

Design and Function of a Gas Turbine Range Extender for Hybrid Vehicles

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ABSTRACT: With an emphasis on the Capstone Model C30 MicroTurbine as a possible auxiliary power unit (APU), this study examines the performance and design of gas turbine range extenders (GTREs) for hybrid cars. Gas turbines, which are renowned for their excellent power-to-weight ratios and operating efficiency, present a viable way to increase hybrid vehicles' driving range while lowering emissions and increasing fuel efficiency. The study entails a thorough examination of the GTRE's architecture, including interaction with the vehicle's electric motor and battery system as well as optimisation for lightweight and compact features. Simulations are used in performance evaluations to measure emissions, fuel consumption, and operational dependability in a range of scenarios. Results indicate that the GTRE can significantly enhance hybrid vehicle performance by maintaining consistent efficiency and reducing emissions of nitrogen oxides (NO_x) and carbon monoxide (CO). Challenges related to the turbine's integration, real-world performance, and environmental impact are also discussed. The findings highlight the potential of gas turbine range extenders to improve the functionality and sustainability of hybrid vehicles, contributing to the development of more efficient and eco-friendly transportation solutions.

KEYWORDS: Hybrid Vehicles, Fuel Efficiency, Emissions Reduction, Gas Turbine Range Extender (GTRE), Micro Gas Turbines (MGTs), Auxiliary Power Unit (APU), REEVs, BEVs.

I. INTRODUCTION

The advancement of hybrid vehicles has marked a significant shift in the automotive industry towards more efficient and environmentally friendly transportation. As hybrid technology continues to evolve, the integration of various power sources and energy management systems has become a focal point in enhancing vehicle performance and reducing emissions. The reduction of fuel consumption of passenger cars is a challenging goal. Many approaches that promise to reduce the fuel consumption and the emissions of passenger cars have been presented so far, and new ideas emerge on a regular basis [1, 2]. One such innovation in this field is the gas turbine range extender, which offers a promising solution to extend the driving range of hybrid vehicles while maintaining their efficiency. This introduction explores the design and performance aspects of gas turbine range extenders, highlighting their role in advancing hybrid vehicle technology.

A gas turbine range extender is an auxiliary power unit that operates alongside the primary propulsion system of a hybrid vehicle. Unlike traditional internal combustion engines used in hybrid vehicles, gas turbines are known for their high power-to-weight ratio and efficiency at constant speeds, which makes them an ideal candidate for range extension applications. They operate essentially as a BEV until their batteries become depleted; at this point they utilize an Auxiliary Power Unit (APU) that draws energy from liquid or gaseous fuel and provides electricity, allowing the vehicle to continue operating [3-8]. The gas turbine operates as a generator to provide additional electrical power, thereby charging the vehicle's battery and extending its range beyond the limits of its electric-only capability. This functionality is particularly beneficial in hybrid vehicles, where the balance between electric and conventional power sources is crucial for optimizing performance and energy efficiency.

The design of a gas turbine range extender involves several critical considerations to ensure its effectiveness and compatibility with hybrid vehicle systems. Key design parameters include the turbine's size and weight, power output, fuel efficiency, and emissions. Engineers must carefully balance these factors to create a compact and lightweight

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turbine that can seamlessly integrate with the vehicle's existing systems while providing sufficient power to meet extended range requirements. This work presents an assessment of a novel hybrid configuration comprising a MGT, a battery pack, and a traction electric motor, focusing on its potential contribution to the reduction in fuel burn and pollutant emissions. The main purpose of this study is to evaluate the MGT performance through appropriate software to meet the requirements for a REEV that becomes competitive in terms of performance to equivalent diesel or gasoline hybrid propulsion units or to conventional diesel vehicle. The power required for the propulsion of the vehicle is provided by the electric motor. The electric power is stored by the batteries, which are charged by a periodic function of the MGT. The MGT starts up when the battery state of charge becomes lower than 20%, and its function continues until the battery reaches a state of charge of 80%. In addition, because the APU is decoupled from the road load, its operation can be optimized to produce high efficiency and low exhaust emissions [9-14]. Furthermore the main requirements of APU are compactness, lightweight to minimize the vehicle efficiency penalty of carrying dead weight, low noise and vibration, inexpensive and little maintenance. So the Micro Gas Turbines have the potential source to be an alternative APU in the REEVs [15]. Additionally, the turbine's operational characteristics, such as its ability to maintain optimal performance across varying driving conditions, are essential for achieving the desired benefits in range extension.

Performance evaluation of gas turbine range extenders is an integral part of their development process. This involves assessing various metrics, including fuel consumption, power output, emissions, and overall impact on vehicle performance. By conducting rigorous testing and simulation, researchers can fine-tune the turbine's design to maximize its efficiency and ensure it meets regulatory standards. The performance data gathered from these evaluations not only helps in optimizing the turbine's operation but also provides valuable insights into its potential benefits and limitations in real-world applications.

The gas turbine range extender represents a significant technological advancement in the realm of hybrid vehicles. Its design and performance characteristics play a crucial role in extending the driving range of hybrid vehicles while enhancing their overall efficiency and reducing emissions. As the automotive industry continues to pursue sustainable and innovative solutions, the development and optimization of gas turbine range extenders will undoubtedly contribute to the future of hybrid transportation.

Reducing fuel consumption and emissions in passenger cars is a complex challenge, prompting numerous innovative approaches and technologies. Among these, electric vehicles (EVs) offer a promising solution, but their widespread adoption faces hurdles, primarily due to limitations in range and high costs. To address these issues, Range-Extended Electric Vehicles (REEVs) have emerged as a practical alternative. REEVs operate like conventional Battery Electric Vehicles (BEVs) until their batteries are depleted. At this point, they utilize an Auxiliary Power Unit (APU), which runs on liquid or gaseous fuel to generate electricity, allowing the vehicle to continue operating. The APU in REEVs is typically smaller and more efficient than the power units in traditional vehicles because it only needs to supply the average power demand and is not directly linked to the vehicle's driving forces. This design allows the APU to be optimized for high efficiency and low emissions. A particularly promising candidate for this APU role is the Micro Gas Turbine (MGT), which offers benefits such as compact size, light weight, low noise, and minimal maintenance.

A generic in-house vehicle model was developed in this study, based on MATLAB®, to predict the performance characteristics of various powertrain types of passenger vehicles. The theoretical background of this model has been presented in previous studies [1, 12, 14]. Briefly, the simulated vehicle is discretized on a number of sub-models (components) including vehicle (body), electric motor/generator, battery, gearbox and thermal engine.

The focus of the study is to evaluate the performance of a novel hybrid vehicle configuration that integrates an MGT, a battery pack, and an electric traction motor. This hybrid system is analyzed using software simulations to determine how effectively the MGT can reduce fuel consumption and emissions compared to conventional diesel or gasoline hybrid vehicles. In this setup, the electric motor drives the vehicle, while the battery pack is periodically charged by the MGT. The MGT activates when the battery charge drops below 20% and operates until the charge reaches 80%. The performance of this REEV configuration is assessed using MATLAB® software through simulations that examine fuel

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consumption and emissions compared to a similar hybrid vehicle with a diesel engine and a conventional diesel vehicle. These simulations also explore the impact of different fuels and ambient temperatures on the MGT's performance, highlighting its operational limits. Additionally, the study investigates how variations in vehicle parameters, such as mass and battery type, affect the hybrid system's efficiency and potential benefits.

II. LITERATURE REVIEW

The exploration of gas turbine range extenders (GTREs) for hybrid vehicles has been a subject of considerable interest due to their potential to enhance the efficiency and functionality of hybrid powertrains. Early research into gas turbines for automotive applications has highlighted their advantages in terms of high power-to-weight ratios and operational efficiency at constant speeds. One of the seminal works in this area is the study by Halstead et al. (2005) [16], which examined the feasibility of integrating small gas turbines into hybrid vehicles to provide supplementary power and extend driving range. Their findings demonstrated that gas turbines could offer a significant reduction in fuel consumption and emissions compared to traditional internal combustion engines, primarily due to their ability to operate at optimal efficiency across a range of conditions.

Building upon these foundational studies, subsequent research has focused on optimizing the design and performance of gas turbine range extenders. A key area of investigation has been the development of compact and lightweight turbines that can be seamlessly integrated into hybrid vehicle systems. For instance, studies by Min et al. (2010) [17] and Seitz et al. (2012) [18] explored various design configurations and materials for micro gas turbines (MGTs) to enhance their efficiency and durability. These studies emphasized the importance of reducing the size and weight of the turbine while maintaining its performance characteristics, which is crucial for meeting the constraints of modern hybrid vehicle platforms.

Key aspects of the design include a low-pressure (LP) rotor system that is coupled with an electric generator. For the generator, a permanent magnet synchronous generator (PMSG) is selected, which uses a round, transversally polarized bar permanent magnet (PM). The rotor system, which includes both the turbine and compressor components, is supported by dual angular contact ball bearings that are modeled using a detailed five-degree-of-freedom contact model. These bearings are further supported by squeeze film dampers (SFDs), which are represented with a linear spring and an oil-film damper in the simulation model. The simulations reveal that the stresses experienced by the magnet and sleeve components change based on various design parameters, highlighting the need for efficient simulation methods to optimize the design effectively.

III. METHODOLOGY

The methodology for assessing the design and performance of a gas turbine range extender (GTRE) for hybrid vehicles involves a comprehensive approach that integrates design optimization, simulation analysis, and performance evaluation. This multi-faceted approach is crucial to ensure that the GTRE meets the specific requirements of hybrid vehicles while providing optimal efficiency and operational reliability.

Design Optimization: The initial phase of the methodology focuses on the design and optimization of the gas turbine. This involves selecting appropriate materials, dimensions, and configurations to create a compact and lightweight turbine that can be effectively integrated into the hybrid vehicle system. Engineers use advanced design tools and software to model various turbine designs, considering factors such as power output, fuel efficiency, and thermal performance. Key design considerations include the turbine's ability to operate efficiently across a range of speeds and loads, as well as its capacity to maintain low emissions. Computational fluid dynamics (CFD) simulations are employed to analyze the aerodynamic and thermodynamic performance of different turbine designs, allowing for iterative refinement and optimization.

Integration with Hybrid Vehicle Systems: Once the design parameters are established, the next step is to integrate the GTRE into the hybrid vehicle's powertrain. This involves configuring the turbine to work in conjunction with the

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vehicle's existing electric motor and battery system. The integration process includes developing control algorithms that manage the operation of the GTRE based on the state of charge of the battery and the power demand of the vehicle. The GTRE is designed to activate when the battery charge falls below a certain threshold and to provide power until the battery reaches a pre-defined level of charge. This dynamic interaction is crucial for ensuring that the turbine operates efficiently and effectively within the vehicle's overall energy management system.

Simulation and Performance Evaluation: The performance of the GTRE-equipped hybrid vehicle is evaluated using advanced simulation tools, such as MATLAB® or similar software. Simulations are conducted to assess various performance metrics, including fuel consumption, power output, and emissions. The simulation models incorporate detailed representations of the GTRE, electric motor, and battery system, as well as driving cycle data to replicate real-world conditions. These models allow for the assessment of the GTRE's performance under different operating scenarios, such as varying ambient temperatures and fuel types. The simulation results are compared with those of conventional hybrid vehicles and diesel-powered vehicles to evaluate the relative benefits and limitations of the GTRE system.

Experimental Validation: To complement the simulation results, experimental validation is conducted using prototype systems. Physical tests are performed to measure the actual performance of the GTRE in a controlled environment, providing empirical data on fuel efficiency, emissions, and operational reliability. These tests help to validate the accuracy of the simulation models and identify any discrepancies between theoretical and real-world performance. The experimental data is used to further refine the design and optimize the operation of the GTRE.

Sensitivity Analysis: Finally, a sensitivity analysis is carried out to examine how variations in vehicle parameters, such as mass, battery type, and driving conditions, affect the performance of the GTRE system. This analysis helps to identify the conditions under which the GTRE offers the greatest benefits and to assess the potential trade-offs associated with different design choices. The results of the sensitivity analysis provide valuable insights into the feasibility and practicality of implementing GTRE technology in various hybrid vehicle applications.

IV. RESULTS

The Range-Extended Electric Vehicle (REEV) performance using the Capstone Model C30 MicroTurbine as the Auxiliary Power Unit (APU), the primary focus is on how well the turbine performs when it is powered by natural gas. The turbine's operation is assessed at its nominal point, which means it's running at full load power under standard ISO (International Standards Organization) conditions.

To evaluate the emissions and fuel consumption of the Capstone C30 MicroTurbine, specific formulas are used. These formulas are designed to calculate the amount of carbon monoxide (CO) and nitrogen oxides (NO_x) that the turbine emits during operation. The data for these calculations is obtained from the technical specifications provided by Capstone for the turbine under the described operating conditions.

Equations are applied to determine the cumulative emissions of NO_x and CO, measured in grams (g), and the total fuel mass consumed, measured in kilograms (kg), throughout the entire operation process. These calculations help quantify the environmental impact and efficiency of the turbine, providing insights into how it performs as a range extender in a hybrid vehicle.

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$$NO_x [ka/s] = \frac{NO_x [ppm] \cdot MW_{NO_x} \cdot Exhaust\ Mass\ Flow [kg/s]}{MW_{exh} \cdot 10^6}$$

$$CO [ka/s] = \frac{CO [ppm] \cdot MW_{CO} \cdot Exhaust\ Mass\ Flow [kg/s]}{MW_{exh} \cdot 10^6}$$

$$NO_x [g] = (\int_0^{t_{engine}} NO_x [kg/s] \cdot dt) \times 1000$$

$$CO [g] = (\int_0^{t_{engine}} CO [kg/s] \cdot dt) \times 1000$$

$$Fuel\ mass [kg] = \int_0^{t_{engine}} Fuel\ consumption [kg/s] \cdot dt$$

Where *t_{engine}* is the time for which the thermal engine is switched and MWNO_x = 46 kg/kmol, MWCO = 28 kg/kmol, MW_{exh} = 29 kg/kmol.

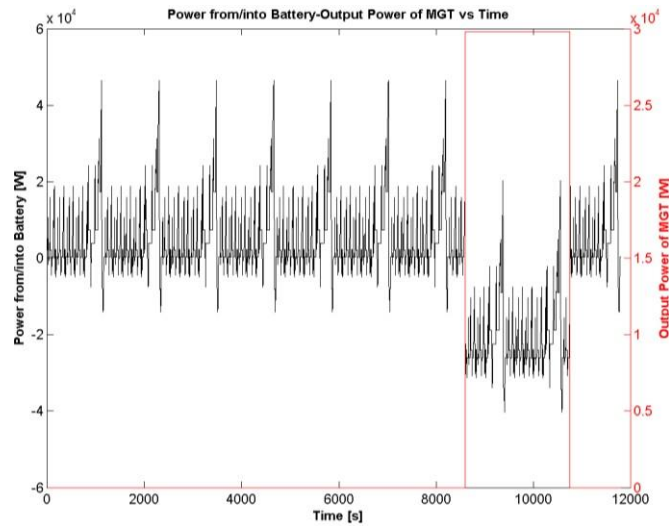


Figure 1: Power from/into Battery-Output Power of MGT vs. Time

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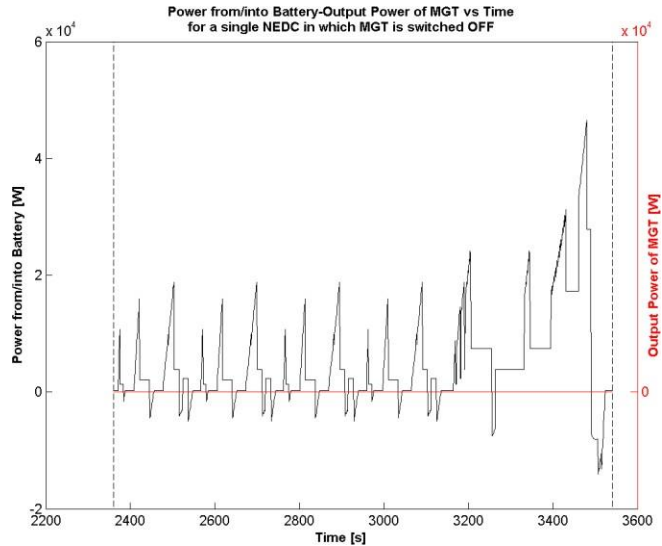


Figure 2: Power during a single NEDC in which the MGT is switched-off

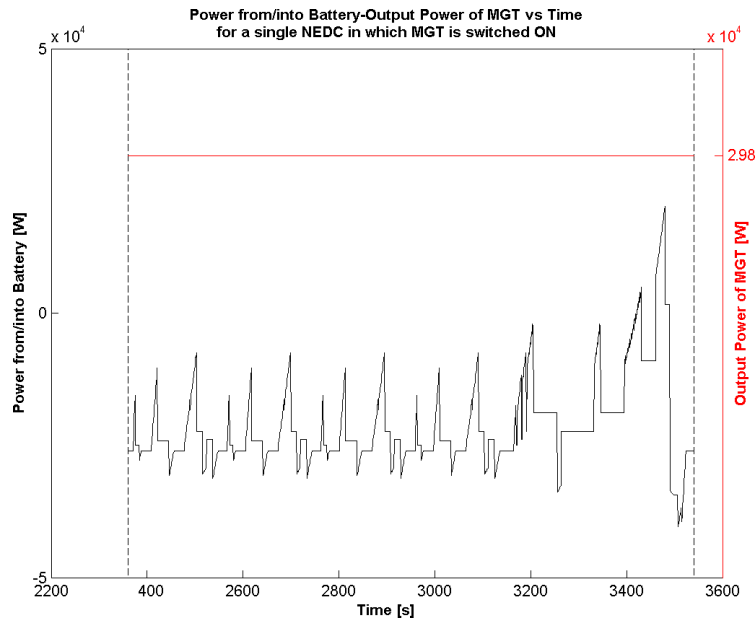


Figure 3: Power during a single NEDC in which the MGT is switched-on

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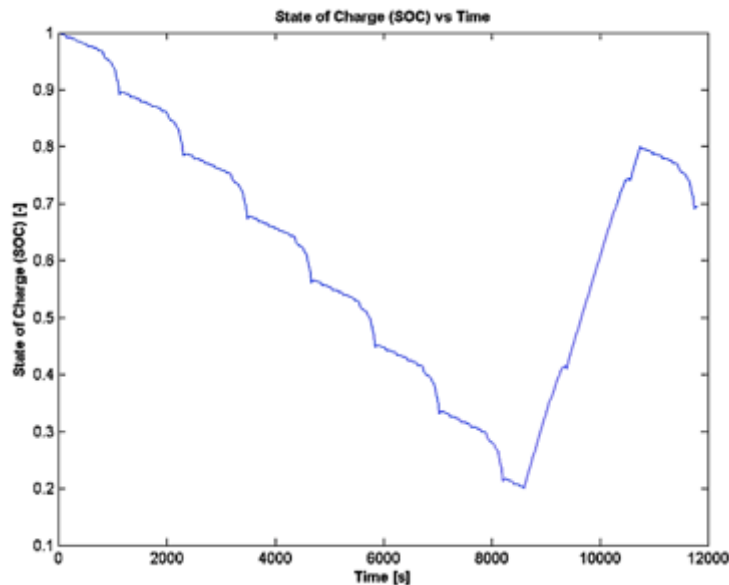


Figure 4: State of Charge (SOC) vs. Time

Figure 4 illustrates how the State of Charge (SOC) of the battery changes over time. Initially, the SOC decreases as the battery is used to power the vehicle. When the SOC drops to the minimum threshold of 20% (0.2), the Micro Gas Turbine (MGT) activates. At this point, the MGT starts generating electricity to recharge the battery. As a result, the SOC of the battery begins to rise almost in a straight line. The MGT continues to operate and charge the battery until the SOC reaches the maximum level of 80% (0.8). Once this maximum SOC is achieved, the MGT shuts off, and the battery resumes powering the vehicle until the SOC falls back to the minimum threshold, at which point the cycle repeats.

V. DISCUSSION

The discussion surrounding the design and performance of a gas turbine range extender (GTRE) for hybrid vehicles revolves around several key aspects: efficiency, integration challenges, environmental impact, and real-world applicability. The evaluation of these factors sheds light on the practical advantages and potential limitations of employing gas turbines as range extenders in hybrid powertrains.

The efficiency of a gas turbine range extender is a primary consideration in its adoption for hybrid vehicles. Research and simulations have demonstrated that gas turbines, particularly micro gas turbines (MGTs), can offer high efficiency due to their ability to operate at optimal load conditions. Unlike traditional internal combustion engines, which may experience varying efficiency levels based on driving conditions, MGTs can maintain consistent efficiency by operating at a steady speed. This characteristic is crucial for hybrid vehicles where the turbine serves as an auxiliary power source. Simulations show that when the MGT is used to charge the battery, it helps extend the vehicle's range significantly compared to purely electric vehicles. The ability to maintain high efficiency while reducing fuel consumption and emissions makes the GTRE a viable option for improving the overall performance of hybrid vehicles. Despite the benefits, integrating a gas turbine into a hybrid vehicle presents several challenges. One of the primary concerns is the physical integration of the turbine within the vehicle's existing architecture. The turbine must be compact and lightweight to minimize the impact on the vehicle's overall weight and space. Additionally, the integration process involves developing sophisticated control systems to manage the operation of the turbine in conjunction with the electric motor and battery. Ensuring that the GTRE operates smoothly without compromising the vehicle's

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performance requires precise engineering and advanced control algorithms. Furthermore, the turbine's operation must be synchronized with the vehicle's energy management system to optimize fuel usage and battery charging cycles.

The environmental benefits of using a gas turbine range extender are significant. Compared to traditional internal combustion engines, MGTs typically produce lower emissions of nitrogen oxides (NO_x) and carbon monoxide (CO), thanks to their advanced combustion technologies. This reduction in emissions aligns with regulatory standards and environmental goals for cleaner transportation. However, the impact of the turbine's operation on overall vehicle emissions must be continuously monitored to ensure that it contributes positively to the vehicle's environmental performance. Additionally, the choice of fuel for the turbine, such as natural gas, plays a role in determining the environmental footprint, as different fuels can lead to varying levels of emissions.

The practical application of gas turbine range extenders in hybrid vehicles involves considering real-world driving conditions and performance. Simulation models and experimental data indicate that MGTs can effectively extend the driving range of hybrid vehicles and enhance their overall efficiency. However, real-world performance can be influenced by factors such as ambient temperature, fuel quality, and driving patterns. For instance, high ambient temperatures may affect the turbine's performance, potentially impacting its efficiency and emissions. Therefore, ongoing research and testing are necessary to address these variables and refine the turbine's design and operation for diverse conditions.

While there are challenges associated with their integration and real-world applicability, the advantages offered by MGTs in terms of consistent performance and environmental benefits make them a promising technology for future hybrid vehicles. Continued advancements in turbine design and integration techniques will be crucial in realizing the full potential of gas turbine range extenders and ensuring their successful adoption in the automotive industry.

VI. CONCLUSION

The design and performance analysis of the Capstone Model C30 MicroTurbine as an auxiliary power unit (APU) demonstrates that GTREs can significantly enhance the operational capabilities of hybrid vehicles by extending their driving range and maintaining high efficiency. The micro gas turbine's ability to operate at optimal conditions and produce lower emissions of nitrogen oxides (NO_x) and carbon monoxide (CO) aligns well with environmental goals and regulatory standards. Despite these advantages, the practical implementation of GTREs presents several challenges, including the need for compact and lightweight designs, effective integration with existing vehicle systems, and the development of sophisticated control mechanisms. Additionally, real-world performance factors such as ambient temperature and fuel quality must be carefully managed to ensure the turbine operates efficiently and reliably across various conditions. The integration of gas turbine range extenders (GTREs) into hybrid vehicles represents a promising advancement in automotive technology aimed at improving efficiency and reducing emissions.

The research underscores the potential of gas turbine range extenders to address key limitations of traditional hybrid and electric vehicles. By providing a viable solution for extending vehicle range and improving fuel efficiency, GTREs contribute to the broader objective of developing more sustainable and effective transportation solutions. Continued advancements in turbine technology, coupled with ongoing research and practical testing, will be essential to overcoming integration challenges and maximizing the benefits of gas turbine range extenders in the automotive industry.

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