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High Hopes for New Green Hydrogen Power Plants in LA

An EcoMotion/ Climate Resolve White Paper

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Introduction

The purpose of writing this white paper is to find out if there are environmentally clean ways to combust green hydrogen. Not just clean in terms of CO_2 but also in terms of criteria pollutants… notably nitrogen oxides (NO_x).

This research was instigated by a local consideration: The City of Los Angeles has proclaimed that it will green its power sector to zero carbon emissions by 2035. Admirable, and ten years ahead of California's most progressive policy. But to do so, Los Angeles Department of Water and Power (LADWP) will need to use green hydrogen in peaker plants and potentially for baseload generation.

The challenge at hand is that when green hydrogen is combusted, just like natural gas, it produces nitrogen oxides. Thus, using green hydrogen cleans the air in terms of CO_2 but not in terms of NO_x. The hydrogen itself may be green… produced by renewable power sources like offshore wind and excess daytime solar…. but can the production of this criteria pollutant be mitigated or even eliminated?

Green hydrogen is produced through electrolysis which splits water (H_2O) into its two constituent ingredients, hydrogen and oxygen. But when it burns in the presence of air it's problematic from an NO_x standpoint. Burning hydrogen can result in more NO_x emissions than natural gas combustion.

So we dig in. Does burning hydrogen result in significant NOx levels? Right now, LADWP-owned powerplants contribute 0.4% of NO_x emissions in the Los Angeles Basin, approximately 200 metric tons annually. Would this go up if hydrogen were burned? Are there other criteria pollutants in play? How about remedies? Are there safe means for green hydrogen peaker plants to meet growing electricity peak demands? How about baseload plants? Is the technology available? How much would that cost?

Hydrogen Basics

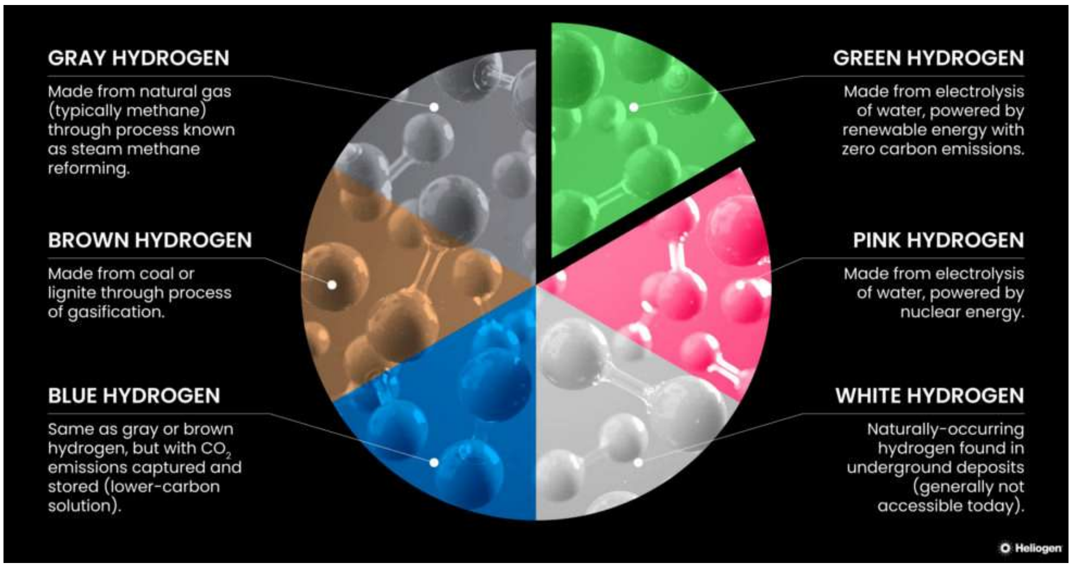
Hydrogen is the most abundant element on Earth. It has a huge benefit as a fuel source; it is a combustible element with relatively high energy density. One kilogram of hydrogen, 2.2 pounds, yields the same amount of energy as 1 U.S. gallon of gasoline which weighs 6.2 pounds.

But to get it, you have to take a feedstock which contains hydrogen and release the hydrogen.[1] This takes energy. Then you have a gas that can be stored. It can be piped. It can be used in fuel cells and it can be combusted. Fuel cells generate power with zero emissions other than water. They can power cars, and buildings, and industries and power plants. But they are expensive… so a second choice application of hydrogen is considered and applied: combustion.

[1] "What's the difference between hydrogen fuel cells and hydrogen combustion?" Carbuzz, Robert Biermann, November 22, 2023.

Sourcing Hydrogen

The rainbow of colors! All sorts of means of getting hydrogen. Wikipedia reports that at the end of 2021, 96% of global hydrogen production was from fossil fuels: natural gas (47%), coal (27%), oil (22%), and only 4% from electrolysis in which water is split into hydrogen and oxygen. Most hydrogen is produced using a process called steam reformation heated by fossil fuels. It is the most established and cost-effective method of producing hydrogen gas. The result is hydrogen that costs $1.30 - $1.50 per kilogram. Green hydrogen, also known as green electrolytic hydrogen, is formed through electrolysis using electricity derived from renewable resources. Currently, the price of green hydrogen is ~$5.00/kilogram.



Source: Hydrogen in the Built Environment, Green Building Alliance

The Hydrogen Shot

Energy experts have dreamed of a solar hydrogen future for decades. The challenge we face to realize this dream is getting enough green hydrogen. The U.S. Department of Energy is promoting green hydrogen through a $9.5 billion initiative called the Hydrogen Shot. Just like the Moon Shot initiated by President John F. Kennedy in 1961, the Hydrogen Shot's purpose is to achieve the unattainable – tackling something really big – in this case driving down the costs of hydrogen fuel. The Hydrogen Shot's goal is to reduce the current price of clean hydrogen, currently at ~$5.00/kg by 80%, down to a cost of $1/kg within a decade.

Academics note that it took 40 years for solar to become cost competitive. They are hoping to achieve similar activation of hydrogen technology by helping to reduce its cost. HydroGEN is a consortium of U.S. Department of Energy labs and others focused on clean, sustainable, and low-cost hydrogen production.

Considered to be the environmentally conscious method of generating hydrogen, electrolysis occurs when water is split into hydrogen and oxygen gasses using electricity. Since this process is powered by electricity, it can be carbon neutral if it is made using renewable energy sources. Currently, electrolysis has a high efficiency and is a mature technology that can be implemented on a large scale. The major downsides of this process are the costs and the low availability of excess renewable electricity.

Hydrogen Challenges

The promise that hydrogen holds is great. There are, however, challenges related to hydrogen even if it is green and assuming it's available: It is hard to transport. It needs high pressure for transport as a gas, or very low temperatures to be stored as a liquid. Due to hydrogen molecules' small size, hydrogen can infiltrate metal pipe structure and make the metal more susceptible to cracking, called "hydrogen embrittlement." When hydrogen is leaked it becomes an indirect greenhouse gas as it combines and forms methane and tropospheric ozone.

Downsides of Hydrogen

- Limited availability
- Difficult to harness
- Energy intensive to produce
- Gaseous storage inefficiencies
- Liquid hydrogen storage temperatures

Combusting Hydrogen

Hydrogen can be used in different ways. The most environmentally preferable means is using hydrogen in fuel cells. In that scenario, neither CO_2 nor NO_x are released. There is no combustion, instead power is created electrochemically. While fuel cells are silent and reliable, they are expensive, typically used for baseload applications, and their performance suffers in cold weather conditions.

Because of the limitations of fuel cells, some advocate that there are applications where it is necessary to combust hydrogen, that combusting hydrogen may be key to a clean energy future marked by green vehicles, buildings, and industries.

But an oft-cited European research paper – let's call it "the 6x study" – stated that burning hydrogen-enriched natural gas results in as much as six times that of methane, dangerously high levels of nitrogen Combusting Hydrogen

While there may be an increase in Nox in certain combustion applications, some experts believe that the "6x research" was significantly flawed, that it was based on computational fluid dynamics modelling of simple diffusion combustion, versus physical field study, and that it was not peer reviewed. More importantly, some say, is that the "6x-study" has been misinterpreted – or at best that its conclusions have been promulgated without explanation. With advanced technology, such as pre-mixed fuel, lean fuel ratios, and advanced scrubbers, the amount of NOx produced is far less than the 6x research suggests.

Hydrogen for Vehicles

There has been considerable attention on using hydrogen to replace fuel in cars and trucks. Toyota has been a leading company promoting hydrogen. Its Mirai is a hydrogen fuel cell-powered vehicle. It is not alone. There have been dozens of prototype fuel cell electric vehicles. Manufacturers of trucks are also trying to get ahead of zero emissions requirements in Europe and the States, particularly California. As these become more stringent, fuel cell electric vehicles make more and more sense.

Hydrogen has been used in cars with internal combustion engines, modified versions of traditional gasoline-powered internal combustion engines. No CO_2 is produced. Pure hydrogen contains no carbon, thus there are no carbon-based pollutants. There is no carbon monoxide (CO), no hydrocarbons HC, and no CO_2 in the exhaust. But in the presence of air – which is predominantly nitrogen – these engines produce NOx. H_2ICE engines are just like kerosene, gasoline, diesel, and natural gas-powered engines. They produce NO_x emissions. Thus, hydrogen combustion engines are not zero emission.

Hydrogen for Power Plants

In 2023, 43% of U.S. electricity generation was powered with natural gas-powered power plants, 16% was coal.[2] Many of the gas plants can be updated, repowered, and converted to use green hydrogen. Their costly infrastructure can be repurposed. Green hydrogen can cut emissions to zero for carbon dioxide, carbon monoxide, sulfur oxides, volatile organic compounds, and particulate matter. And unlike the German study that suggested a 6x increase over natural gas combustion, "With appropriate treatment it is possible to maintain emissions of nitrogen oxides resulting from green hydrogen combustion at or below levels from the combustion of fossil-derived fuels on a kilowatt-hour basis."[3]

The City of Los Angeles has a goal – a stretch goal indeed – to be carbon free by 2035. That's ten years ahead of the State of California's decree for a carbon-free power sector by 2045. Martin Adams, former Chief Engineer and General Manager at LADWP, stated that there is "no way" to get to 100% renewable energy without hydrogen in the mix.[4] "Power to gas" is the notion of using stored hydrogen as a fuel for peaker plants and potentially even for baseload plants. That may be true, but environmentalists are concerned about this because burning hydrogen at peaker plants will cause other harmful pollutants… notably nitrogen oxides.

The quest for green hydrogen power production is not only local. The International Energy Agency Energy Outlook 2023 reported that to achieve a net zero global power system by 2050, it will require the use of hydrogen, fully 17 MT of hydrogen by 2030 and 51 MT by 2050. The question is whether this will feed fuel cells or combustion.

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[2] Statista, Distribution of Electricity Generation in the United States from 2007 - 2023, by Fuel Type, March 2024.

[3] Green Hydrogen Guidebook, Second Edition, Green Hydrogen Coalition, April 2022, page 23.

[4] Martin Adams, Chief Engineer and General Manager, Los Angeles Department of Water and Power, Green Hydrogen Guidebook, Second Edition, Green Hydrogen Coalition, April 2022, page 24.

Utility Operations

Smog, the presence of photochemical oxidants in the air, is a huge challenge to human health. As such, in Southern California there is a program to reduce use of power plants and industrial facilities during peak ozone periods. Nitrogen oxides are culprits, and thus combusting fuels – even hydrogen – can be at odds with environmental objectives, especially during peak power and peak ozone periods. Given Ozone Ambient Air Quality Standards, Southern California neighboring utilities use an allowance-based, ozone-season trading scheme.

The Environmental Protection Agency (EPA) and organizations like it in the European Union are focused on minimizing harmful emissions. Utility companies are faced with the challenge of employing the most efficient and cost-effective strategies for compliance with the regulations they impose. NO_x control in the United States, European Union, and Asia specify NOx emission limits of 30 - 200 mg/NM3, milligrams per cubic nanometer. Seasonal "good neighbor" rules minimize NO_x during high-smog months and "ozone season."

The U.S. Department of Energy reports on multiple mitigation strategies to prevent or reduce NO_x emissions. NO_x can be reduced using existing and emerging technologies. Flue gas treatment approaches convert harmful emissions into less harmful compounds using processes similar to those in the catalytic converters currently integrated into gas and diesel-powered vehicles. These "scrubbers" can remove up to 95% of the nitrogen oxides.

Environmental Justice

California used to have about 1,000 power plants. Now there are many more given the plethora of distributed generation. "Peaker plants" are those operated for relatively short periods to address peak demand. Half of the 80 peaker plants in California are located in areas designated as disadvantaged communities due to high cumulative socioeconomic, environmental, and health burdens. Environmental justice makes the issue of NO_x from hydrogen combustion that much more profound.[5]

Nearly one-half of all Americans—an estimated 150 million people —live in areas that do not meet federal air quality standards. Poor air quality directly results from emissions produced by the burning of fossil fuels for energy, especially diesel and coal, which release gasses and chemicals into the air with serious adverse health effects. Unfortunately, too often the burden of poor air quality is concentrated in lower-income neighborhoods and communities of color.

[5] "California Peaker Power Plants: Energy Storage Replacement Opportunities," PSE Healthy Energy, May 2020.

Even when controlled using the best available technology, nitrogen-oxide emissions from hydrogen-fueled peak power plants will be concentrated in areas of high-density housing, often associated with low-income households. This widens the inequality of exposure to criteria pollutants.[6]

Prioritizing NO_x Abatement

Jack Brouwer, Professor in the Civil Engineering and Aerospace program at University of California Irvine, has stated his preference is zero emissions technologies.[7] He cannot support permanent solutions that increase NO_x emissions. But he stressed that NO_x emissions from power plants are very low compared to emissions from trucks and the movement of freight. NO_x emissions from power plants currently represent less than 1% of the total NO_x emissions in the LA Basin. To limit and cut NO_x, policies need to focus on those sectors that are responsible for the most NO_x.

The biggest sources of NO_x emissions are diesel trucks, airports, and ships at port. For that reason, Brouwer is proud of the California Regional Hydrogen Hub, a project that will deliver hydrogen in the Los Angeles area. But power plants are not prioritized for this new and premium fuel. Instead, the Hub has prioritized this premium fuel for diesel trucks, freight transport, airports, and ports emissions. Cutting NO_x in these segments will make the biggest difference.

Electricity enables green mobility,
and the decarbonization of our buildings and industries. Green power,
and its resulting transformations, is at the core of climate action.

Like Jack Brouwer, LADWP has its eyes on overall NO_x emissions in the LA Basin. NO_x from in-basin power plants is very small, again, less than 1% of overall NO_x emissions. And consider the benefits that electricity unlocks and provides: Power plants delivering reliable power helps our society achieve and enable electrification of vehicles. They enable electrification of buildings. Power plants are making possible the cuts of emissions in these tougher, more important sectors.

The Ultimate Solution: Fuel Cells

So now, let’s say that you have ample and competitively priced green hydrogen, and it’s time to use it. Fuel cell use is preferable because fuel cells only emit pure water vapor. They use an electrochemical reaction instead of combustion. There is no flame. Even high-temperature fuel cells operating up to 1,000 degrees Celsius do not create harmful emissions. But it’s expensive technology and generally a baseload technology as most fuel cells at this time cannot be ramped up and down to meet peak demand.[8]

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[6] “Pollution from Hydrogen Fuel Could Widen Inequality,” Nature, July 13, 2021.

[7] Dr. Jack Brouwer, University of California Irvine, Civil Engineering and Aerospace, Personal Communications, November, 2024.

[8] Energy Information Agency, “Annual Energy Outlook 2023, Table: Table 55. Overnight Capital Costs for New Electricity Generating Plants,” 2023

That said, fuel cells hold great promise. With heat recovery, they can be 70 - 85% efficient.[9] That compares favorably with traditional, simple-cycle combustion technologies which have an efficiency of 35 - 40%.[10] Fuel cells are twice as efficient as conventional generation technologies, and they can be powered with a variety of fuels… biogas, electrolytic hydrogen, natural gas, propane, and methanol. The space program has a history of fuel cell use given the technology's near zero emissions at the point of operation. Fuel cells draw in oxygen in the presence of a fuel and silently generate power. They do not release CO_2 or NO_x.

There are lots of examples of fuel cells in action. There are four primary types that are commercially available:

- First, solid oxide fuel cells operate at high temperatures. Bloom Energy uses this technology, tapping the waste heat for fuel reformation at the front end of its process. In other cases, "waste heat" from fuel cells is recaptured for domestic heating.
- Second, phosphoric acid fuel cells are currently being used to provide power to office buildings, hospitals, nursing homes, banks, schools, and utility power plants. In Anchorage, Alaska the mail processing facility uses fuel cells' waste heat for space heating.
- Third, molten carbonate fuel cells are generally utility-scale, 300 kW to 3 MW in size. The Santa Rita Jail Complex, for example, has a 1 MW fuel cell.
- The fourth common form of fuel cell is polymer electrolyte membrane fuel cells, also known as proton exchange fuel cells. They operate at low temperatures and are suited for automotive and small stationary applications. They have also been configured for 1 - 100 kW back-up power systems.

South Korea is home to the world's largest hydrogen fuel cell power plant. It is located in the western port city of Incheon. There, large tanks of liquid hydrogen feed into thousands of hydrogen fuel cells. These cells are solid structures containing an electrolyte fluid and two terminals much like batteries. Reactants flow into the cells, hydrogen and oxygen intermingle with electrolyte to produce electrical charge. Water is the only other byproduct. The 79 MW "eco-friendly power plant" uses Doosan fuel cell technology. It was put in service in 2021.

Jack Brouwer is a fan of fuel cells but he is pessimistic about them being cost-effective anytime soon. When pressed, he said that he expects that it will take two decades before they are cost-effective.[11] While the cost of electrolysis is going down, fuel cells won't financially compete with combustion turbines for some time.

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[9] U.S. Department of Energy, Fuel Cell Technologies Office, "Hydrogen and Fuel Cell Technology Basics."

[10] Note that combined-cycle technologies are ~50 – 60% efficient. Utilities such as LADWP use these more advanced turbines routinely to save fuel and minimize emissions, relying on simple cycle units only during extreme peak periods.

[11] Dr. Jack Brouwer, ibid.

Mitigating Nitrogen Oxide Emissions

So, we are back to combusting hydrogen and addressing its issues. Combusting hydrogen will not result in CO_2 emissions but does result in NO_x. Emissions related to combusting hydrogen are problematic. Harmful emissions form during high temperature combustion, greater than 1,500 degrees Celsius in air. When comparing hydrogen use to natural gas use, hydrogen can be the same or even worse.[12] So combustion of green hydrogen can be carbon-free but not thoroughly clean and green.

The nitrogen oxides include nitric oxide (NO) and nitrogen dioxide (NO_2). These gasses contribute to smog formation – causing the reddish haze in smog – and acid rain. They also affect tropospheric ozone. How are they formed? Oxygen and nitrogen do not react at ambient temperatures. But at high temperatures they undergo an endothermic reaction, absorbing heat, producing oxides of nitrogen. This occurs in engines, power plants, and during lightning storms.

The nitrogen oxides (NO_x) are the world's forgotten greenhouse gasses. They constitute the third most emitted greenhouse gasses after carbon dioxide and methane. They are 300 times as potent as CO_2 and the NO_x concentration is rising. NO_x damages the ozone layer which prevents harmful ultraviolet rays from reaching the Earth's surface. NO_x also causes asthma attacks, respiratory illness, and irritation to mucus membranes in humans and other animals.

Because hydrogen burns at higher temperatures than natural gas, combustion of pure hydrogen may result in higher NO_x emissions. But apparently this is not always the case.[13] Jack Brouwer responded to our query about whether it is correct that burning hydrogen results in more NO_x emissions than natural gas. "No, not necessarily. It's complicated," he said. Yes, there are some circumstances where you make more emissions, but in other cases it can be less. It depends on whether the hydrogen is "pre-mixed" with air or is using a "diffusion-type flame." And it depends on whether the resulting NO_x emissions are "scrubbed."

Selective Catalytic Reduction

Selective Catalytic Reduction (SCR) was developed in the 1950s and then matured in the 1970s. SCR is a post-combustion treatment process that reduces NO_x emissions in exhaust gasses. A Japanese company, IHI Corporation, installed SCR at a power plant in 1978 in Germany. The result was better air quality, decreased smog formation, and lower acid rain levels.

SCR is a process that converts nitrogen oxides, with the aid of a catalyst, into diatomic nitrogen and water. The process also involves a liquid "reductant," either anhydrous ammonia (NH3), aqueous ammonia (NH_4OH), or a urea solution (CO/NH_2). The catalysts take many forms: There are "base metal" catalysts that use vanadium and titanium; "zeolite-based" catalysts using iron-exchanged and copper-exchanged zeolites

[12] Forbes, "Estimating the Footprint of Carbon Production" 2023

[13] Dr. Jack Brouwer, ibid.

(often used in power plants); and "precious metal" catalysts. The latter can operate at lower temperatures but are more expensive and are used for cars.[14]

Selective Catalytic Reduction for NO_x is common in large utility boilers, industrial boilers, and municipal solid waste boilers. SCR can reduce NO_x by 70 - 95%. Recent applications are diesel engines on ships, diesel locomotives, and gas turbines. In power stations, SCR removes NO_x from the flue gas of boilers. The "reductant" is injected into the catalyst chamber. Temperature control is critical. In the presence of a catalyst, nitrogen oxides are broken down.

Automotive Catalytic Converters

Let's consider catalytic converters in cars. A work colleague has had two stolen right out from underneath his Prius that was parked in front of his house. Why? Precious metals are the catalysts in the converters. They reduce carbon monoxide (CO), hydrocarbons (HC), and nitrogen oxides ($NO_{x)}$. Palladium, platinum, and rhodium facilitate the reduction of NO_x.

Most modern cars are equipped with three-way catalytic converters… referring to the three regulated emissions that they mitigate: CO, unburned HC, and NO_x. A typical catalytic converter for a car is about the size of a toaster. It's in line in the exhaust system, often tucked under the passenger seat. It takes two hands to hold one. Inside, there are two different types of catalysts at work: a reduction catalyst and oxidation catalyst. Together they are formed in a ceramic structure.

Catalytic converters require heat, so when internal combustion engine cars start up, the catalytic converters are inoperable. Inside the converter, when a NO_2 molecule contacts the catalyst, the catalyst rips the nitrogen from the oxygen, freeing oxygen in the form of O_2. The nitrogen atom then bonds with another nitrogen atom to form N_2. From a design standpoint, the idea is to get the maximum surface area of the catalyst to the exhaust stream, while minimizing the amount of expensive catalyst required.

The Environmental Protection Agency introduced significant federal regulation pertaining to auto and truck emissions in 2007. Then, in 2010, the regulations became stricter for NO_x. For trucks to fuel their catalytic converters, reductants are sold in jugs at truck stops, often a DEF (Diesel Exhaust Fluid) urea solution. It's available at Costco. At some truck stops, there are DEF dispensers near trucks' fuel pumps.[15]

Jack Brouwer explained how catalytic converters in cars work. They need no injection of reductants – ammonia or urea or DEF to cut their NO_x. Most cars do not emit much NO_x emissions as they have relatively low compression ratios. Trucks have a higher compression ratio and this causes more NO_x emissions. Thus, trucks have to use the reductant. Mercedes Benz diesels today, he says, use a DEF fluid that customers buy to refill a reservoir like windshield wiper fluid.

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[14] "Selective Catalytic Reduction (SCR) Technology," Guide to Selective Catalytic Reduction Technology, February 25, 2024.

[15] Mark Quasius, May 1, 2013, "2010 EPA Emissions Standards and Diesel Exhaust Fluid," FamilyRVing.

Blending Hydrogen and Natural Gas

There are two forms of hydrogen generators: The first relates to producing the hydrogen fuel itself. The second type takes the hydrogen fuel and uses it to generate electricity.[16]

The combustion of hydrogen in power plants is the focus of considerable research. Much of the focus has been on blending hydrogen into natural gas, incrementally greening power production. Siemens and all the major turbine manufacturers are exploring this, testing higher and higher concentrations of hydrogen, preparing for carbon-free operations.

There are critics of blending hydrogen into natural gas for power plants. Just as proposed injections of hydrogen into the natural gas grid also come with the claim of being green, they say that utilities may be blending in hydrogen to keep gas plants running and extending their lives, under the guise of going green. This has raised concerns of environmental justice. Advocates do not want neighborhood power plants to be the test sites for different fuels that may create new and different problems. In particular, they do not want to compromise local air quality with nitrogen oxide.

General Electric (GE) gas turbines have been operating on hydrogen and similar low BTU fuels for more than 30 years. GE claims more than 4.5 million operating hours on these fuels. GE boasts several projects, one at the Daesan refinery in South Korea. It has operated on a 70% hydrogen fuel blend for 20 years. ENEL's Fusina plant in Italy used a GE turbine to operate on a fuel that was more than 98% hydrogen by volume.

With funding from the U.S. Department of Energy, GE has developed a low-NO_x hydrogen combustion system. It is based on the operating principle of a small-scale jet in crossflow mixing of the fuel and air streams, what GE calls "advanced pre-mixing capability." It is now available in GE's 9HA turbine. GE is now focused on its 50% hydrogen engine.

MHPS is a joint venture between Hitachi and Mitsubishi Heavy Industries. It has been using 30 - 90% blends of hydrogen in its test power plant since 1970. Its tests have spanned 3.5 million hours. A key research challenge has been to reduce NO_x emissions from hydrogen combustion without compromising efficiency.

Because hydrogen has a higher flame speed compared to natural gas, MHPS engineers seek to reduce risk of "combustion oscillation" and "flashback" (backfire) in higher hydrogen mixes. One solution it tested uses a "diffusion combustor" for injecting fuel into air. The combustor reduces NO_x using steam or water injection. In some tests, this reduced NO_x by 10% compared to conventional combined-cycle gas turbines.[17]

Utility-scale Wartsila reciprocating engines are produced in Finland. They can run on 30% hydrogen now; the company plans to have a unit that will burn 100% hydrogen in 2025. Wartsila routinely equips its units

[16] "How does a Hydrogen Power Plant Work?" Sciencing, John Albers, April 24, 2017.

[17] "High Volume Hydrogen Takes Shape," Power, May 1, 2019, Sona Patel, Associate Editor.

with pollution control. The Wartsila NO_x Reducer (NOR) is an emission after-treatment system that uses oxidation catalyst units. While reciprocating engines can be low-NO_x in operation, they have the challenge of keeping emissions down when the engines are operated with lots of starts and stops, ramping up and down generating capacity. This form of operation causes emissions to be greater.[18,19]

Advanced Hydrogen Combustion

Combustion turbines have been used by utilities for decades to meet peak demand. They are rarely run but their operation is essential during extreme peak periods. Affectionately known as "CTs," they are inexpensive. But in their simplest, least-cost form, they are highly polluting.

Fortunately, there are ways to equip CTs with advanced pollution control technology. There are means to cut NO_x emissions… before the fuel enters the combustion chamber, inside the combustion chamber, and in the stack as gases are exhausted. There are several key factors to do so. For instance, CTs typically have "non-pre-mixed flames." This form of combustion causes significant levels of NO_x. But there are other factors as well such as the air-fuel ratio, the flame spread and angle, and the compression pressure.[20]

Means to Minimize NOx

- Create lean burn, reducing oxygen in the fuel-to-air mixture
- Manage the combustion temperature
- Use pre-mixing technology
- Use sophisticated flame control
- Decrease flue gas residence time in the high temperature zone
- Employ "secondary abatement" using catalytic converters

Hydrogen has many unique properties that make it suitable for combustion: Hydrogen has a wide flammability range, it can be combusted in a wide range of fuel-air mixtures. Running on a lean mixture means that the amount of fuel used is less, resulting in a greater fuel economy. Hydrogen's larger "stable combustion temperature range" allows for a higher air-to-fuel ratio. This diluted hydrogen cools off the flame and results in lower-temperature combustion, thereby reducing the amount of NO_X emissions produced. Research has shown that hydrogen combustion can achieve comparable performance and NO_x emissions to those of today's turbines running on pure natural gas.[21]

CTs can be configured with pre-mixed fuel too. Hydrogen's high auto-ignition temperature enables higher compression ratios in a hydrogen engine compared to a hydrocarbon engine. A higher compression ratio

[18] Dr. Jack Brouwer, ibid.

[19] Chris Heck, Engineer, Wartsila Power Systems, Personal Communications, November 2024.

[20] "Understanding hydrogen combustion and NOX emissions," Feb 23, 2024, SLR, Greg Altria and Hannah Jacobs.

[21] "Does the use of hydrogen produce air pollutants such as nitrogen oxides?" Fact Sheet from the Hydrogen and Fuel Cell Technologies Office, Office of Energy Efficiency and Renewable Energy, USDOE.

results in greater thermal efficiency, or less energy loss during combustion.[22] This however, results in more NO_x unless carefully controlled.

There has been considerable research on mitigating NO_x during hydrogen combustion. Some of it explores the flow characteristics and fuel mixing in a pre-mixed tube leading to the combustion chamber. Simulations have been conducted to investigate the impact of spray angle, spray pressure, and fuel-to-air ratio on fuel atomization, fragmentation, and fuel-air mixing efficiency.

- Spray Angle: The findings highlight the critical role of the spray angle in fuel atomization and breakup. Increasing the spray angle enhances atomization, resulting in smaller fuel droplet sizes and improved fuel-air mixing.

- Spray Pressure: Additionally, spray pressure significantly influences particle diameter, velocity, and turbulent kinetic energy. Higher spray pressures promote efficient atomization, fragmentation, and smaller particle sizes, enhancing fuel dispersion and mixing.

- Swirl Motion: In addition to spray pressure, the swirling motion induced by airflow and lower fuel-to-air ratios enhances fuel atomization and breakup, resulting in finer spray characteristics. These insights contribute to optimizing spray angle, pressure, and fuel-to-air ratio, ultimately improving fuel injection systems, combustion efficiency, and emissions reduction across various applications.

- Atomization of Fuel Droplets: The performance and emissions of turbine engines are highly influenced by fuel atomization and mixing processes. Atomization of liquid hydrogen is a process that transforms the fuel into fine droplets before introducing it to the air stream for mixing. This process, primarily controlled by the spray angle and pressure, significantly influences the mixing characteristics and combustion efficiency.

- Premixing Fuel Injectors: A new premixing fuel injector for high-hydrogen fuels was designed to balance reliable flashback-free operation, reasonable pressure drop and low emissions. The concept relies on small-scale jet-in-crossflow mixing that is a departure from traditional swirl-based premixing concepts.

Interest in hydrogen as a primary fuel stream in heavy-duty gas turbine engines has increased and has led to working to find means to cut NO_x emissions. The U.S. Department of Energy has funded the Advanced IGCC/Hydrogen Gas Turbine Program since 2005 with an aggressive plant-level NO_x target of 2 ppm at 15% O_2 for an advanced gas turbine cycle. Approaching this NO_x level with highly reactive hydrogen fuel at the conditions required is a formidable challenge that requires sophisticated combustion technology.

[22] Reference: Airbus, 26 November 2020, "Hydrogen Combustion, explained," www.nature.com › articles › d41586/021/01926-8.

Addressing LA's Peak Demand

The City of Los Angeles is leading the charge to go green. The City aims for its municipal utility - Los Angeles Department of Water and Power – to be carbon free by 2035, ten years ahead of California's utility requirement. And note that SB 100, which requires the State's utilities to be 100% renewable and carbon-free by 2045, is defined as a percent of electricity sales. LADWP's goal is more stringent, to be 100% carbon-free as a percentage of generation. LADWP is a transmission-rich power system, serving 10% of the State's load with 25% of the State's transmission. With system losses up to 10% losses, LADWP's goal is an even-more accelerated than the State's SB 100 requirement.

Some experts believe that the only way for Los Angeles to meet its most serious peak demands in 2035 is to combust green hydrogen in peaker plants. The concern from the environmental community is that if hydrogen combustion is used in power plants, they will emit nitrogen oxides and disproportionately so in disadvantaged communities. A member of Food and Water Watch has already described hydrogen use as, "fundamentally racist and inequitable."

Los Angeles Plans for Green Hydrogen

Los Angeles Department of Water and Power plans to ready its Scattergood Generating Station Units 1 and 2 for hydrogen in its current plant modernization project. LA's 100% Renewable Energy Study (LA100) makes clear that hydrogen-ready provisions at Scattergood and other plants are required to assure a carbon-free system by 2035. The units must have the capability to use renewable-derived fuel.[23]

Scattergood is LADWP's second-largest in-basin gas-fired power plant. It is located along the coast in El Segundo. It will be the first to be modernized to be hydrogen capable. Ultimately, other plants may also be converted: Harbor and Haynes and Valley generating stations. Their conversion to being hydrogen ready has not been determined yet and will be contingent on additional studies, technology and infrastructure development, stakeholder engagement, and other influencing factors.

Comparing Power Plant Costs and Emissions

This paper questions whether concerns about combusting green hydrogen have basis. Yes, if SCR technology is used on the peaker plants, there will be 75 - 95% less NO_x produced. The table below shows the relative costs of power plants. There's a wide variation in cost per kilowatt of generating capacity, a cost differential that utility executives and ratepayer advocates know well. Note the extremely low cost of simple-cycle and combined-cycle CTs.

[23] "Scattergood Generating Station Units 1 and 2 Green Hydrogen-Ready Modernization Project," LADWP Press Release, 2023.

The Relative Costs of Power Plants

Technology	$/kW	NO_x (pounds/MMbtu)	CO_2 (pounds/MMbtu)
Coal without carbon capture	$4,103	0.06	206
Coal with 95% carbon capture	$7,346	0.06	10.3
Aeroderivative CTs, simple cycle	$1,606	0.0075	117
Combustion turbines, simple cycle	$836	0.0075	117
Combined-cycle turbines	$921	0.0075	117
Advanced nuclear	$7,861	0	0
Small modular reactor	$8,936	0	0
Onshore wind	$1,489	0	0
Offshore wind	$3,689	0	0
Solar PV single-axis tracking	$1,502	0	0
Solar with battery storage	$2,175	0	0
Battery energy storage	$1,744/$436/kWh	0	0

The values in the table above are from the U.S. Energy Information Administration data published in December 2023. They show the relative costs of generating technologies, some baseload, others renewable and intermittent.[24] For this article, we focus on the suitable technologies to address peak load… fuel cells, combustion turbines, and battery energy storage.

Fuel cells are not presented in the table above. The cost of fuel cells is as high as $8,000/kW, on par with nuclear reactors Researchers believe that the goal to drive down fuel cells' cost to $2,000/kW is attainable. South Korea's Incheon fuel cell installation cost was $3,698 per kilowatt of capacity. On the upside, that plant also provides heat for 44,000 households, partially offsetting its capital cost which is 4.4 times the cost of the basic combustion turbine cost.[25]

The hydrogen fuel cell configuration tops the price of a Wartsila engine solution proposed for Glendale, California. There, five units of 18.6 MW were slated to cost less than fuel cells but more than combustion turbines. Glendale Water and Power is moving forward with the engines after a lengthy Council process, to

[24] Capital Cost and Performance Characteristics for Utility-Scale Electric Generating Capacity," January 2024, U.S. Energy Information Administration, prepared by Sargent & Lundy.

[25] Hydrogen Central: Hydrogen Industry News & Market Intelligence, "World's largest fuel cell power plant was built in Korea by Kospo - 78 MW," October 27,2021.

install three units at a cost of $140 million, or 55. 8 MW at ~$2,500/kW of installed capacity.[26] This price includes SCR emissions control technology.

Ranking Technologies from Least Cost to Highest Cost

- Combustion turbines
- CTs configured with pre-mixed fuels
- Wartsila reciprocating engines
- Hydrogen fuel cells

Simple-cycle combustion turbines (CTs) cost $836 per kilowatt. That's half of batteries at $1,744/kW, and about a tenth of the cost of either coal with carbon capture ("clean coal") or building nuclear reactors. CTs have been and will be the cheap solution to having sufficient capacity to meet peak demand. One can see why many utilities across the country would be favoring CTs, and then blending in hydrogen, and ultimately replacing gas with green hydrogen. This is the least capital-intensive form of generation. Is it the best? NO_x remains a thorny issue.

Peakers are defined in California as not operating more than 15% of the time, having a capacity factor no greater than 15%. Of the 80 so-called "peakers" in California that help meet statewide demand, 65 of these are combustion turbines, designed to ramp up quickly. Many are aging facilities, poised for retirement. When used, they exacerbate local air quality issues. They are high-emitting plants. Ten are aging steam and combined-cycle turbines that are used infrequently.

LADWP's Leadership Position

LADWP is making moves with hydrogen. It is a leader, preparing for the hydrogen future.

Its Scattergood power plant is now the subject of a repowering plan. It has become contentious. The neighborhood was looking forward to its permanent closure. One of the issues is NO_x… and whether to repower at all. The surrounding community would like it shut down. But LADWP is planning repowering and making the plant hydrogen-ready. It does not want to shutter the plant as it plays a key role in grid stability and was important to the power system during the Palisades fires.

LADWP has been studying and planning for a carbon-free future, and it has done so with the fundamental responsibility to keep the lights on. A study commissioned by LADWP and prepared by the National Renewable Energy Laboratory (NREL) cost ~$14 million dollars. It laid out a roadmap for the City to be carbon free. The roadmap included the combustion of green hydrogen during extreme conditions.

[26] Glendale Water and Power Commission Meetings; Comms with City of Glendale Councilmember, October 2024.

Due to public concern, a follow-up NREL study evaluated the potential to completely eliminate combustion at LADWP's four in-basin plants. What would life without in-basin power plants look like? Is it achievable? The second study shows that there is no viable alternative to in-basin combustion for emergency conditions. It found that to completely back out in-basin power plants would require 14 square miles of in-basin solar, huge amounts of storage (on top of LADWP's new 200 MW demand response program), and new transmission lines within the City. Without massive and unrealistic upgrades to be able to meet growing peak demand, in-basin power plants will be needed. Yes, they can be carbon free thanks to the use of green hydrogen.

What NREL made clear is that having in-basin plants is and will be essential during emergency conditions. Using green hydrogen, combusting it, may well be the way to decarbonize and to keep the grid up and running. LADWP must lead, it cannot fail the City's cutting-edge decarbonization effort. Los Angeles has become a national and international leader in electrifying mobility and buildings. And to be a leader that can be emulated far and wide, LADWP needs to continue to deliver reliable power. To do so, unless there is a new technology breakthrough of some kind, LADWP must maintain back-up emergency power generation based on green hydrogen combustion.

Already "the 6x finding" has created a tough public relations challenge. "More NO_x" is the popular perception/belief on burning hydrogen, even green hydrogen. But there will not be more NO_x. The South Coast Air Quality Management District limits NOx emissions of all power plants in the L.A. Basin to 2 parts per million (PPM). Some of LADWP's plants are operating at less than 1 PPM. LADWP's oldest in-basin plant, the Harbor Generating Station, was retrofitted in 2024 with a combustor upgrade which reduced its NO_x emissions by 70%. It now emits less than 1 PPM NO_x. Whatever green hydrogen combustion takes place must meet the 2 PPM.

To meet the SCAQMD regulations, LADWP will have to use green hydrogen production with pre-mix technologies to reduce emissions in the combustion chamber, complete with scrubbers – SCR with ammonia-based oxidation catalysts – to clear flue gases of NO_x by up to 95%.

Summary

A favorite quote from this research is, "Hydrogen is having a moment." It certainly is. There's buzz about record-breaking electrolysis plants that are built to make green hydrogen, and about fuel cells and power plants to use it and convert its energy to power.

The hydrogen industry has come a long way… and it is still rooted in the past: The primary role for hydrogen today is as a chemical feedstock, used for oil refining and fertilizer production. But stay tuned… hydrogen may well be applied broadly… from industrial applications, to long-haul aviation, maritime shipping, and heavy freight. "Hydrogen has significant, sector-spanning potential, a carbon-free fuel that can be used in all sorts of otherwise-hard-to-decarbonize applications where fossil fuels have long been considered required."[27]

To be truly pollution free, fuel cells are preferable. But fuel cells are still costly and generally used in baseload applications. This takes us to combustion. If combustion is used, NO_x has to be scrubbed. Controlling NOx emissions is critical to avoid shifting from one problem (CO2) to another (NO_x). But we caution that scrubbing is generally 75 - 95% effective. There is still a quantity of NO_x being formed and released due to hydrogen combustion. It may be true that hydrogen combustion can be as clean as natural gas combustion… but in both cases, there is NO_x, a pesky criteria pollutant.

Can there be a win-win solution between tropospheric (CO_2) and atmospheric (NO_x) issues? It appears to be a matter of cost. The low first cost of peaker plants – combustion turbines – is appealing for keeping power rates in check, yet the environmental reality persists. If hydrogen is used in peaker plants, the plants must be configured for pre-mixed fuel and fitted with advanced pollution control technology.

Recommendations

First, keep an eye on fuel cells and their declining costs. If the cost comes down enough, forget combustion of hydrogen. Forget about NO_x. And fuel cells need not be solely used as peaker plants. They can be used as carbon-free, nitrogen-free baseload plants.

The authors commend LADWP for its promotion of hydrogen coupled with the best of pollution control technology. We also recommend that LADWP make clear its commitment to caring for disadvantaged communities. With appropriate treatment, it is possible to maintain emissions of nitrogen oxides (NO_x) resulting from green hydrogen combustion at or below levels from the combustion of fossil-derived fuels on a kilowatt-hour (kWh) basis.

But let's be real: Combusting hydrogen is not as green as it seems. Even the greenest hydrogen, when combusted, creates NO_x… a criteria pollutant. This has to be mitigated to the greatest extent possible or completely avoided.

[27] "What's the Role of Hydrogen in a Clean Energy Transition?" December 9, 2020, The Equation, Union of Concerned Scientists, Jule McNamara, Senior Energy Analyst.