



CONTROL-SYSTEM STRATEGIES FOR EMISSION REDUCTION IN BRAYTON-CYCLE GAS TURBINES: A CONCISE OVERVIEW

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ABSTRACT:

Reducing emissions from Brayton-cycle gas turbines is critical for meeting stringent environmental standards while maintaining efficiency and operational flexibility. This overview highlights advanced control-system strategies that manage combustion dynamics, airflow, and fuel distribution to minimize NO_x, CO, and unburned hydrocarbons. Key approaches include real-time sensor feedback, model-predictive and digital-twin-based control, lean-premixed combustion, fuel staging, and precise management of turbine-inlet temperature and variable air pathways. By integrating predictive modelling, adaptive control, and optimized actuator coordination, these strategies enable stable, low-emission operation across varying loads and fuel types, including hydrogen and biofuels. The synergy of these techniques demonstrates the vital role of intelligent control in achieving clean, efficient, and reliable gas-turbine performance.

INTRODUCTION:

Control-system strategies play a crucial role in reducing emissions from Brayton-cycle gas turbines by precisely regulating combustion processes and adapting turbine operation to changing conditions (Figure 1). Emissions such as NO_x, CO, and unburned hydrocarbons are strongly influenced by flame temperature, fuel-air mixing, combustion stability, and transient behaviour [1]. Modern control systems are designed to operate turbines in low-emission regimes while preventing problems like flashback, blowout, and thermoacoustic instabilities that arise when pushing toward ultra-lean combustion.

A central approach is the use of real-time sensor feedback, where exhaust-gas measurements, pressure sensors, and optical diagnostics continuously inform adjustments to fuel splits, airflow, and combustor operating modes. This closed-loop monitoring ensures complete combustion and stable operation across varying loads [2]. Building on this, model-predictive and digital-twin-based control methods use dynamic models and real-time system replicas to forecast combustion behaviour, anticipate instability, and optimize coordinated actuator responses. These predictive tools allow turbines to maintain low emissions even during rapid transients and under changing environmental or fuel conditions.

Complementing these strategies is lean-premixed combustion control, in which the controller maintains an ultra-lean fuel-air mixture that reduces flame temperature and suppresses NO_x formation. Because lean operation is highly sensitive, it requires fast-response

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valves, variable inlet guide vanes, and active mitigation of thermoacoustic oscillations to ensure smooth and clean combustion [3]. Finally, fuel staging and precise management of turbine-inlet temperature and variable air pathways help distribute fuel evenly, control local temperatures, and optimize airflow. Together, these measures promote stable, low-emission combustion over a wide operating envelope and support flexible operation with diverse fuels. Collectively, these control innovations enable Brayton-cycle systems to satisfy stringent emissions standards while maintaining high efficiency, operational flexibility, and long-term reliability.

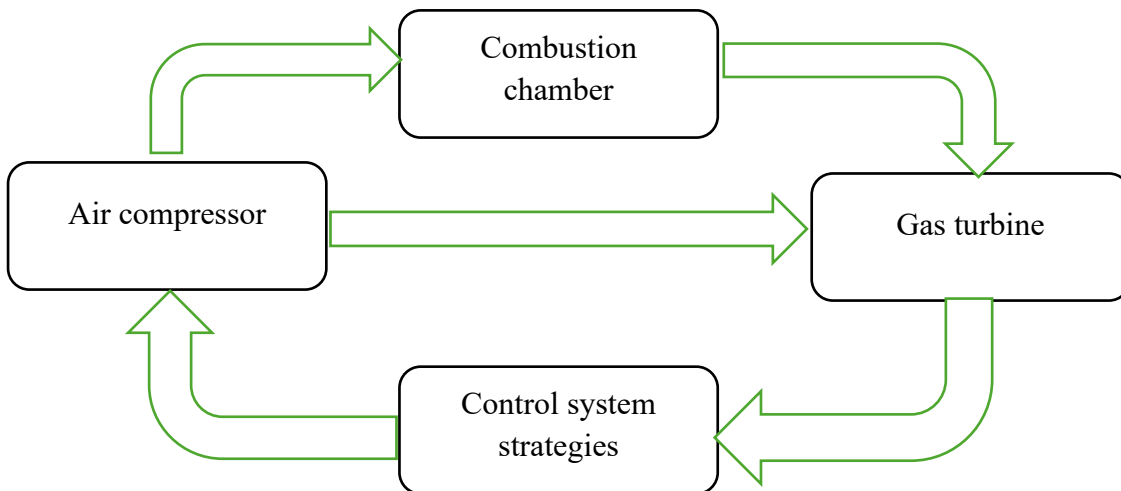


Figure 1. Control system strategies for controlling emissions from gas turbine by tuning air flow in compressor

BRAYTON CYCLE:

The Brayton cycle is the fundamental thermodynamic cycle used in gas turbines and jet engines, describing the process of converting fuel energy into mechanical work (Figure 2). It consists of four main stages: (1) isentropic compression of ambient air in a compressor, (2) constant-pressure heat addition through fuel combustion, (3) isentropic expansion of the high-temperature and high-pressure gas through a turbine to produce work, and (4) heat rejection at nearly constant pressure [4]. The cycle is widely favoured for power generation and propulsion because of its high power-to-weight ratio, rapid start-up, and adaptability to various fuels. Its efficiency is largely determined by the compressor-to-turbine pressure ratio and the turbine-inlet temperature, which also directly influence emission characteristics, making precise control of these parameters critical for clean and efficient operation.

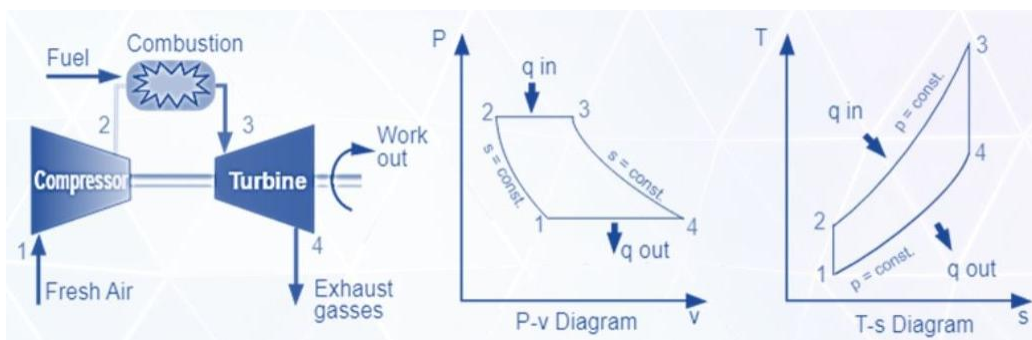


Figure 2: Working principle of Brayton cycle with P-V and T-S diagrams

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CONTROL-SYSTEM STRATEGIES FOR EMISSION REDUCTION IN BRAYTON-CYCLE

Control-system strategies for emission reduction in Brayton-cycle gas turbines involve using advanced monitoring and actuator coordination to minimize pollutants such as NO_x , CO, and unburned hydrocarbons while maintaining efficiency and stability. These strategies include real-time sensor feedback, predictive and digital-twin-based controls, lean-premixed combustion, fuel staging, and precise management of turbine-inlet temperature and airflow [5]. By continuously adjusting fuel-air mixing, combustion parameters, and operating conditions, these control systems optimize flame temperature, prevent instabilities, and ensure clean, efficient operation across varying loads and fuel types. They are essential for meeting stringent environmental regulations and enabling flexible, reliable turbine performance.

Real-time sensor feedback:

Real-time sensor feedback is a cornerstone of modern emission-reduction strategies in Brayton-cycle gas turbines because it enables continuous monitoring and precise control of the combustion process [6]. Unlike open-loop systems that rely only on predefined operating schedules, real-time sensor-based control uses live data from the operating environment of turbine to make rapid adjustments to fuel flow, airflow, and combustor staging. This dynamic approach is essential for maintaining low emissions under varying loads, ambient conditions, and fuel qualities.

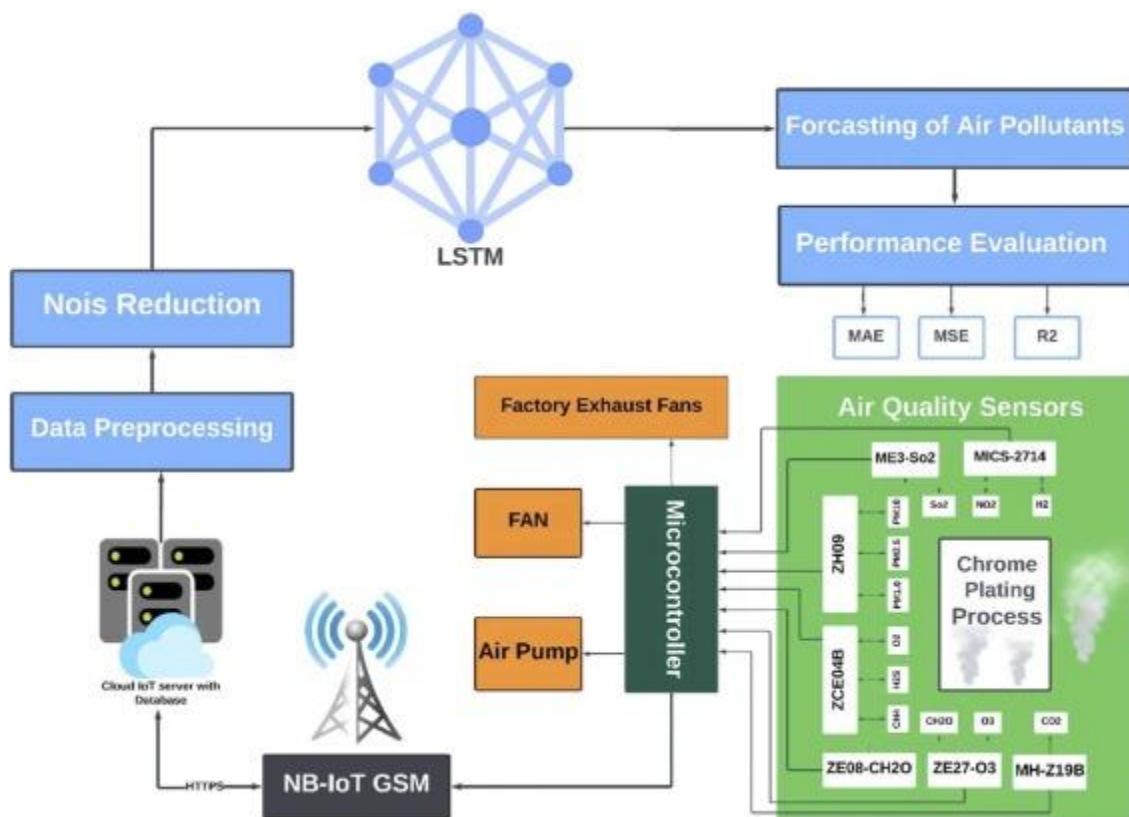


Figure 3. Real-time sensor feedback for emission control in Brayton cycle

Several categories of sensors contribute to this system (Figure 3). Exhaust-gas sensors measure key species such as NO_x , CO, O_2 , and sometimes unburned hydrocarbons. These data are used in closed-loop emission controls: if NO_x levels rise, for example, the controller may

lean out the mixture or adjust fuel staging; if CO levels increase, the system may enrich slightly or modify airflow to ensure more complete combustion [7]. Exhaust sensors thus act as direct indicators of whether the turbine is operating in a clean combustion regime.

Inside the combustor, pressure transducers provide high-frequency measurements of thermoacoustic oscillations. These oscillations emerge when the turbine operates near ultra-lean conditions, precisely where NO_x emissions are minimized [8]. Real-time pressure feedback allows active combustion control systems to detect the onset of instability and counter it through actuators such as variable fuel injectors, modulated valves, or acoustic drivers. By managing these instabilities actively, turbines operate safely at much lower flame temperatures, reducing NO_x formation.

In addition to pressure sensing, optical and laser-based diagnostics, including chemiluminescence sensors and tuneable diode laser absorption spectroscopy (TDLAS), monitor parameters such as flame position, equivalence ratio, and temperature distribution. These sensors provide fast, non-intrusive measurements that help detect issues like flashback, poor mixing, or localized hot spots that drive up emissions or threaten hardware integrity [9]. Optical feedback is especially valuable during transient events, such as rapid load changes, where combustion conditions fluctuate quickly.

Another crucial element is airflow and temperature sensing, particularly at compressor discharge and turbine inlet locations. Small variations in inlet air temperature, humidity, or pressure shift the combustor away from its optimal low-emission operating point [10]. Real-time feedback enables the control system to adjust inlet guide vanes, bleed valves, and cooling air flows to compensate for these changes. This ensures stable combustion even when external conditions vary significantly.

The effectiveness of real-time sensor feedback is amplified by advanced control algorithms, including adaptive and model-predictive control. These systems interpret sensor data in context, forecast future operating states, and calculate optimal actuator responses [11]. They balance competing priorities, such as minimizing NO_x while avoiding CO spikes or maintaining combustion stability, better than traditional control loops.

Overall, real-time sensor feedback transforms gas turbines from rigid mechanical systems into responsive, data-driven platforms capable of maintaining ultra-low-emission performance across a wide operating envelope. By continuously monitoring combustion behaviour and enabling fast, precise corrective actions, these sensors play a vital role in achieving reliable, efficient, and environmentally compliant Brayton-cycle operation.

Model predictive control:

Model Predictive Control (MPC) is an advanced control strategy increasingly applied in Brayton-cycle gas turbines to reduce emissions while maintaining efficiency, stability, and operational flexibility [12]. MPC uses a dynamic mathematical model of the turbine, including its combustion, airflow, and thermal behaviour, to predict future system states over a short time horizon. Instead of reacting only to current sensor readings, MPC evaluates how control actions taken now will influence future NO_x and CO emissions, temperatures, and stability margins. It then selects the optimal sequence of control inputs, such as fuel splits, variable inlet guide vane positions, or cooling-air adjustments, to keep the system within safe and clean operating limits.

In gas turbines, combustion dynamics and emissions are strongly interdependent. Running lean reduces NO_x but increases the risk of blowout or CO formation; operating near thermoacoustic instability limits damage hardware; and rapid load changes shift the combustor away from its optimal emission point [13]. MPC is especially useful in managing these trade-offs because it considers multiple constraints simultaneously. For instance, its lower flame

temperature to reduce NO_x while ensuring the equivalence ratio stays above a threshold that avoids incomplete combustion. It also plans control actions that maintain stable combustion during transients, preventing sudden spikes in emissions.

MPC integrates naturally with real-time sensor data, using measurements of pressure, temperature, and exhaust-gas composition to update the internal model and correct prediction errors (Figure 4). This adaptive capability allows MPC to handle system nonlinearities, component degradation, and variations in fuel quality, including hydrogen-rich blends [14]. As a result, turbines equipped with MPC maintain low emissions across a wider operating range than those relying on conventional proportional–integral–derivative (PID) loops.

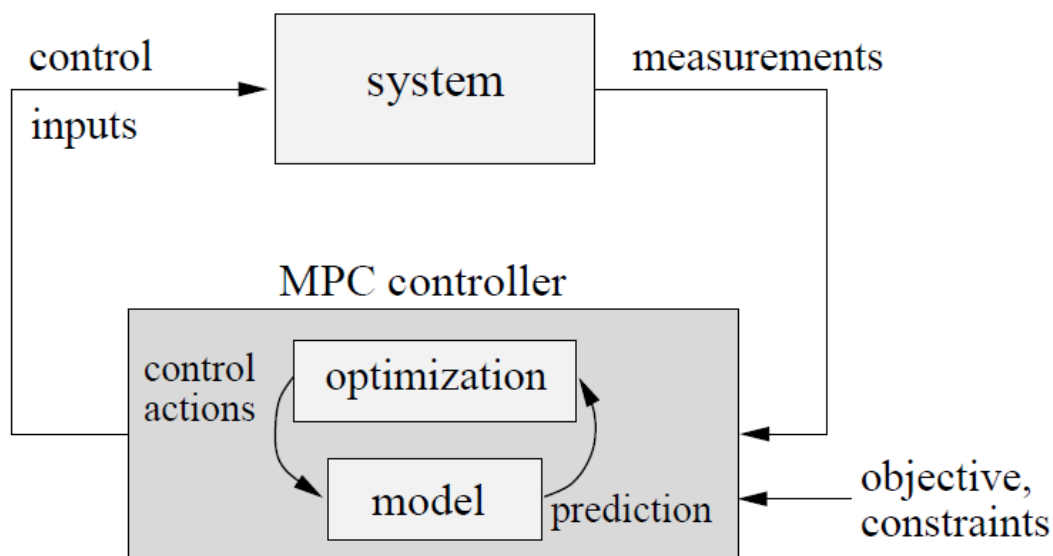


Figure 4. Model predictive control for minimizing emission in Brayton cycle

Overall, model-predictive control enables cleaner and more flexible Brayton-cycle operation by forecasting system behaviour, respecting operational constraints, and coordinating multiple actuators in a unified optimization framework.

Digital-twin-based control:

Digital-twin-based control is an emerging strategy in Brayton-cycle gas turbines that uses a high-fidelity virtual model, known as a digital twin, to monitor, predict, and optimize real-time turbine behaviour [15]. A digital twin is a continuously updated computational replica of the physical turbine, incorporating thermodynamic models, combustion dynamics, material behaviour, and actuator responses. It receives live data from sensors throughout the engine and uses this information to keep its internal state synchronized with the actual machine. Because it reflects both current operating conditions and predicted future states, the digital twin serves as an intelligent decision-making tool for guiding control actions that reduce emissions and improve overall performance.

In emission control, digital twins help identify the onset of conditions that could lead to increased NO_x , CO, or unburned hydrocarbons (Figure 5). By simulating thousands of potential future trajectories in real time, the twin predicts how changes in fuel–air ratio, fuel staging, or inlet guide vane adjustments will affect flame temperature, mixing quality, and combustion stability. This allows the controller to intervene early, long before the physical system drifts into a high-emission state or experiences instability [16]. For example, the twin

may anticipate that a rapid load increase will create a temporary hot spot and recommend adjusting fuel splits or airflow distribution to suppress local temperature spikes that drive NO_x formation.

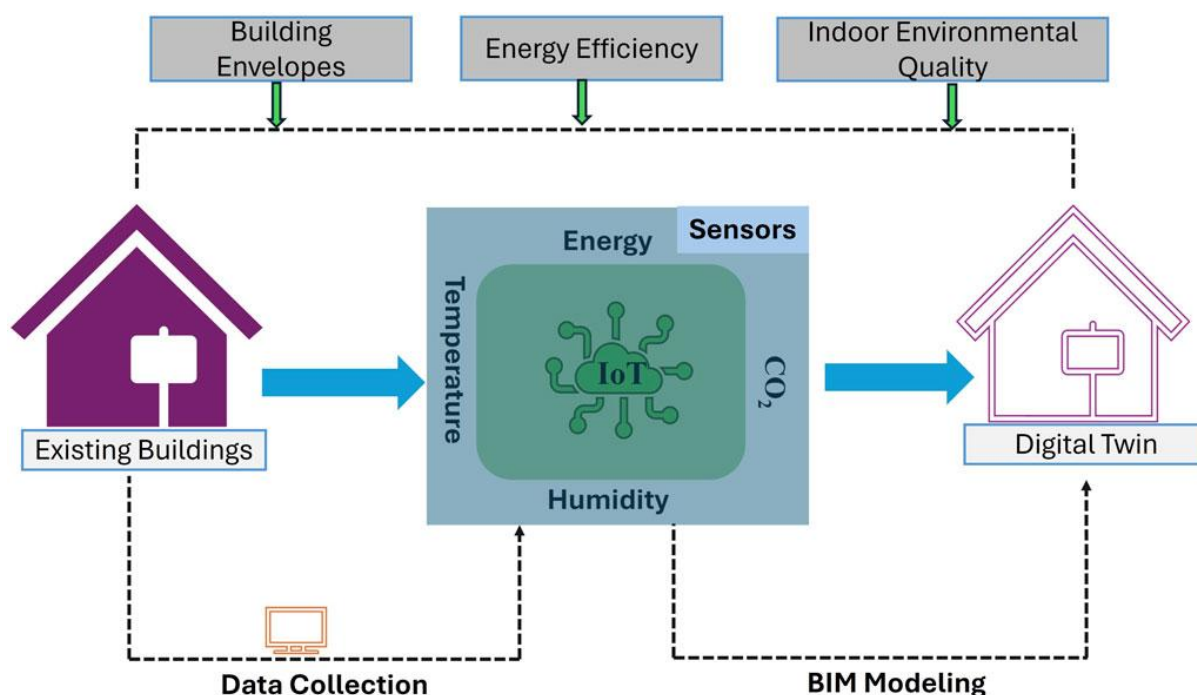


Figure 5. Digital-twin-based control for minimizing emission in Brayton cycle

A major advantage of digital-twin-based control is its ability to account for aging and degradation, which traditional fixed-parameter controllers often ignore. As components such as compressors, burners, and turbines wear over time, their performance characteristics shift, potentially increasing emissions [17]. The digital twin updates its model using real-time data and machine-learning techniques, ensuring that control actions remain accurate even as hardware changes. This adaptability is particularly valuable in fleets that operate under diverse environmental conditions or use variable fuel compositions, including hydrogen-rich or biofuel blends.

Digital twins also support optimal scheduling of start-ups, shutdowns, and transient operations, periods when emissions typically spike. By predicting how temperature gradients, ignition sequences, and airflow transitions will evolve, the controller executes smoother, cleaner operating profiles [18]. Combined with model-predictive control, digital twins enhance decision-making by reducing uncertainty and providing a more precise representation of the dynamic behaviour of turbine.

Overall, digital-twin-based control enables gas turbines to achieve consistently low emissions, higher reliability, and improved operational flexibility. It transforms monitoring and control from reactive to predictive, allowing Brayton-cycle systems to meet demanding environmental standards while operating efficiently across a wide range of conditions.

Lean-premixed combustion:

Lean-premixed combustion (LPC) is a widely used strategy in modern gas turbines to reduce nitrogen oxide (NO_x) emissions, which primarily form at high flame temperatures. In LPC, fuel and air are thoroughly mixed before entering the combustor, creating a uniform, fuel-lean mixture with an equivalence ratio below stoichiometric conditions [19]. Because this mixture

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burns at a lower peak temperature, it suppresses the thermal NO_x formation mechanism, making LPC one of the most effective in-combustor emission-reduction techniques for Brayton-cycle systems.

Achieving stable lean-premixed combustion, however, is technically challenging. As the mixture becomes leaner, the flame speed decreases, increasing the risk of blowout (flame extinction) and incomplete combustion, which raise CO and unburned hydrocarbon emissions [20]. Premixed systems are also more susceptible to flashback, where the flame propagates upstream into the premixing zone, and to thermoacoustic instabilities, which are pressure oscillations caused by interactions between heat release and acoustic waves in the combustor. These instabilities damage hardware and disrupt stable operation.

To maintain stable LPC, gas turbines rely on advanced control strategies. Fast-acting fuel-control valves, variable airflow devices (such as variable inlet guide vanes), and real-time monitoring of pressure, temperature, and equivalence ratio help keep the combustion process within safe, low- NO_x limits [21]. In many systems, active combustion control uses sensors and actuators to detect and counteract oscillations. Additionally, staged fuel injection and optimized combustor geometry enhance mixing quality and broaden the stable operating range.

Overall, lean-premixed combustion significantly reduces NO_x emissions while preserving high efficiency, but it requires precise control and careful management of stability to function reliably in modern high-performance gas turbines.

Additional Combustion-Optimization Strategies

Fuel staging reduces emissions by distributing fuel across multiple burners or combustion zones so that each operates at an optimal, lean condition [22]. By adjusting fuel splits in real time, the system avoids local rich pockets that generate CO and unburned hydrocarbons while keeping flame temperatures low enough to minimize NO_x .

Precise management of turbine-inlet temperature (TIT) ensures that combustion stays hot enough for complete fuel oxidation but not so hot that thermal NO_x rises sharply [23]. Controllers regulate TIT through coordinated adjustments of fuel flow, cooling air, and combustor operating modes, maintaining a narrow, low-emission temperature window.

Variable air pathways, including inlet guide vanes, variable stator blades, and compressor bleed systems, fine-tune airflow to match fuel supply and maintain stable lean combustion [24]. By controlling air distribution and pressure ratios across different loads, these systems prevent instabilities, support clean combustion, and keep emissions low throughout the operating range of turbine.

CONCLUSION:

Advanced control-system strategies are essential for minimizing emissions from Brayton-cycle gas turbines while maintaining high efficiency and operational flexibility. Real-time sensor feedback allows continuous monitoring of combustion conditions, while model-predictive and digital-twin-based controls provide predictive, coordinated management of multiple actuators. Lean-premixed combustion, fuel staging, and precise control of turbine-inlet temperature and variable air pathways optimize flame stability and reduce NO_x , CO, and unburned hydrocarbons. Collectively, these approaches enable turbines to operate reliably across diverse fuels and load conditions, meeting stringent environmental standards and supporting the transition toward cleaner and more sustainable power generation.

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