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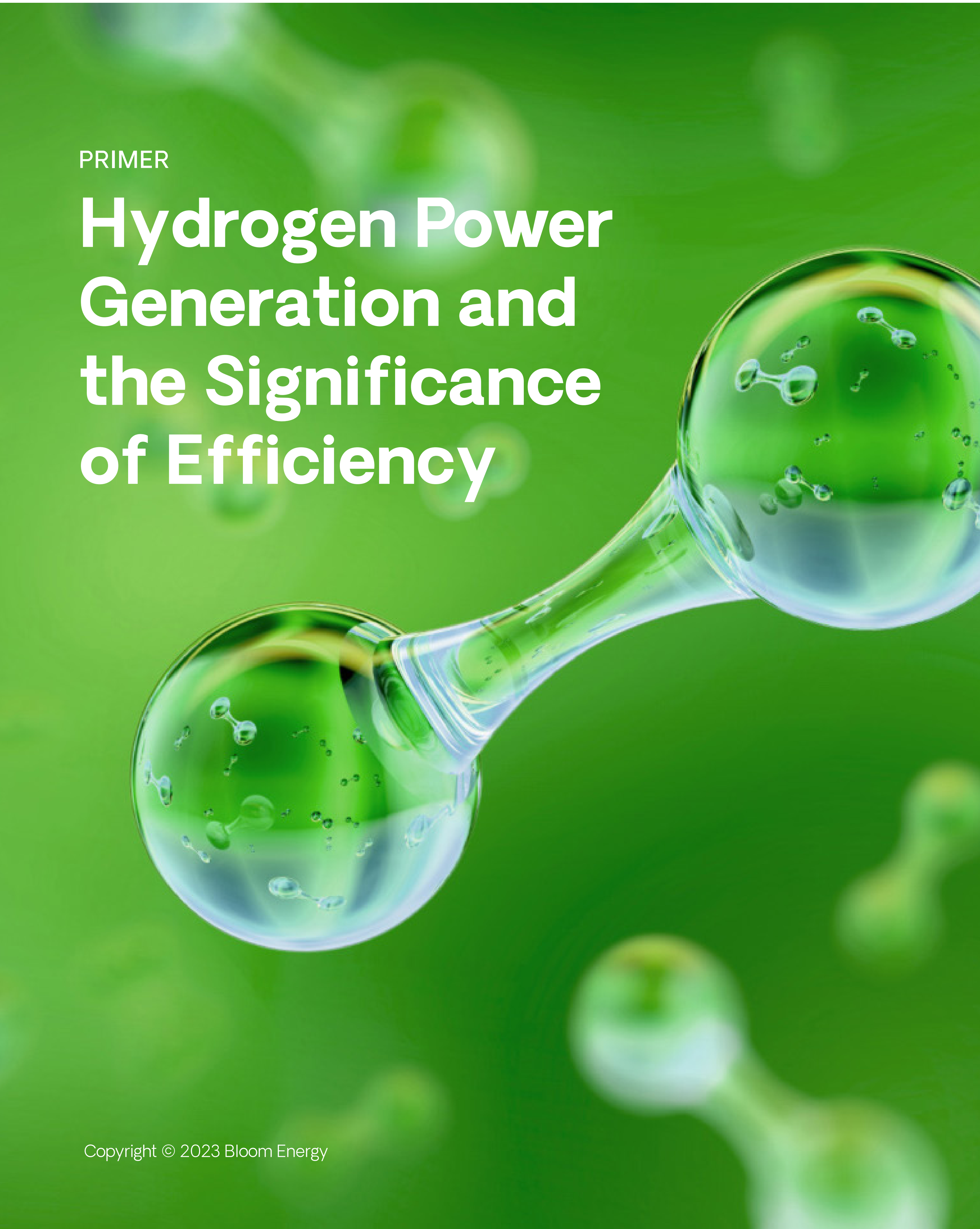
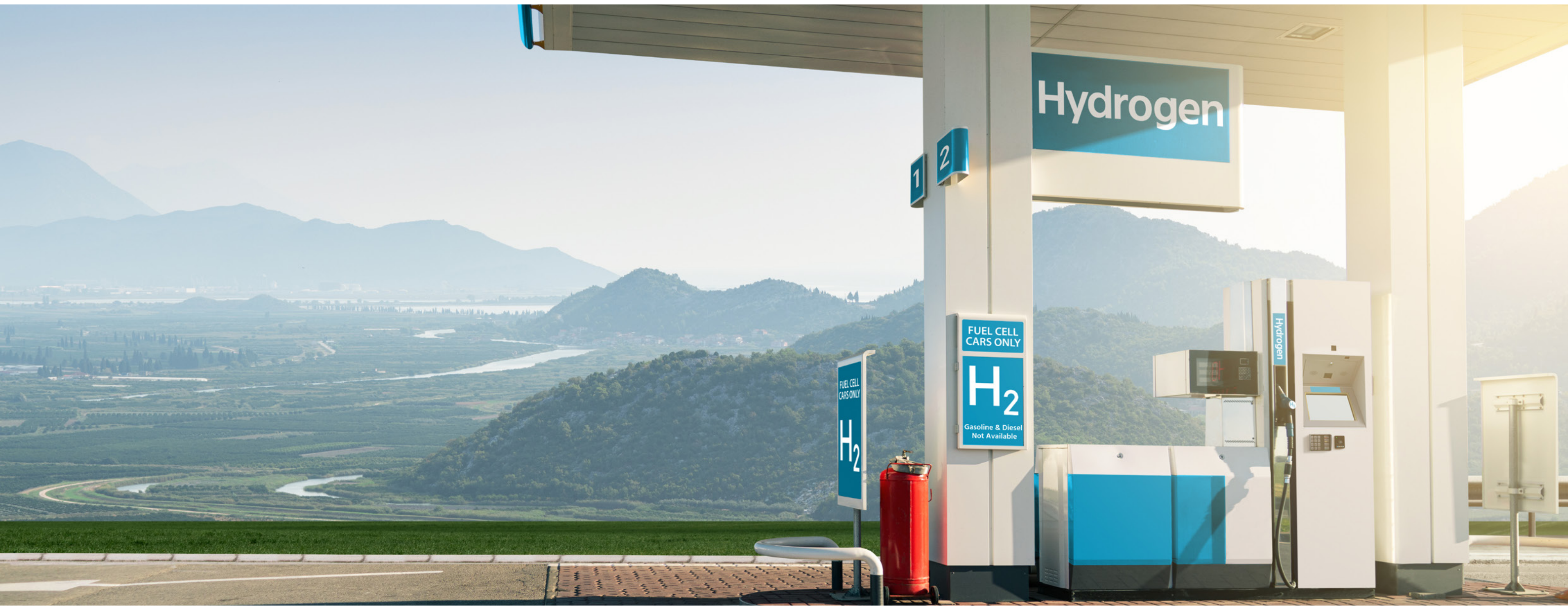
PRIMER

Hydrogen Power Generation and the Significance of Efficiency



Introduction



As the planet moves away from carbon based fossil fuels, hydrogen has become one of the most promising advanced fuels for the future, due to its high amount of stored energy per unit weight and the absence of carbon. Hydrogen atoms are found commonly in nature but not as hydrogen molecules. Clean ways to make and use Hydrogen for power generation will be critical to replace conventional methods of power production that use petroleum-based products.

The industry prevailing understanding is that hydrogen is essential to meet global decarbonization goals by 2025 across industries. The International Renewable Energy Agency (IRENA) estimates that by 2050, clean hydrogen could meet 12 percent of energy consumption,[1] and could abate seven gigatons of CO_2 emissions annually.[2] If these projections are true, both hydrogen production and hydrogen power plants are necessary to produce green renewable electricity while still maintaining a reliable grid.

In five to 10 years, green hydrogen is expected to be widely available. By one estimate, global green hydrogen capacity is expected to rise 280 times by 2030, with the price falling 40% by 2025.[3] In the U.S., the U.S. Government in June 2021 launched the Hydrogen Energy Earthshot initiative, aiming to reduce the cost of clean hydrogen to $1 per kilogram in one decade.[4]

As some companies work to ramp up green hydrogen production, other companies are working on sustainable

[1] Source: IRENA analysis.
[2] Source: McKinsey analysis https://www.mckinsey.com/capabilities/sustainability/our-insights/five-charts-on-hydrogens-role-in-a-net-zero-future
[3] Source: https://www.forbes.com/sites/mikescott/2020/12/14/green-hydrogen-the-fuel-of-the-future-set-for-50-fold-expansion/
[4] Source: https://www.energy.gov/eere/fuelcells/hydrogen-shot

Global green hydrogen capacity is expected to rise 280 times by 2030.

ways to use this super fuel. Power generation accounts for 25 percent of global CO_2 emissions[5] and having technology ready that can use this clean hydrogen to generate highly efficient power will play a key role in decarbonizing this sector.

Today, combustion of fossil fuels makes up 62 percent of global electricity production, pumping gigatons of unacceptable emissions into the atmosphere. These resources, however, currently play a significant role in the energy sector because they provide firm, dispatchable and affordable power.

Electricity production using renewable technologies is essential to the energy transition for their zero-carbon profile. In the past decade, renewable resources have scaled up drastically. Increasingly low cost hydro, solar and wind power are enabling progress in clean electricity generation. Intrinsic limitations of these technologies such as intermittency, required footprint, energy availability and grid connectivity, means renewables alone cannot meet the growing demand for power, especially in the face of increasing unpredictable weather patterns. The planet needs other sources of energy that are commercially available, proven to work, meet a high level of sustainability and ideally are ready to operate on green hydrogen.

[5] Source: EPA.gov https://www.epa.gov/ghgemissions/global-greenhouse-gas-emissions-data

As the planet races to increase the production of affordable green hydrogen for fuel, the planet is also racing to find solutions that can come alongside wind and solar power to use this green hydrogen and buildout a more sustainable power grid. Exploring the right technology to generate power using green hydrogen is the subject of this paper.

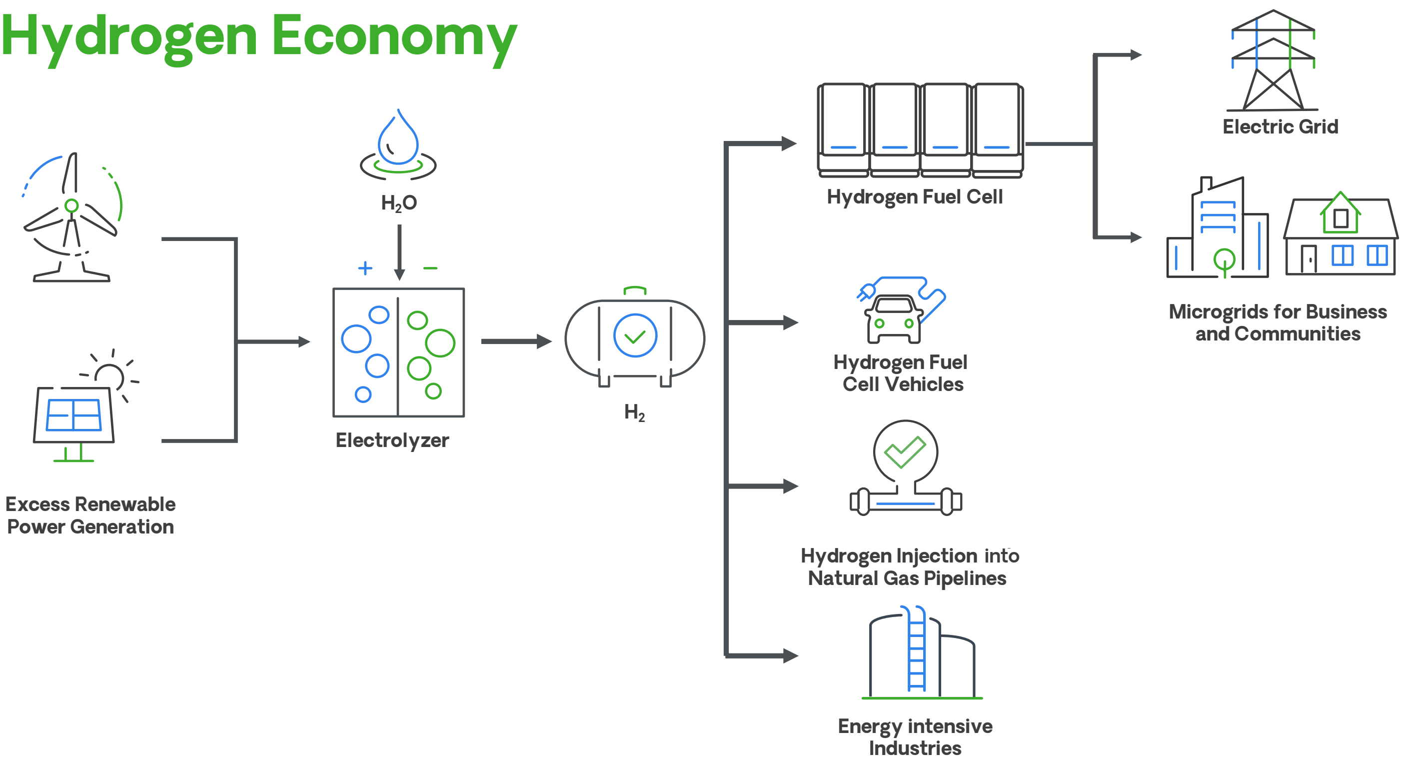
The Rise of the Hydrogen Power Plant

Since most power generation is produced by the combustion of fossil fuels and power generation represents a quarter of all CO_2 emissions, hydrogen will undeniably be a big part of our energy future and can help decarbonize power generation. Since hydrogen gas is scarcely found in nature, most hydrogen on the market today is created from fossil-fuel processes via steam methane reforming, a carbon intensive process (gray hydrogen). The good news is there are greener and better ways to get hydrogen. Green hydrogen for power generation can be generated via electrolysis using zero carbon electricity like wind, solar and hydro power (Figure 1).

The most common way to produce hydrogen through electrolysis is through fuel cell technology, which has been around for over 150 years. This same fuel cell technology can also be used as a stationary hydrogen power plant converting hydrogen into electricity.

Figure 1:

The Future Hydrogen Economy



Manufacturers can build fuel cell systems at scale to run on 100% hydrogen

Another technology that has the potential to use hydrogen fuel for power generation is gas turbines. As the energy industry continues developing gas turbines technologies for the new hydrogen power plant, tackling the mitigation of NOx emissions becomes critical due to the very high flame temperatures when hydrogen is used.

Technology Readiness Matters

Since the invention of fuel cells by Sir William Robert Grove in 1839, scientists have been experimenting with hydrogen and other fuels in laboratories all over the world. So, working with and operating safely and efficiently with hydrogen is not new to the fuel cell industry. There are manufacturers today that can build fuel cell systems at scale to run on 100% hydrogen and some of these manufacturers have designed their products in a modular way to easily maintain, retrofit and scale those systems, which would explain the growing number of fuel cell installations over the last decade.

Technology Efficiency Matters

Today, the economics for hydrogen fueled power generation technologies vary and is highly dependent on the cost of hydrogen. Even though the hydrogen Energy Earthshot initiative has a target price of $1/kg, recent analysis suggests $2/kg production cost is a potential tipping point that will make green hydrogen competitive in multiple sectors including power generation.[6] Many people in the industry believe this $2/kg production cost could be reached earlier than 2030.

Strong commitments from the industry and governments around the globe have

[6] Source: Green Hydrogen, The Fuel of The Future, Set For 50-Fold Expansion, Forbes.com

been made to develop technologies to decarbonize the grid energy system tackling the goals to reduce the hydrogen production cost and develop high efficient technologies so this transformation take place swiftly.

The Efficiencies for Fuel Cells

The theoretical electrical efficiency limit attainable by a fuel cell system can be represented by the Gibbs free energy divided by the heat of combustion of the fuel in a fuel cell system. Based on LHV of hydrogen at 25 ℃, this efficiency is calculated as follows:

$$\eta = \frac{\Delta G}{\Delta H} = \frac{228.6\frac{kJ}{mole}}{241.8\frac{kJ}{mole}} = 94.54\ \%$$ [7]

In practice, fuel cells cannot reach these maximum electrical efficiency numbers due to internal resistance losses. Practical electrical efficiency for hydrogen fuel cells can reach as high as 65%.[7] This electrical efficiency is calculated using the Voltage efficiency:

$$\text{Voltage efficiency} = \frac{\text{Operating Voltage (V)}}{\text{Thermodynamic voltage (E)}}$$

Depending on the type of fuel cell technology being used, practical electrical efficiency for fuel cells can range between 40 - 65% at the beginning of life and when it is used with combined heat and power (CHP) systems, the total efficiency can be as high as >90%, which makes it ideal for operating on hydrogen.

In addition to the very high potential efficiencies of the fuel cell, these electrochemical processes do not produce NOx when they convert hydrogen into electricity. According to the Environmental Protection Agency, NOx represents 7% of the US greenhouse gas emission in the US in 2020, The impact of 1 pound of N_2O on warming the atmosphere is almost 300 times that of 1 pound of carbon dioxide.[8]

Project Economics

CHP technology in combination with fuel cells and turbines will raise efficiency of power generation and will help escalate the production of clean hydrogen. "Power and heat applications offer an easily expandable demand segment for hydrogen that could support the scale-up of the production industry, which will drive down costs for all other segments.

[7] Source: Hydrogen Production: Fundamentals and Case Study Summaries, Conference Paper NREL/CP-550-47302 January 2010
[8] Source: Source: IPCC (2007) Climate Change 2007: The Physical Science Basis.

Applying hydrogen in heat and power can also help regions increase their energy autonomy and reduce industry-related emissions of fine particulate matter and other pollutants."[9]

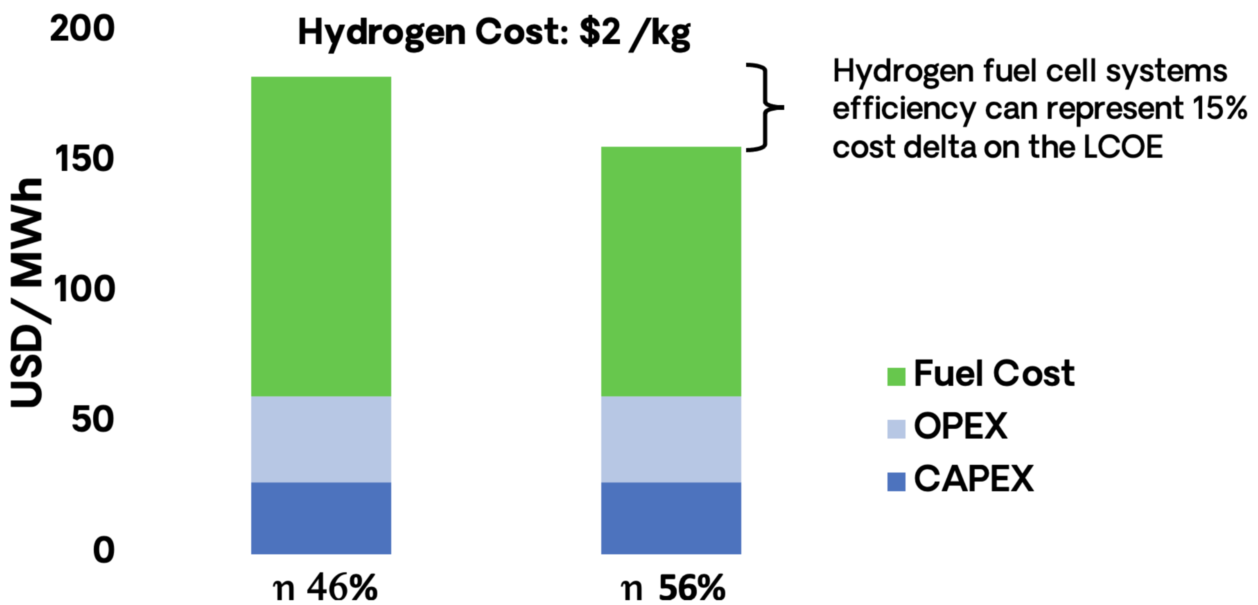
In the short and medium term, clean hydrogen will still be expensive. This puts additional emphasis on the electrical efficiency of the power generation used in the economic model. As different hydrogen prices are available depending on the production method, hydrogen transportation, geographic location and other site-specific condition, the electrical efficiency plays a critical role in the project economics (see Figure 3).

Since hydrogen production cost matters greatly to competitiveness in power generation, it is important to understand its cost trajectory. Low-carbon and renewable hydrogen costs will likely decline significantly in the coming years. "Within five to ten years – driven by strong reductions in electrolyzer capex of about 70 to 80 per cent and falling renewables' levelized costs of energy (LCOE) – renewable hydrogen costs could drop to about USD 1 to 1.50 per kg in optimal locations, and roughly USD 2 to 3 per kg under average conditions".[10]

High efficiency fuel cell can reduce +15% the levelized cost of electricity (LCOE)

Figure 3:

Levelized electricity generation cost for hydrogen fuel cell



[9 and 10] Source: www.hydrogencouncil.com, Path to hydrogen competitiveness full study 2020

According to Wood Mackenzie, the global demand for power generation using hydrogen as a fuel will reach 5.7 GW by 2030 and 137 GW by 2040 and the readiness, cleanliness and efficiency of fuel cell systems in hydrogen power production , makes fuel cell technology an excellent choice as the basis for large scale hydrogen power plants.

Choosing the right Fuel Cell Technology for Power Generation

Fuel cell technologies are often categorized by the type of electrolyte used in the fuel cell. The fuel cell type determines the kind of electro-chemical reaction that takes place in the cell, the kind of catalysis required, the temperature ranges in which the cell operates, the fuel required, and other factors. Fuel cells can also be classified as low-temperature and high temperature since the temperature[11] at which the chemical reactions take place can often impact how efficient the fuel cell is at producing energy (see Table 2).

Table 2:

Fuel Cell Technology Types[12/13]

Fuel Cell Type	Operating Temperature	BOL Electrical Efficiency (LHV)	Typical Applications	Comments
Polymer Electrolyte Membrane (PEM)	<120°C	55%	• Stationary application • Transportation	Low-temperature operation allows them to start quickly (less warm-up time)
Phosphoric Acid (PAFC)	150 - 200°C	40%	• Distributed generation • Transportation	Low-temperature More tolerant of impurities in fossil fuels that have been reformed into hydrogen than PEM cells.
Molten Carbonate (MCFC)	600 - 700°C	50%	• Electric Utility • Distributed Generation	High temperature–type fuel cell.
Solid Oxide (SOFC)	700 - 850°C	64%	• Electric Utility • Distributed Generation • Transportation	The high-power generation efficiency is more possible for the high temperature–type fuel cell than for the low-temperature type.

[11] Source: Source: Takehisa Fukui, in Nanoparticle Technology Handbook (Third Edition), 2018
[12] Source: https://www.energy.gov/eere/fuelcells/comparison-fuel-cell-technologies
[13] Source: The Fuel CellIndustryReview2020, E4Tech

Figure 4:

Natural Gas Solid Oxide Fuel Cell

SOFC Fuel Flexibility

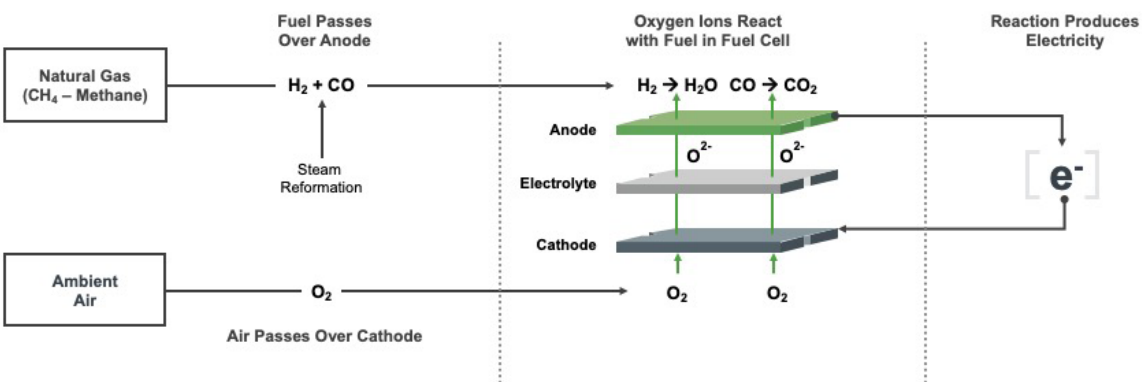
In the last decade, there has been a surge of fuel cell companies entering the market because of the technology capability to efficiently generate clean energy supplementing wind and solar power and build a more sustainable power grid. SOFC has several intrinsic advantages such high efficiency, stability, reliability, and fuel flexibility distinguishing the SOFC from other fuel cell technologies.

The technology, production lines, form factor are all the same within a fuel cell manufacturer regardless of feed fuel. Fuel cell manufacturers are already aligned in product development to make the step change to use H_2 as a fuel source. When fuel cell manufacturers move from natural gas to hydrogen, the technology becomes simpler as some of the components required for natural gas fuel cells can be removed.

For example, natural gas or biogas fuel cell systems operate at high temperatures, ambient air enters the cathode side of the fuel cell. Meanwhile, steam mixes with fuel (natural gas or biogas) entering the anode side piping to enable production

Figure 5:

Natural Gas Solid Oxide Fuel Cell



of a reformed fuel (H_2 + CO). As the reformed fuel crosses the anode, it attracts oxygen ions from the cathode. The oxygen ions combine with the reformed fuel to produce electricity, steam, and carbon dioxide (Figure 5). This reformation step is not required when the fuel cell is fed with pure hydrogen, so the fuel cell system is simplified. The fuel cell products generating electricity on the market today are driven by the needs of the market and since natural gas and biogas are readily available, most systems installed today run on natural gas or close derivatives.

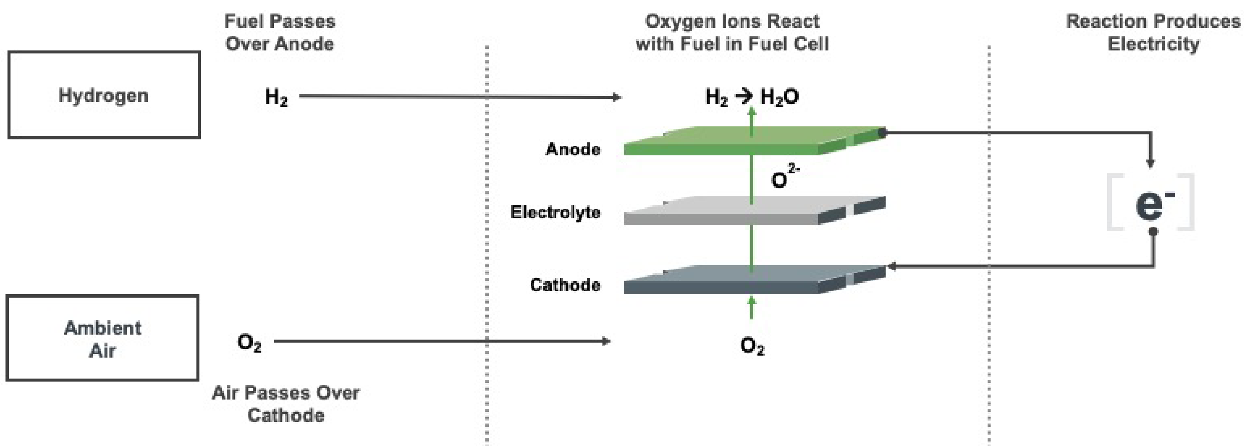
Fuel cells can operate with a hydrogen or a hydrocarbon fuel source to produce electricity.

When pure hydrogen (H_2) is used as a fuel, the electrochemical reaction does not produce any carbon emissions or other harmful greenhouse gases. Hydrogen fuel cells generate power by electrochemically combining H_2 fuel with oxygen ions harvested from ambient air, as shown in Figure 6.

The fact that SOFC fuel cells are a clear leader in fuel cell technology, one company that stands out as a clear industry leader in stationary power generation with SOFC technology is Bloom Energy. Bloom Energy has over 1 GW of installed power generation, most of which is running currently on readily available natural gas. This installed base can also run with blended hydrogen with natural gas following the Bloom Energy guidance.[14]

Figure 6:

Hydrogen Solid Oxide Fuel Cell



[14] Source: https://www.bloomenergy.com/wp-content/uploads/Energy-Server-H2-Blending-Technical-Note.pdf

Using Hydrogen in a SOFC

The performance of the fuel cell varies depending on the type of fuel being used, for example, the typical start life of a Bloom Energy fuel cell system, also known as Energy Server, fueled with natural gas is ~62 % LHV electrical efficiency. If the same Energy Server is fueled with hydrogen, the starting efficiency is only ~50 % LHV electrical efficiency, this occurs because hydrogen has a higher Lower Heat Value (LHV) per electron ratio (see Table 3).

Table 3:

Fuel LHV and Ratio of LHV per Electron

Molecule	Lower Heating Value (kJ/mole)	Number of Electrons Generated per molecule	Lower Heating Value per Electron (kJ/mol e^-)
Methane	**806.3**	**8**	**100.3**
Hydrogen	**241.8**	**2**	**120.9**

Therefore, if the fuel utilization of an SOFC is held constant, and the cell voltage is constant, the LHV efficiency of a hydrogen fueled SOFC should be lower than the efficiency of a methane fueled SOFC by a factor of 1.205.

Thus 62 % LHV electrical efficiency on methane should theoretically produce 51.4 % LHV efficiency on hydrogen. However, the higher LHV per electron for hydrogen also means the fuel cell generates more heat that needs to be rejected. This increased heat is carried away by an increase in air flow. The increased air flow for a hydrogen SOFC at the same power level causes a higher parasitic power draw from the air blower, leading to an actual starting efficiency on hydrogen of only ~ 50 % LHV.

Innovative Solution for a High Efficiency Hydrogen Fuel Cell

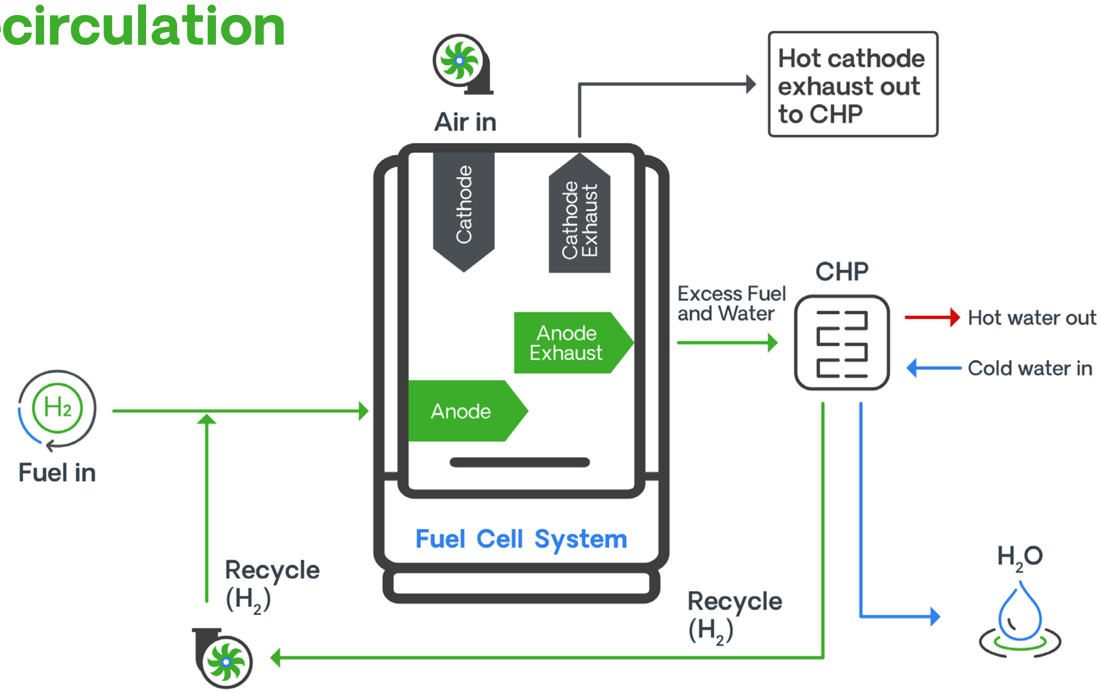
The lower efficiency for a hydrogen fueled Energy Server is predicated on the assumption of keeping fuel utilization and cell voltage constant. Bloom Energy has invented a new product design that enables significant improvement in both fuel utilization and cell voltage. Fuel cells cannot operate at 100 % fuel utilization in a single pass, thus, the anode exhaust from a hydrogen fueled SOFC contains unreacted hydrogen and steam. By cooling this H_2/ steam stream, water can be condensed and separated from the unreacted H_2. The unreacted H_2 can then be recycled back to the fuel cells as additional fuel. This change enabled >99.9% overall fuel utilization of the hydrogen in the Energy Server (Figure 7).

H2 recirculation enables >99.9% Fuel Utilization

Condensing clean water as a by-product from the anode exhaust has a secondary benefit. By removing water from the anode exhaust/anode recycle stream, the concentration of hydrogen in the fuel cells is increased, thereby increasing both the Nernst potential for each cell, as well as the actual operating voltage. The degree of improvement in the cell voltage depends on how much water can be removed from the anode exhaust. Whether the condenser is cooled with ambient air or with cooling water, the degree of water removal is expected to depend on ambient temperature. 62 % LHV efficiency at beginning of life is normally achievable. During winter operation, when the condenser outlet temperature could be as low as 20 ℃, 64% LHV efficiency at the beginning of life is possible.

Figure 7:

Water and unreacted H_2 recirculation



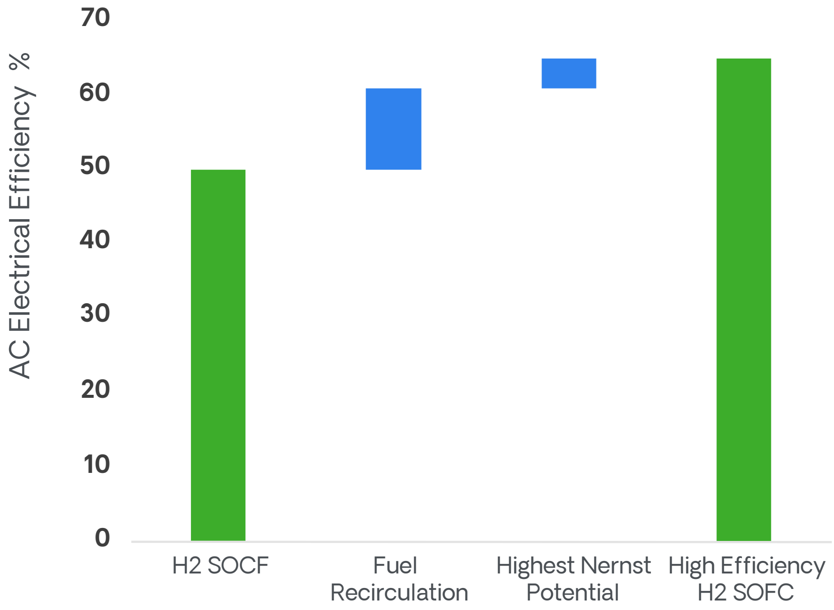


Figure 8:

Electrical Efficiency impact using Bloom Novel Solution

As a result of Bloom's innovation, expertise in fuel cells, sophisticated modeling and simulation methods, Bloom's hydrogen fueled Energy Server reaches an electrical efficiency as high as 64% LHV at the Beginning of Life. (Figure 8). The industry leading efficiency of Bloom Energy's Solid Oxide platform, the Energy Server, provides the best opportunity to scale hydrogen power generation.

Unbeatable Efficiency

η: 92%

Additionally, to the high electrical efficiencies, the Energy Server operating on hydrogen, has a much broader potential for Combined Heat and Power (CHP) applications. CHP systems are often installed to repurpose wasted heat energy to heat water for a host of applications including swimming

The high electrical efficiency plus the high temperatures in the Solid Oxide Fuel Cell system enables an unbeatable efficiency of 92% when used in a CHP system

pools, creature comforts, manufacturing, pressurized hot water for space heating and direct use of heat in industrial applications. The high electrical efficiency plus the high temperatures in the Solid Oxide Fuel Cell system enables an unbeatable efficiency of 92% when used in a CHP system (Figure 9).

This high efficiency can be achieved by recovering heat from the anode and cathode exhaust streams. With exhaust temperatures of 290 ℃ and 180 ℃ from the cathode and anode correspondingly, the total thermal capacity can be as high as 38%.

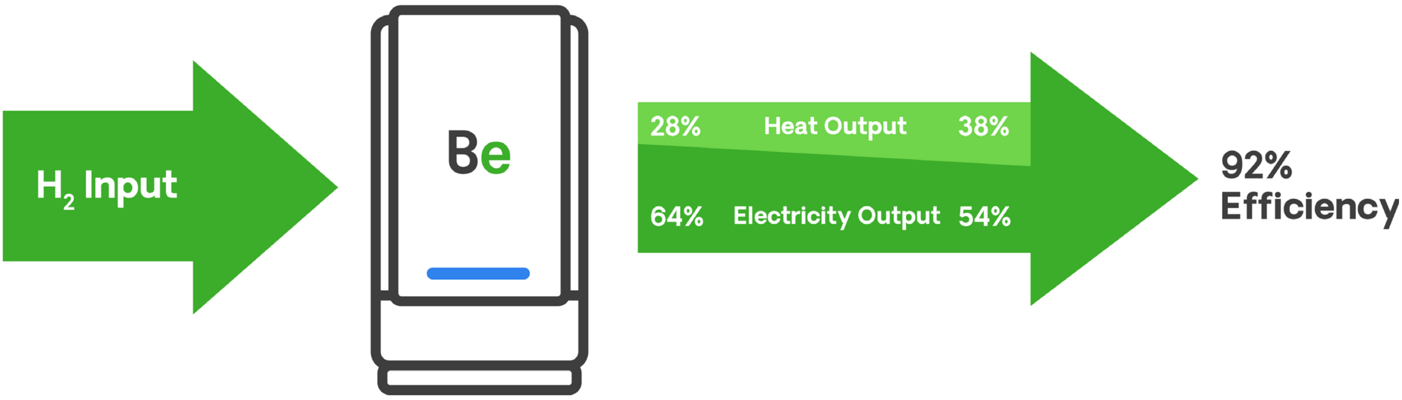


Figure 9:

Hydrogen fueled Bloom Energy Server efficiencies

Conclusions

The world is going to need a variety of different sources of clean power generation to decarbonize our planet. We need both renewables as well as other proven reliable and efficient sources of power, to handle not only the existing grid load but the new loads that will be added over the next decades. Due to the intermittent nature of core renewable power like wind, hydro and solar, customers are now looking rightfully so at other technologies like combined cycle gas turbines and fuel cell products. Gas turbines running on 100% hydrogen is a new concept that has not been widely deployed and when it is, it is expected to still contribute NO_X emissions, however, fuel cells are a great addition to the decarbonization journey because they are a proven technology with proven sustainability and reliability benefits. Of the fuel cell technologies on the market, solid oxide fuel cells (SOFC) is the clear winner in providing efficient, reliable, and sustainable stationary power due to their high operating temperatures, high efficiencies and Bloom Energy has continued to invest and innovate in this space.

Since green hydrogen is the future of the energy transition and green hydrogen cost is still relatively expensive, finding the most efficient and established SOFC product that is readily available today to deploy in projects is essential. Bloom Energy has both highly efficient SOFC based hydrogen fueled power generation, the Energy Server, as well as a solid oxide-based way to make green hydrogen, the Bloom Electrolyzer. Bloom can not only optimize hydrogen utilization but help green hydrogen scale quickly to meet the planet's needs for decarbonization.

For more information about Bloom's Energy Server operating on 100% Hydrogen gas or the Bloom Electrolyzer, please visit bloomenergy.com/resources for more information.