].

In, Hassan, Burek and Farrag (2018) this study aims to evaluate the possibility of implementing several cogeneration systems that use biofuel (rice husk) and are based on Rankine, Brayton, and combined cycles at a medium-sized paper mill in Pakistan. The goal is to find ways to save energy in this sector by making it more efficient. From both a technical and financial standpoint, the Brayton cycle cogeneration system was determined to be the best fit for the mill under investigation [36].

In, Motylewski (2019) summarises the findings from the investigation of several HRSG arrangements. An explanation of the difficulties faced by Poland's electricity grid and the potential future contribution of CCGT has been provided prior to the study. Then, solutions that have been calculated in Ebsilon Professional and analysed are shown. In order to obtain maximum nett efficiency, the parameters of the shown cycles were optimised using the program's optimisation module [37].

I. Summary of related work on gas turbine energy generation reviews

Reference	Research Focus	Key Technologies	Findings/Outcomes	Applications/Implications	Future Work
Gabbar et al. (2014)	Integration of gas and renewable energy technologies in resilient MEG designs	Advanced algorithms, key performance indicators (economic, power quality, reliability, environmental friendliness)	Developed designs for resilient microenergy grids (MEG) and evaluated scenarios for optimal performance based on KPIs.	Promotes design optimisation for MEGs ensuring economic and environmental sustainability.	Investigating the scalability of MEG designs and integration with future smart grid technologies.
De Angelis and U. Grasselli (2015)	Modified PUE metric for CCHP biogas-fueled systems for data centres	Combined Cooling, Heat, and Power (CCHP), local gas storage, biogas utilisation	Highlighted the benefits of biogas-fueled CCHP systems in reducing air pollution, carbon emissions, and increasing source energy efficiency.	Enhances data centre sustainability and reliability through optimised energy metrics.	Developing advanced tools for assessing sustainability and cost-efficiency of data centre energy systems.
Alexander et al. (2016)	Thermotechnologies for siderite ore roasting using carbon dioxide conversion	Gas turbine plant (GTP), energy-efficient ore roasting schemes	Proposed energy-efficient schemes for ore roasting integrated with GTP, improving processing efficiency.	Optimises industrial processes in siderite ore processing with energy-efficient methods.	Extending thermotechnological schemes to other ore types and industrial applications.

Hu et al. (2017)	Probabilistic energy flow model in integrated electricity-gas energy systems (IEGES)	Power-to-gas (P2G) technology, wind power integration	Demonstrated that P2G technology enhances wind power consumption and reduces its impact on power system security.	Improves renewable energy integration and power grid stability.	Expanding the probabilistic model to incorporate additional renewable energy sources and storage technologies.
De Melo et al. (2017)	Hybrid systems with cogeneration using SOFC and micro gas turbine	Solid Oxide Fuel Cell (SOFC), micro gas turbine (MGT), hybrid cogeneration	Showed increased efficiency when SOFC is combined with MGT, generating more power for the same fuel amount.	Suitable for scalable power generation from small residential systems to industrial applications.	Exploring advanced hybrid system configurations for higher efficiency and lower emissions.
Chen et al. (2018)	Predicting SO2 emissions in CCGT power plants using AI	Support Vector Regression (SVR), big data analysis (meteorological, terrain, land use, and emission data)	Developed a regression-based AI model to accurately predict SO2 emissions, enhancing environmental monitoring capabilities.	Enables improved environmental impact assessments for CCGT power plants.	Integrating AI models with real-time monitoring systems for dynamic emission control.
Hassan, Burek and Farrag (2018)	Feasibility analysis of cogeneration systems using biofuel for a paper mill	Cogeneration systems (Rankine, Brayton, Combined cycles), thermodynamic and economic analysis	Identified Brayton cycle-based cogeneration as the most feasible option for energy savings in the paper mill.	Boosts energy efficiency in industrial units, particularly medium-sized paper mills.	Evaluating the long-term operational reliability of biofuel-based cogeneration systems.
Motylewski (2019)	Analysis of HRSG structures for optimised CCGT performance	Heat Recovery Steam Generator (HRSG), Ebsilon Professional optimisation module	Optimised HRSG parameters to achieve maximum net efficiency for Combined Cycle Gas Turbines (CCGT).	Supports the role of CCGT in enhancing energy efficiency in power systems, particularly in Polish contexts.	Investigating novel HRSG designs for further efficiency improvements and integration with renewable energy systems.

VI. CONCLUSION AND FUTURE WORK

Gas turbines are important elements of the contemporary power systems using them for their high efficiency and flexibility. In their operation, they are not immunity to challenges as far as sustainability and emissions are concerned; especially considering fossil fuel dependence. Their efficiency and their environmental impact have been enhanced in recent years due to such factors as cleaner fuels, new materials for their construction, and combined cycle systems. These technologies show the versatility of gas turbines in catering to global energy requirements while

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embracing a green energy approach to energy production.

Further studies should be directed at improving the utilisation of hydrogen and biofuels in gas turbines for the production of zero emissions. New developments in the field of manufacture by addition and thermal barrier coatings can increase the level of efficiency and decrease the need for maintenance. Further, the possibility of using artificial intelligence and using machine learning for preventive and real-time tracking can help improve operating dependability. Investigating possible integration of gas turbines with other renewable resources will also need to be studied comprehensively to enhance alignment with other global trends towards decarbonisation.

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