EPRI

TAKING GAS TURBINE HYDROGEN BLENDING TO THE NEXT LEVEL



September 2022



Introduction

Climate change, *energy independence*, *renewable power*, and *the hydrogen economy* are among the terms used in recent years and decades to describe society's most pressing challenges. Although the best way to face these challenges is a topic of controversy, it is important to estimate the potential of candidate technologies for reaching the goals before society commits to them completely. It is common to look for a quick fix, but solutions almost always require numerous technologies implemented throughout the entire energy value chain, involving millions of people and costing hundreds of billions (if not trillions) of dollars. These solutions are also likely to involve technologies that require incremental steps to prove that parts of the process are feasible. This typical case around technology innovation encapsulates the successful testing expounded on in this white paper. Moreover, for gas turbines, Noble et al. give a basis for the current capabilities on hydrogen inclusion for large-scale units [1].

Combustion or *gas* turbines are a highly valuable power generation and heating commodity. In many gas turbines, natural gas (NG) is the fuel used. NG is generally a low-cost and relatively high-energy-density fuel with a lower carbon content than coal or liquid fuels. This leads to reduced carbon emissions relative to those of fossil fuels. However, while burning NG, carbon dioxide (CO_2) remains a primary constituent of the exhaust emissions. Therefore, shutting down gas turbines or re-envisioning them for a low-carbon future is a popular focus of research, discussion, and development. One such proposed reconfiguration is blending hydrogen (H_2) with the NG fuel stream to further reduce CO_2 emissions.

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The reduction in CO_2 emissions trends generally with the mass ratio of H_2 in the fuel—burning 100% H_2 reduces CO_2 emissions by 100%. Note that the reduction of CO_2 is nonlinear with volume % of H_2 in the fuel, with the largest reductions being realized at the higher H_2 volumetric percentages (20% by volume is 3% by mass; 80% by volume is 33% by mass). Since the early 1980s, reduction of emissions such as oxides of nitrogen (NOx) and carbon monoxide (CO) has been a part of development efforts by the original equipment manufacturers (OEMs) of gas turbines. This has led to the advent of multiple varieties of dry, low-NOx (DLN) or dry, low-emissions (DLE) combustion systems. DLN systems are considered "dry" because they have eliminated the need for water injection into the gas turbine as a way to reduce regulated emissions. Older-style combustion systems that required water injection are generally referred to as *non-premixed* or *diffusion systems*, whereas DLN systems are generally referred to as *premixed systems*. These names refer to how thoroughly the fuel and air are mixed before combustion occurs. Diffusion systems typically combust fuel and air without premixing, resulting in combustion at the interface between the fuel and air. Consequently, the fuel-to-air ratio in the local combustion zone is usually high, with no control over combustion temperatures. Premixed combustion systems mix the fuel and air upstream of the combustion zone, controlling the fuel-to-air ratio more closely. This localized reduction in fuel-to-air ratio results in lower combustion temperatures and lower NOx emissions. Figure 1 is a visual representation of these architecture differences and the resulting lower-temperature regions, even if the desired reference firing temperature is the same for both styles of combustors. Figure 2 gives a chronological progression of NOx emission capabilities with combustor architecture evolutions from non-premixed combustors to current state-of-the-art DLN systems.

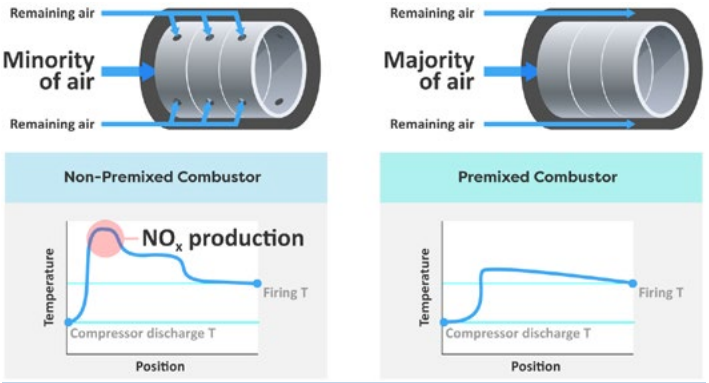


Figure 1. Comparison of non-premixed (diffusion style) versus lean-premixed (DLN style) combustors [2]

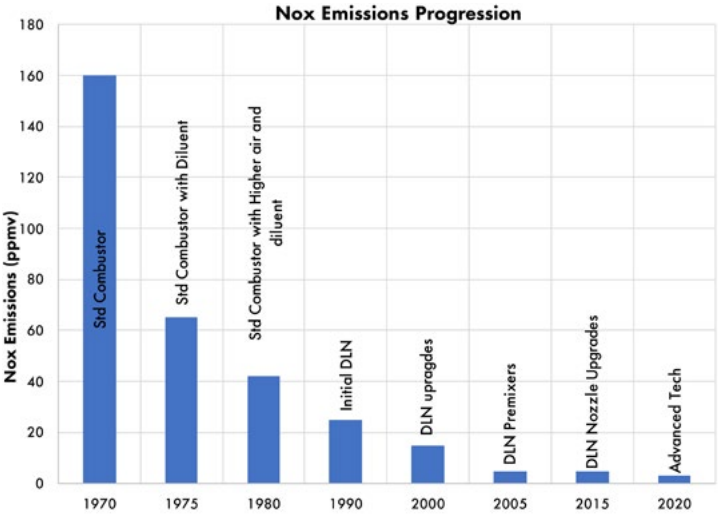


Figure 2. Progression of NOx emissions over time with emissions controls and DLN technology development

For many years, gas turbine combustion systems have burned gases that contain H_2—even as much as 100% H_2. To some degree, it would seem possible to easily convert gas turbines to H_2-burning systems if enough H_2 were readily available. However, two facts are important to consider.

The first fact is that, in most cases, the H_2 used in gas turbines to date has not been from a dedicated H_2 source, but rather from a process that produces H_2 as part of a large commercial operation. Thus, the H_2 source, H_2 blending, and H_2 control typically used, although valuable in some sense for the present investigations, are not typical of the H_2 systems that will be used in potential future power generation applications.

Second, systems that have historically combusted H_2 are typically older, non-DLN, diffusion-type systems. (Some DLN systems have been running H_2 as well, but generally in very low percentages of less than 5%. Exceptions include the W501D5As at Sweeny Cogeneration facility in Texas, which has four gas turbines that have consumed refinery off-gas with H_2 blended at a rate of 15–35% H_2 using DLN combustors). These combustion systems have advantages over DLN systems in burning H_2 due to the combustion process used. An H_2 flame reacts, or burns, much faster than an NG flame, and there is a risk of flashback. When H_2 and air are premixed, there is a possibility that the flame will move upstream due to flashback, and it can lead to the flame reaching upstream parts of the combustion hardware that are not designed to withstand flame temperatures. This can cause catastrophic damage to the gas turbine's internal components. Because fuel and air are near each other only at the point of combustion in diffusion systems, the flashback risk is low, and the risk of combustion hardware damage minimized.

However, OEMs have been working for many years to prove out or upgrade their combustion systems for higher H_2 content than which they were originally designed. Mitsubishi Power has been doing this same work for its M501G advanced-class gas turbine.

Getting to an H_2 economy that provides H_2 into gas turbines for low- or no-carbon emissions will require many technology advancements. This fact should not dissuade the reader. These advancements appear achievable because several OEMs and third-party vendors are working on viable options. This white paper details the work of Mitsubishi Power, the Electric Power Research Institute (EPRI), and Southern Company, who have joined forces to advance the technology. The value of this project cannot be overstated. The project will allow the industry and society to view H_2 as a real potential fuel source for modern turbines, one that will reduce emissions of CO_2 and allow further flexibility of operation of gas turbines with no, or minimal, changes to NOx emissions compared to traditional natural-gas turbines.

Hydrogen Impacts on Gas Turbines

The impacts of H_2 on gas turbines are varied and often misunderstood. Recent publications and reports in development provide more information around the impacts of H_2 on emissions, performance, durability, and service life. This white paper will not restate that information in detail; however, some information is pertinent to the project covered herein.

Flame Speed

As indicted in Figure 3, the flame speed of H_2 is much faster than that of NG. As a result, the combustion system design must account for this flame speed in multiple ways, including the control of fuel-to-air ratios in the combustor. In some combustion systems, this might lead to the inability to run high levels of H_2. In others, it might not significantly affect durability, operability, or emissions. The H_2 flame speed will not impact each combustion system equally; analysis and testing are required to determine the capability of each system.



Figure 3. Stoichiometric property comparisons between NG and H_2 [1]

Heating Value

The heating value (a measure of the amount of energy contained in a "chunk" of fuel) of H_2 is significantly different from that of NG. It is the impact of the low density of H_2 that makes the comparison with NG heating values a topic that can lead to incorrect conclusions. Figure 3 compares the heating values of H_2 and NG in mass and volume bases.

First, the volume basis heating value (or energy density) of H_2 is less than one-third of NG's, which will impact fuel circuit sizing. Valves, piping, metering devices and their control systems, and so on can also be significantly impacted by this change in energy density. However, the volume-based heating value of H_2 (see Figure 4) should not significantly impact gas turbine performance because the same amount of energy is added to the gas turbine regardless of the fuel.

A second important factor to consider is that gas turbines control fuel flow based on reaching a particular total energy, generally measured by temperatures post-combustion with compressor and turbine pressure ratios or inlet conditions to the gas turbine. Fuel flows will change based on the energy content of the fuel. Although the power of the gas turbine will increase slightly (described later), the combustion exit temperatures are generally unchanged going from NG to H_2 or H_2-NG blends because the fuel flows are adjusted by the gas turbine control system to hold constant temperatures or loads (power). A general process map of gas turbine control and a typical gas turbine temperature control curve are shown in Figures 5 and 6.

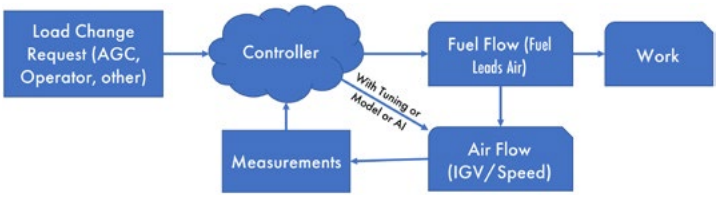


Figure 5. Gas turbine control simplified flow diagram

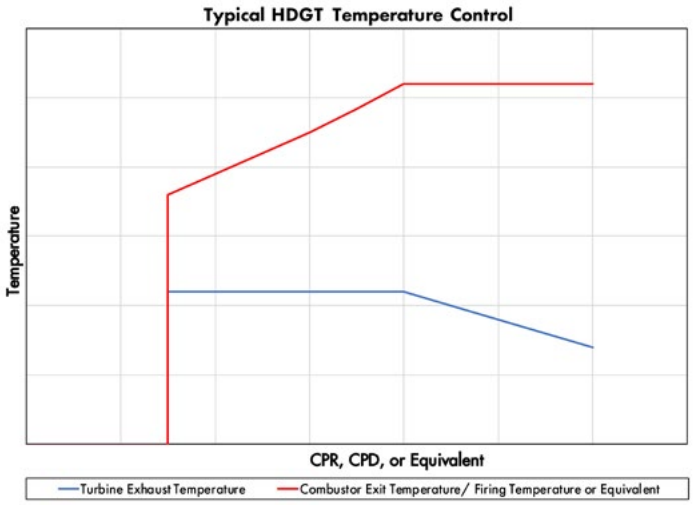


Figure 6. Typical part and baseload combustion and exhaust temperature "control curves"

Performance and Emissions

An increase of H_2 in the fuel will positively influence a gas turbine's performance and efficiency; however, it is not due to volumetric- or mass-based heating value impacts. The impact is related to the exchange of CO_2 emissions for H_2O emissions with hydrogen. As CO_2 decreases in the exhaust, the concentrations of other constituents, namely, oxygen and water, increase. Figure 7 shows the general trend of exhaust products with increasing H_2.

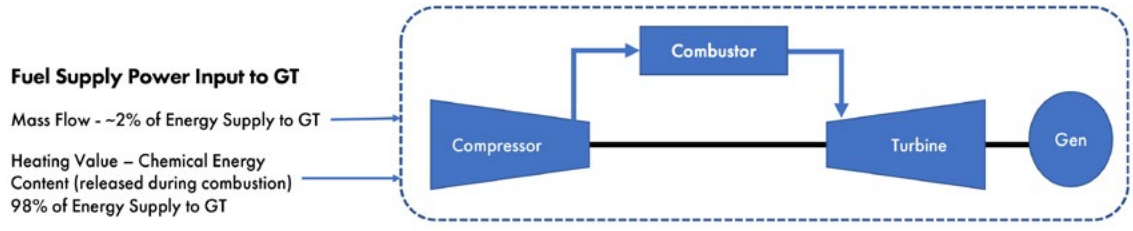


Figure 4. Fuel supply relation to overall power of a gas turbine

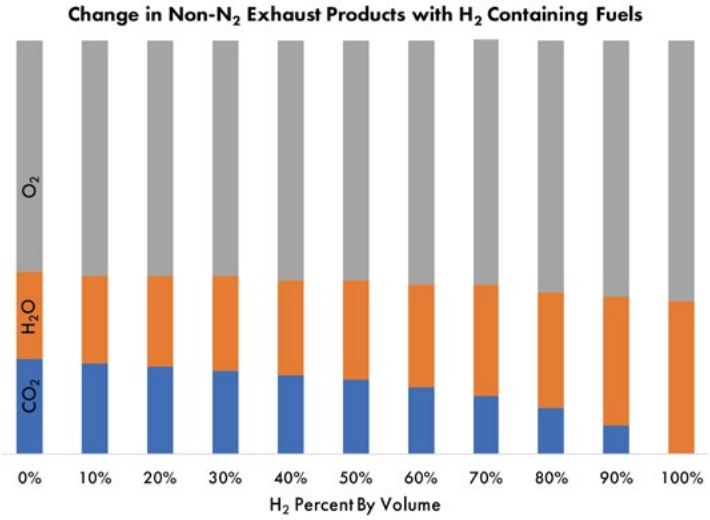


Figure 7. Exhaust constituents relative to increase in H_2 fuel percent

This change in exhaust products has a twofold impact. First, in performance, the change in exhaust products results in an exhaust with a higher energy content relative to its temperature (specific heat, c_p). This results in more work for the same temperature and/or higher efficiency of the gas turbine, depending on the type of control used. This nominal trend in efficiency, performance, and CO_2 reduction with increasing H_2 is shown in Figure 8. This is shown for a nominal turbine, and specific benefits will be model-specific. Measurable impacts of efficiency and performance can be seen with H_2, though those impacts are more pronounced at higher percentages. Notably, an improvement in heat rate was seen at the Southern Company test by holding the firing temperature constant as the H_2 percentage was increased, as is shown in Figure 8.

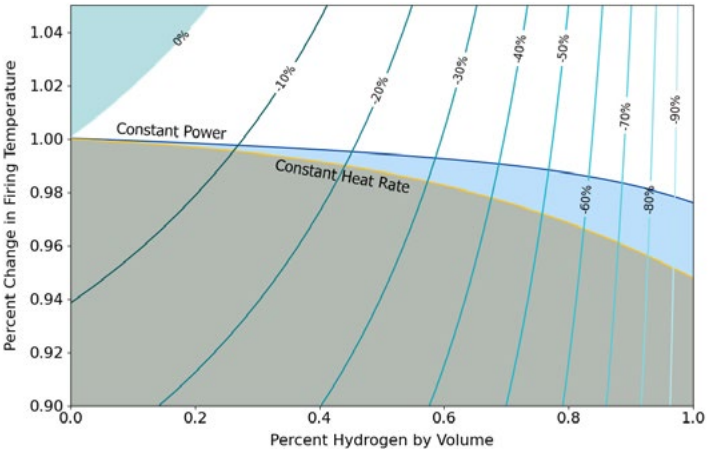


Figure 8. CO_2, performance, and efficiency typical impacts with H_2 percent increase (nominal)

At this point, it is important to realize that mass NOx production or some energy weight ppmvd is volumetric and should be a comparison focus because volumetric corrections artificially increase NOx values [3, 4]. Typically, emission-regulated pollutants, such as NOx and CO, are reported on a dry basis with correction to a constant oxygen percent. Because both water and excess oxygen increase in the exhaust, this results in corrections that inflate the reported corrected emissions. Figure 9 shows the trend of the correction factor typically used versus the CO_2 percent in the exhaust.

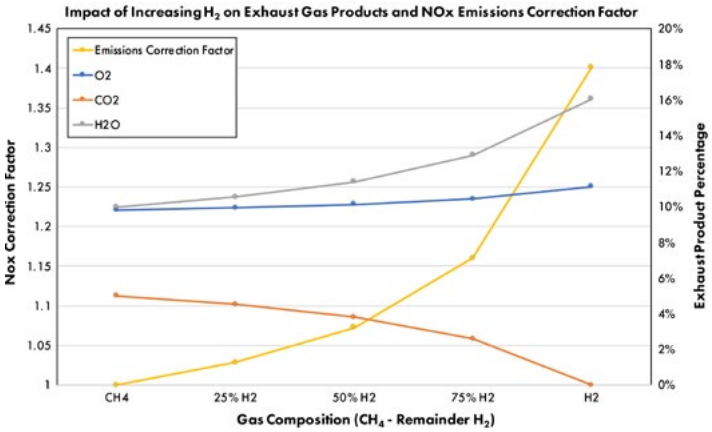


Figure 9. Emissions correction trends with CO_2% in exhaust

Direct, uncorrected NO_x emissions is a topic of active research relative to the H_2 content of fuels. It is true that the impact of H_2 can result in many detailed changes in the combustion process that are outside of the scope of this paper. To account for those changes, some fuel scheduling and control values could change. Likewise, some designs might need to be altered. Direct impacts of H_2 could result in some increase in NOx emissions; however, as indicated in this white paper, this can often be mitigated through fuel scheduling changes without negative impacts otherwise.

As detailed in this white paper, based on the increased reactivity of H_2 and the reduction in carbon for the fuel, CO emissions with H_2 have been shown to reduce dramatically with increasing hydrogen. This decrease in CO can generally serve to expand the emissions-compliant load range of the turbine by decreasing the minimum emissions-compliant load because, typically, the limit of DLN systems in low load is CO emissions (some systems might be limited by an operability limit, such as lean blowout). CO emissions typically have a negative exponential relationship to combustion

temperature, increasing dramatically as combustion temperature is decreased along with load. This was confirmed in the demonstration referred to in this white paper.

Project Background

Hydrogen fuel in gas turbines is seen as a promising bridge to a low- or zero-carbon future power system. Because it contains no carbon, H_2 as a fuel directly reduces the carbon emitted by the gas turbine. Hydrogen fuel has a long history in gas turbines being part of synthetic (off) gases, which have been used for decades. Much of the experience until now has been in older turbines, which have low power ratings and lower efficiencies. These gas turbines are equipped with combustion sections that make high regulated emissions levels (NOx, CO), which are limited by water injection and/or after-treatment in the gas turbine exhaust.

The gas turbine power industry is highly interested in H_2 fuels to reduce CO_2 emissions. This white paper provides information on the execution of the H_2-NG blending and burning project conducted at Southern Company/Georgia Power's Plant McDonough in the Atlanta, Georgia, metro area. The unit is a Mitsubishi Power M501G gas turbine with a nameplate load of 265 MW at baseload and a DLN combustion system. This plant is well suited to serve as an example to other projects given its practicality and commonality to other, modern gas turbines. The gas turbine fuel delivery modifications were done on a temporary basis given the nature of the test (proving the concept) and lack of available H_2 flowing locally that would be required to run the high level of H_2 needed to blend on a continual basis. The results of the preparation and testing execution exhibit positive results meeting the expectation of the testing. The testing showed that with proper design and review, a team atmosphere, and a receptive and engaged customer, success on a difficult goal, such as blending H_2 gas, can be achieved. These results are an example of where further steps can be taken to continue to increase hydrogen/low-carbon fuels blending.

The team members worked in conjunction to ensure that all testing could be done safely, without impacting the reliability of a commercial combined-cycle gas turbine power plant while gaining valuable information to be used now and in the future for the low-carbon and H_2 economy.

Table 1 shows the key takeaways of the project.

Table 1. Key takeaways of H_2 blending project

Test Parameter	Comparison	Results Comparison
General capability	Previous H_2 field experience	Higher blend than previously done in any combined-cycle gas turbine (20.9%)
NOx emissions	NG emissions compliance capability	Maintain emissions compliance capability with H_2 blend
CO emissions, emissions-compliant load range	Emissions-compliant load range with NG	CO emissions improved at low load, emissions-compliant load range extended to lower with H_2
CO_2 emissions	CO_2 emissions with NG	7% reduction in CO_2 with 20% H_2 blend
Gas turbine control	Relative to GT control with NG	No issues with control of GT under test conditions
Durability	Relative to durability with NG	No degradation to system hardware during short-term testing (long-term not evaluated)

The major members of the project team are as follows:

- **Southern Company, power utility**. Southern Company has oversight and approval authority, and they funded the H_2 blending project.
- **Georgia Power, site owner**. Georgia Power, a subsidiary of Southern Company, is the site owner and operator of Plant McDonough. Plant personnel also actively engaged in xecuting the safety recommendations, maintained ownership of the overall plant operation, and kept the plant within emission compliance requirements during the testing activities.
- **Mitsubishi Power, OEM and design lead**. Mitsubishi Power is the OEM for the gas turbine and was the design and design modification lead of the H_2 test. They supplied flow control system components and upgraded the control system logic, contracted the fuel supplier, led development of commissioning and the operating procedure, and led the execution of the plan.
- **Certarus, contractor**. Certarus was a contractor to Mitsubishi Power, providing the compressed H_2 gas and pressure-reduction skid.
- **EPRI, contract and design review lead**. EPRI facilitated and participated in numerous project reviews and oversaw multiple project execution tasks, including design reviews, leak testing, code and procedure reviews, and test execution.

- **Sargent & Lundy/Lectrodryer, contractors**. Sargent & Lundy and Lectrodryer were contractors to EPRI that provided a technical review of the proposed design and a review of applicable codes and standards.

System Design Modifications

The gas turbine itself was not modified for testing, and hardware modifications were limited to the fuel supply. A temporary blending system was added to the NG supply to introduce H_2 gas to the fuel sufficiently upstream of the gas turbine to allow for adequate mixing, as shown in Figure 10.

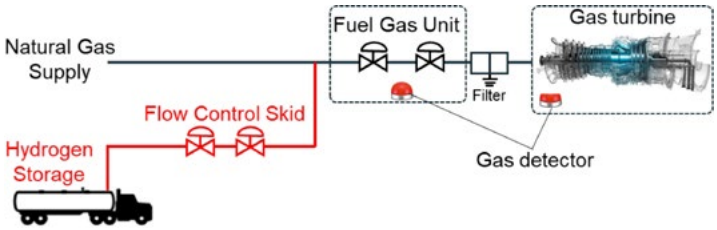


Figure 10. Plant McDonough system design update for H_2 gas blending

Safety and Code Compliance

The importance of safety during the design and execution phases of the project cannot be overstated. All team members served critical roles in ensuring that all applicable design codes and regulations were reviewed and complied with. Systems constructed specifically for hydrogen service (fuel control skids) were designed in accordance with current American Society of Mechanical Engineers (ASME) B31.12 (latest revision) piping and pipeline code, and systems adapted for hydrogen service (such as the pressure-reduction skids) were evaluated and modified accordingly to be in compliance with ASME B31.12 (latest revision) and other relevant standards and/or recommended practices (NFPA, CGA, and so on). Design drawings and fabrication procedures for such equipment were reviewed in detail by codes and standards experts in each organization and/or subcontractor. Functional testing, final inspection, and review of quality documents (that is, material test reports, welding procedure specifications and procedure qualification reports, hydro- and leak testing, and system cleanliness requirements) were performed in person by qualified personnel from each member organization. Although the project itself was intended to operate for a very short test duration of four days of H_2 blending testing, the systems were designed to comply with industry codes, standards, and appropriate safety protocols applicable to permanently installed and operated systems.

Work was performed in a cohesive environment where members from all organizations were encouraged to review all required data/documentation and provide the feedback necessary to ensure a safe and successful outcome. This team atmosphere and detailed review led directly to a successful test that resulted in data that will enhance the state of the art and serve as an example for future projects.

Summary and Conclusions

This white paper provides information on the Mitsubishi Power M501G H_2 blending up to ~20.9% by volume, including the results of testing as well as preparations. This project constitutes the first of a kind in blending large-volume flows of H_2 in an advanced, high-efficiency gas turbine run in combined-cycle operation. The results of this testing can lead to significant investment decisions on further H_2 blending projects in power generation. Testing results show the promise that H_2 blending holds in the energy transformation to a low-/no-carbon future.

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3002023706 August 2022

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