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WHITE PAPER

UNLOCKING THE POWER OF HEAT TO MAXIMIZE CLEAN HYDROGEN PRODUCTION THROUGH ELECTROLYSIS

July 2021

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THE WORLD NEEDS AN ENERGY SOLUTION

Energy is a fundamental human need. Our physical and economic well-being depend on having abundant energy. Modern civilization exists because we have learned how to harness sources of energy to generate power. While this has long worked to society's advantage, we are now seeing the true cost – our current paradigm for generating power is putting our planet in jeopardy. But, it doesn't have to be this way. We can have abundant energy and a sustainable environment without compromise. At Bloom Energy, we have a viable and scalable solution to this problem: the Bloom Electrolyzer.

Today, most of the world's electricity comes from combusting non-renewable fossil fuels that release carbon emissions and air pollutants that harm our communities. Though technological advances have enabled cleaner methods of generating power from fossil fuels, their very existence is finite and our global supply is depleting. The energy sector has increasingly turned to naturally replenishing renewable fuel sources like wind, solar, hydro, geothermal, or biomass to produce power. While there is virtually no shortage of these energy sources available, there are still drawbacks. Some, like geothermal and hydro, are location constrained. Others can only be leveraged on an intermittent basis – solar power cannot be generated when the sun isn't shining; wind cannot generate power if it is not blowing. Batteries can act as a storage medium for excess energy produced by renewables but are not effective for extended periods of time. The world needs a viable, long-term energy solution, and many believe it lies within the universe's most abundant element: hydrogen.

Hydrogen is an alternative that is gaining considerable attention as a transportable, long-term energy storage medium for excess renewable power. Clean hydrogen produced with excess renewable power can be an effective energy storage medium that can be distributed over large distances and offset seasonal variations as well. [Reference 1]

CLEAN HYDROGEN

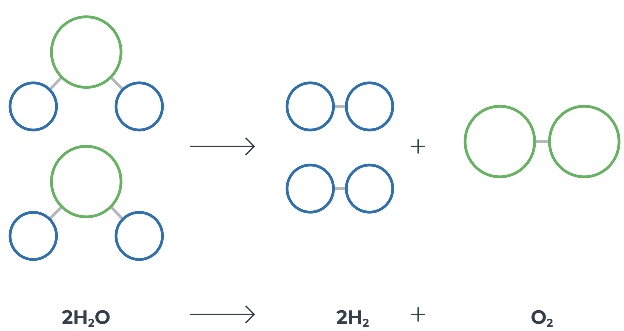
Hydrogen has enormous promise, but it is not naturally occurring as a free substance on earth. Instead, its abundance exists in compound form – with oxygen to form water, or with carbon to form hydrocarbons, key components in the make up of fossil fuels we use today. Since hydrogen isn't a naturally occurring fuel, it requires a primary input energy source to be produced. The conventional process of making hydrogen involves extraction from fossil fuels, which creates a considerable carbon footprint. Clean hydrogen, however, can be made through a process known as electrolysis, which uses zero-carbon electricity to split water at the molecular level into hydrogen and oxygen, through a device called an electrolyzer.

Nearly 80% of the operating cost of clean hydrogen production comes from the electricity used to break the water. Therefore, an electrolyzer that uses less electricity is a game changer for making low cost, clean hydrogen a reality today.

ELECTROLYZER TECHNOLOGIES

Water electrolysis is a process that uses electrical energy to break water molecules into hydrogen and oxygen. At the most basic level, an electrolyzer cell consists of an anode, a cathode and an electrolyte or membrane. The electrolyzer stack is formed with several single repeat units of electrolyzer cells. Water electrolysis is an electrochemical reaction that takes place within the electrolyzer stacks. Electricity supplied to the electrolyzer splits input water into its hydrogen and oxygen molecules as output.

$$2H_2O \rightarrow 2H_2 + O_2$$



The hydrogen produced is stored as a compressed gas for transport such as gas filling stations, power generation, or industrial processes and the oxygen is generally released to atmosphere.

The amount of electricity required to perform electrolysis depends on the temperature of the water. At low water temperatures, more electricity is required to produce hydrogen. At high water temperatures, less electricity is needed. Low temperature electrolysis can be performed with an alkaline electrolyzer, in which electrolysis is done in the presence of a liquid electrolyte solution or using a Proton Exchange Membrane

(PEM). High temperature electrolysis, also called steam electrolysis, employs a solid oxide electrolysis cell (SOEC) operating at higher temperatures (700 to 850^{o}C) to split the water. Low cost steam can be used as an input to further reduce the electricity needs compared to conversational water electrolysis.

Water in liquid form, as used in low temperature electrolyzers, requires approximately 15.9 MJ of energy per kg, as represented by point 'a' in Figure 1. At a temperature of 850^{o} Celsius, where the high temperature Bloom Electrolyzer operates, the total energy demand of electrolysis is reduced to 13.8 MJ/kg of water. Additionally, at this higher temperature, 3.5MJ/kg can be provided by heat, while the remaining 10.3MJ/kg can be provided by electricity. Since heat is generally a cheaper source of energy than electricity, high temperature electrolyzers have an inherent advantage over low temperature electrolyzers. Figure 1 shows that the total energy demand for the electrolysis process is a combination of electrical energy (d) and heat energy (e).

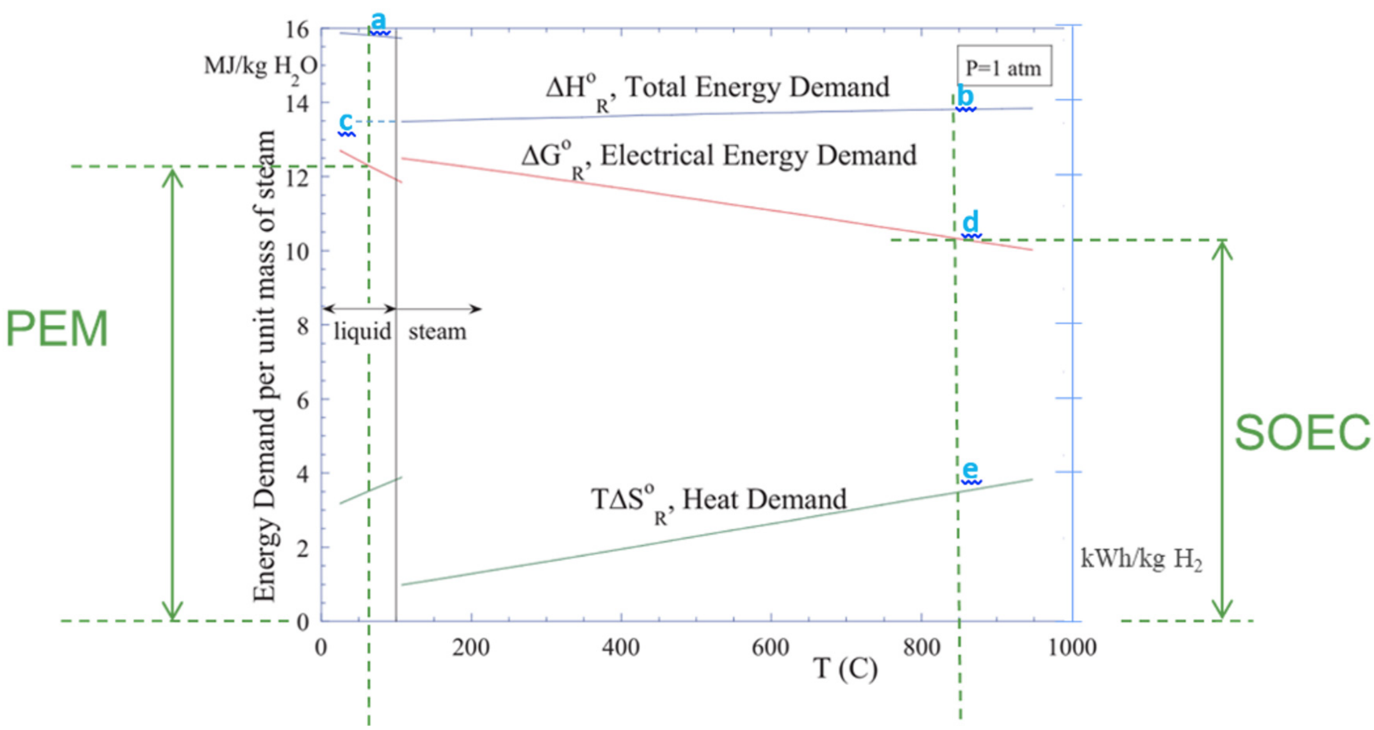


FIGURE 1: ENERGY DEMAND AS A FUNCTION OF TEMPERATURE FOR ELECTROLYSIS OF WATER

THE BLOOM ELECTROLYZER

The Bloom Electrolyzer operates at high temperatures of 700 – 850^{o} C. It can generate steam using internal electrical energy or it can leverage steam that is externally generated from sources such as nuclear power plants, industrial excess heat or solar concentrators.

The results of our hardware testing, shown in Figure 2, illustrate that the high temperature electrolyzer requires 15 percent less electrical energy compared to conventional low temperature electrolyzers when the total energy required for electrolysis is entirely derived from electricity. The testing further shows that when coupled with moderate-temperature external steam sources, the Bloom Electrolyzer requires about 29 percent less electrical energy compared to its low temperature counterpart. There is potential for further efficiency improvement, ranging from 35-45%, when the electrolyzer can be integrated with high-temperature heat sources.

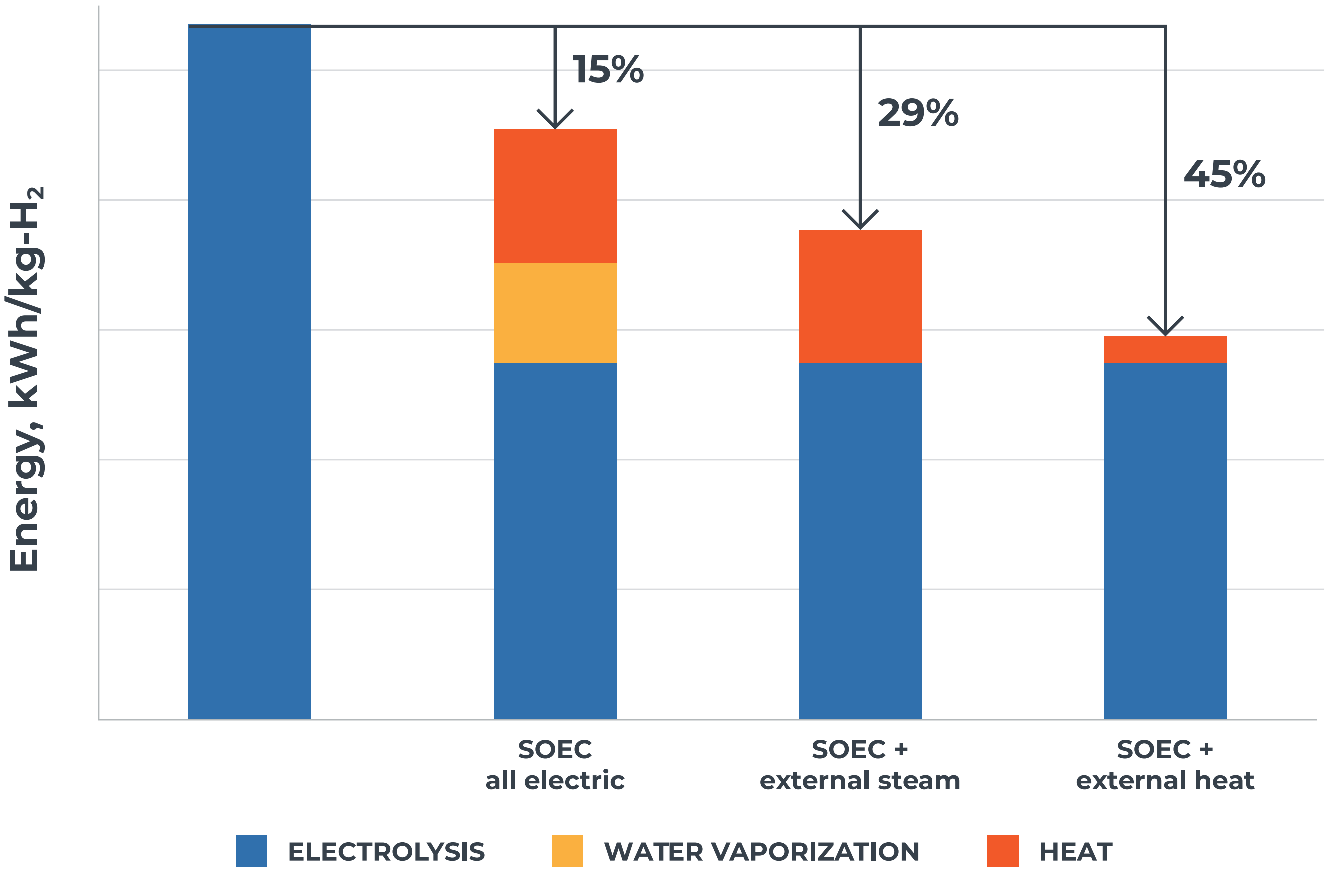


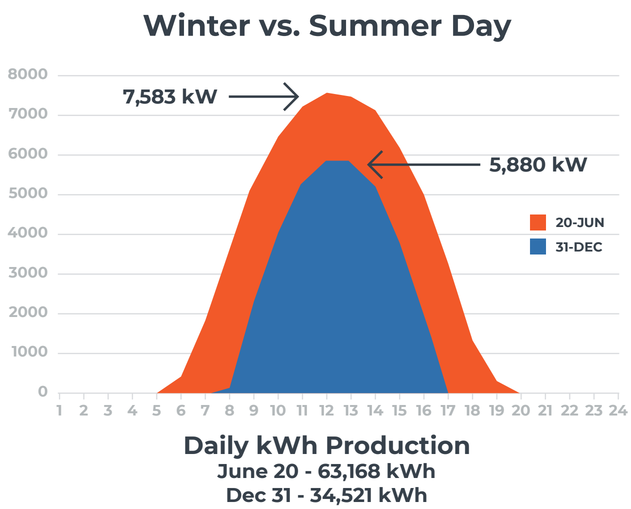
FIGURE 2: ENERGY CONSUMPTION OF LOW TEMPERATURE AND HIGH TEMPERATURE ELECTROLYZERS

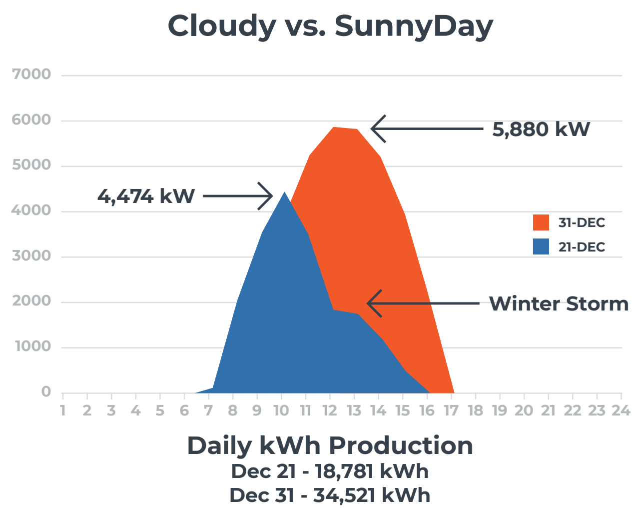
INTERMITTENCY OF RENEWABLE ENERGY GENERATION

While electricity needed for electrolysis can come from any generation source, Bloom is most excited about the pairing of its electrolyzers with intermittent renewables to produce zero-carbon hydrogen at scale.

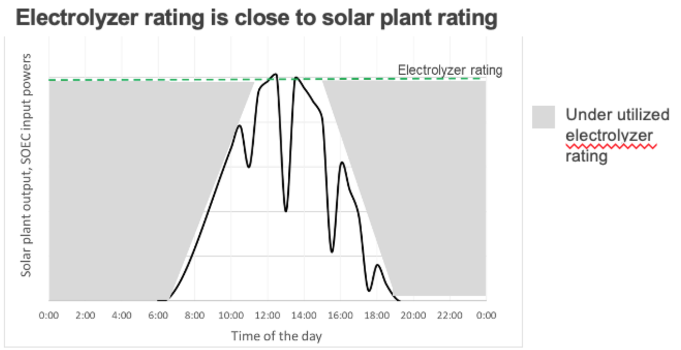
Future solar farms built for the purpose of producing hydrogen in large scale will be in places with lots of sunshine. These hydrogen production sites will be comparable to oil production sites of today's energy environment. Rather than producing hundreds of oil barrels a day, they would produce tons of hydrogens per day.

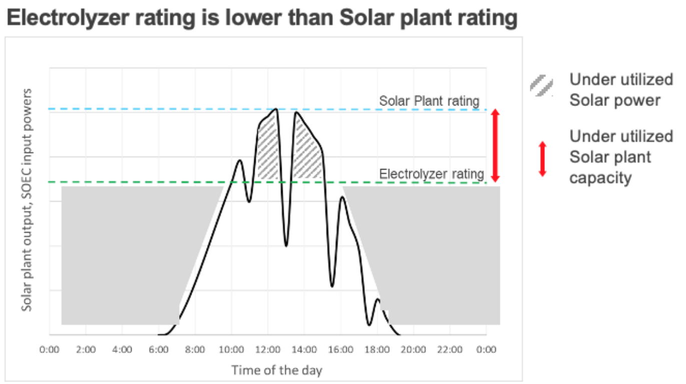
Solar farms have considerable variation of energy production based on season (winter or summer) and daily weather conditions (sunny or cloudy). The typical 10 MW solar plant output during different days of the year is shown below.



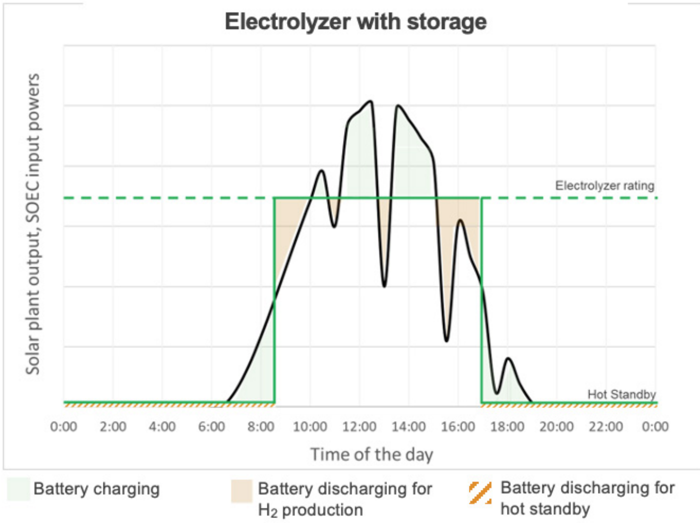


Sizing an electrolyzer close to that of a solar farm will result in underutilized electrolyzer capacity (left, below). Similarly, if the electrolyzer is sized lower than solar plant capacity, the solar plant will not be fully utilized (right, below).





Deploying a combination of batteries and electrolyzers captures maximum energy and optimizes capital and operational costs (right). Both high and low temperature electrolyzers will benefit from this architecture, because both technologies will want to maximize the capacity factor of the equipment.



The image to the right shows a typical solar farm and approximate land needs for electrolyzers and batteries. The overall footprint of batteries and the electrolyzer system are significantly smaller than the solar farm.

A small portion of this battery system can be used to keep high temperature electrolyzer stacks at their desired temperature when the renewable energy is not available.

THE POWER OF HEAT

The ability for solid oxide technology to utilize heat is a critical advantage in electrolyzer performance since the electrical energy required to produce hydrogen changes with the temperature of the water.

Bloom has more than a decade of experience building and optimizing commercial high temperature solid oxide systems that are thermally packaged to minimize heat loss. The Bloom Electrolyzer is a high temperature electrolyzer that operates at 700 – 850^{o}C, using solid oxide electrolysis cells (SOEC) as the catalyst for reaction. Heat serves as a secondary source of energy to help fulfill the reaction, significantly lowering the electrical energy requirement and its associated costs.

Further, the ability to integrate steam elevates electrolyzer efficiency to much higher levels. Our technology is capable of generating steam using electrical energy internal to the electrolyzer or leveraging steam generated from an external source such as nuclear power plants, industrial excess heat or solar concentrators.

Unlike PEM and alkaline electrolyzers that predominantly require electricity to make hydrogen, Bloom Electrolyzers can substitute a good measure of electricity with heat. Bloom Electrolyzers are more energy efficient than low temperature electrolyzers when all energy for electrolysis is derived using electricity. But, when it is integrated with external heat sources the energy advantages are even greater, 35%-45%, as seen in Figure 2. This option can be applied to scenarios where there is excess heat or a cheaper way to produce renewable heat than electricity.

NUCLEAR POWER PLANTS

Nuclear power plants provide clean baseload power, but cannot easily ramp power up and down - which means they generate a lot of excess power during the middle of the day when solar plants are providing large amounts of power. That excess power generated by nuclear plants can be used for electrolysis.

Nuclear plants produce excess heat that can be used to improve the efficiency of hydrogen production using high temperature electrolyzers, such as the Bloom Electrolyzer. This combination will maximize the energy efficiency of both electrical production of the nuclear plant as well as hydrogen production of the electrolyzer.

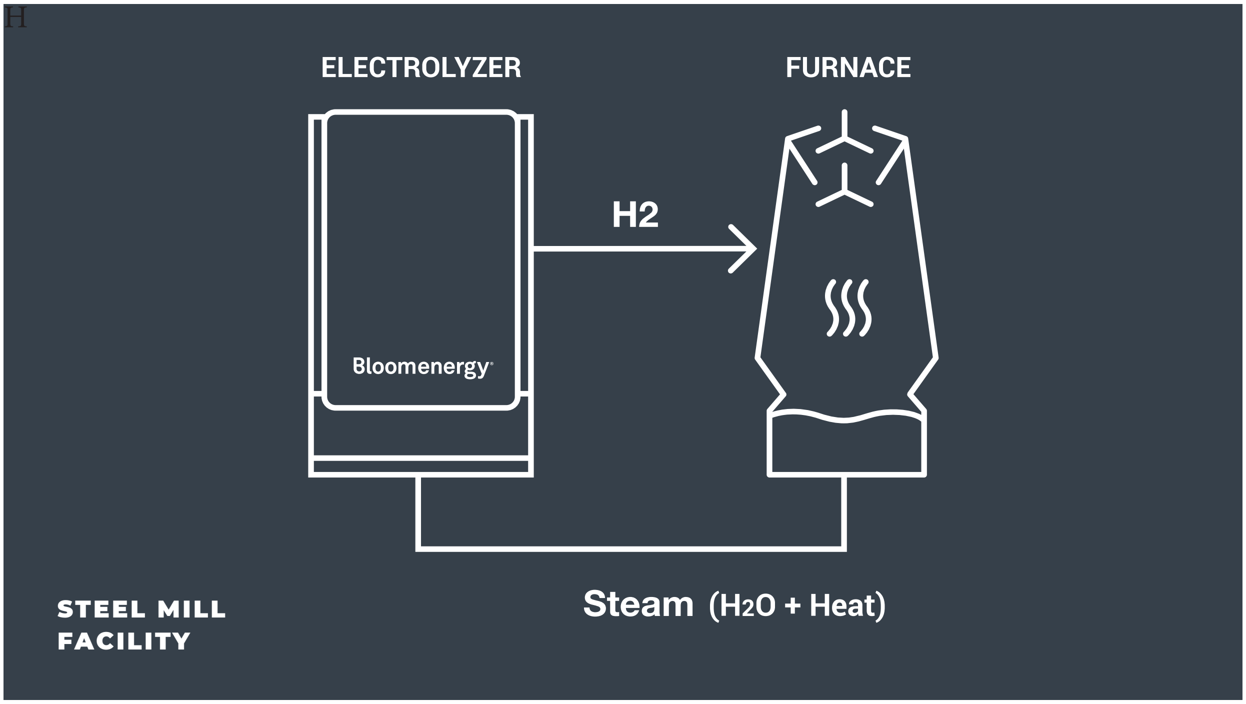
With the U.S. Department of Energy's Idaho National Laboratory, Bloom is demonstrating how this low-cost excess heat from nuclear plants and excess electrical energy during the day can be leveraged by high-temperature Bloom Electrolyzers to produce low cost zero-carbon hydrogen.

COMMODITY MANUFACTURING

The steel, chemical, cement, and glass industries account for 22% of global CO_2 production. These sectors are also very difficult to decarbonize because they must operate throughout the day, they cannot use intermittent renewable power and the market pressure on their commodity prices forces them to seek the lowest cost energy inputs to stay competitive.

At Bloom, we have a game changing solution for these manufacturers. The hydrogen required to heat high-temperature furnaces at these factories can be produced on-site using Bloom Electrolyzers and renewable electricity.

The excess heat from the furnaces can then be fed into the Bloom Electrolyzers as high-temperature steam, reducing the electricity needs of our system. Plus, there's no additional costs of transporting the hydrogen from a remote location. A system level architecture that considers end-to-end process optimization will result in the low-cost hydrogen for these industries.



We've partnered with Baker Hughes to create integrated solutions addressing this sector. Baker Hughes will leverage its strong customer relationships, compressor technology and its thermal engineering expertise while Bloom provides electrolyzer technology and hydrogen expertise.

CONCENTRATED AND PHOTOVOLTAIC SOLAR

Future solar plants, built for producing hydrogen at large scale, will be located in places with lots of sunshine. Such plants can harvest the sun's energy as heat using concentrators, or as electricity using solar panels. Harvesting heat energy from the sun is cheaper and uses less land than producing electricity with solar panels.

The Bloom Electrolyzer will use this solar heat energy, and significantly lower the amount of renewable electricity needed to break water molecules and produce hydrogen at low-cost.

THE BLOOM ENERGY ADVANTAGE

The versatility of our core solid oxide platform creates distinct advantages over alternative electrolyzer technologies. Leveraging the same proven solid oxide technology that powers our global customer fleet, the unmatched efficiencies, high-temperature tolerance, cost-down curve, and scalability of the Bloom Electrolyzer will open the aperture of the hydrogen market and enable diverse applications across the energy landscape.

Over the last few years, our teams have been engaged with a number of key partners in high potential markets to understand user requirements, demonstrate the technology, and create enough market momentum to achieve scale and open up new pathways to growth.

Solid oxide electrolyzers are uniquely suited for a broad variety of hydrogen production scenarios, including utilizing intermittent renewables and integrating with large-scale sources of heat from industrial processes or nuclear reactors.

To summarize, Bloom's high-temperature electrolyzer technology offers a cost-competitive edge through its ability to:

1. Consume less energy per Kg of hydrogen produced
2. Utilize lower cost heat rather than more expensive electricity

Given that electricity accounts for about 80% of hydrogen production costs, Bloom's high temperature electrolyzer will be an important component in delivering low-cost, scalable, renewable hydrogen.

BLOOM ENERGY

At Bloom, we've been working since 2001 to provide energy solutions that create positive global change.

Our founders began innovating and developing solid oxide technology in the 1990s, building their first electrolyzers while working on NASA's Mars exploration program.

They later reversed this technology to create and commercialize solid oxide fuel cells, installing and operating over half a gigawatt throughout the years.

Our Bloom Electrolyzer uses the same solid oxide platform and many similar components, so our supply chain is secure. We have ramped up capacity and are ready to produce half a gigawatt of hydrogen electrolyzers today, one gigawatt within a year, and over two gigawatts annually as market demands.

Along with our partners, we are ready to bring hydrogen to life and deliver abundant, clean, reliable, and affordable energy to everyone in the world.

References:

Reference 1: "Dynamic Behavior of a Solid Oxide Steam Electrolyzer System Using Transient Photovoltaic Generated Power for Renewable Hydrogen Production", a. Sædmanesh, P. Colombo, D. McLarty, J. Brouwer, Journal of Electrochemical Conversion and Storage, ASME, Vol. 16, November 2019.

Reference 2: "High Temperature Electrolysis for Hydrogen Production from Nuclear Energy – Technology Summary", J.e. O'Brien, et. Al, Feb. 2010, Idaho National Laboratory report for US Department of Energy

Reference 3: "Economic Analysis of Integrated Solar Power, Hydrogen Production, and Electricity Markets Josh Eichman", Omar J. Guerra, and Mariya Koleva, September 14, 2020, ICEPAG 2020 Hydrogen: A Platform for Sustainability

Hydrogen Production: Electrolysis; DOE Hydrogen and Fuel Cell Technologies Office

Electrolyzer overview: Lowering the cost of hydrogen and distributing its production. MARCH 26, 2020 CORNELIA LICHNER

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