A FROST & SULLIVAN WHITE PAPER

The Hydrogen Economy:

A Carbon Free Future Beyond Renewables

H_2

Sponsored by Toshiba

FROST & SULLIVAN

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Introduction

Acceleration is Needed

The US power industry has seen rapid advances across conventional and renewable energy technologies in the last 20 years. Improvements in carbon capture technologies and the progression from coal to natural gas has helped drive energy industry emissions to their lowest levels since 1993. Renewable energy has continued to grow at double digit rates, thanks to a variety of factors that have helped it become more financially feasible, such as the rapid decline in solar prices, state-led clean energy mandates and incentives, federal incentives, and a general cultural trend towards demanding an improved environmental footprint.

Yet at the same time, overarching energy trends from decades ago persist: Conventional fossil and nuclear power still account for about three-fourths of the nation's installed power. The energy industry is still one of the most polluting industries in the US, second only to the transportation industry. The central power-plant-and-grid configuration remains entrenched, despite how increasingly costly and inflexible these aging systems have become. The US power system has improved its overall power quality since the rampant outages and brown-outs of early 2000s and has made steady progress toward an improved environmental footprint. However, this slow plodding course toward a cleaner and more efficient future could be sharply accelerated thanks to advances in on-site power, and ways to manage and, more importantly, fuel this power.

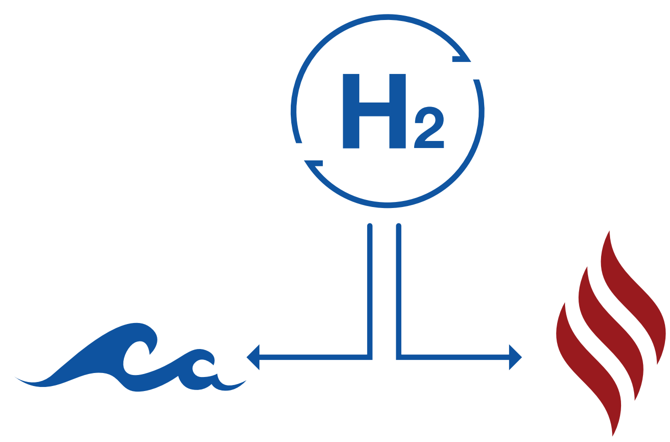
Fueling the Future

The Ideal Fuel

Hydrogen is the simplest, lightest and most abundant element in the universe—it constitutes 75% of normal matter. Despite its ubiquity, hydrogen is not found in pockets or mines, but must be generated or extracted from other sources. In the US, hydrogen is a widely used input for the chemical industry, and plays a role in everything from processing crude oil to metal refining, electronics manufacturing and food processing. Therefore the industrial supply chain for hydrogen is well established, with most of it generated at natural gas plants and transported by a variety of methods such as rail, pipeline, over the road and by sea.

While hydrogen has clear uses across industry, its current use as a fuel for electricity generation is nominal. It has been touted for many years as the ideal fuel, and at the same time a difficult one to leverage: it has the highest amount of energy per weight, but the least amount of energy by volume (in an non-compressed state). It is the cleanest fuel possible—its byproducts in electricity generation are only water and heat. But the current, conventional system for the generation and transportation of hydrogen is reliant on fossil-fuel driven energy and transportation sectors: 95% of US hydrogen produced from natural gas and a large portion of it is transported over roads in trucks. Hence while use of this ultra-clean fuel for energy could leverage the existing supply chain, at this point that system of centralized extraction and compression, through transportation and storage, is rife with complexities, costs and carbon emissions.

Hydrogen is the **cleanest fuel possible,** electricity generation byproducts are only water and heat



A more practical means to leverage hydrogen for energy usage would be to generate it on-site. Extracting hydrogen on-site means the extraction process can be more finely tuned to the volume of demand, thereby reducing excess or inadequate production. Transportation costs (and related environmental emissions) are eliminated. And, while hydrogen will still need to be stored on site, it can be right-sized for the application, rather than requiring excessive storage that may be needed due to the risks in supply from off-site extraction and transportation. One solution that has combined all aspects of the on-site hydrogen system—from extraction, through storage, generation, and overall management of the system—is Toshiba's H_2One. This system is a completely self-sustaining, carbon-free solution for on-site power usage that combines the benefits of renewable energy with the high-quality power of a fuel cell.

Producing Hydrogen for On-site Energy Generation

Hydrogen can be generated onsite in a few different ways: one, it can be extracted from another fuel source, such as using the existing natural gas infrastructure, or waste gasses. However, the process to extract hydrogen from another fuel such as natural gas or methane causes other pollutants to be released, thereby negating hydrogen's environmental advantages.

Electrolysis

Another method is to extract the hydrogen from water with electrolysis. This system results in no emissions, can be done on-site, is scalable, and when used with a fuel cell system that generates heat as a byproduct, can be a fully self-sustaining system.

At its most basic, the process of electrolysis involves running a direct current electricity through water to break apart the H_2O bond, thereby releasing the hydrogen, which is attracted to and captured at the cathode end, and oxygen which moves to the anode end.

There are different systems available by which this can be achieved, and some of the most effective include the following:

- **Large capacity electrolysis**, such as alkaline electrolysis, which uses a liquid electrolyte along with the alkali solution to speed up the reaction, and does not require precious metals such as platinum for the reaction. Hence, the system is more economical than other solutions and can be appropriate for high volume hydrogen production, though there are other methods that are more efficient. It generates approximately 100 normal cubic meters (Nm3) per hour of hydrogen.
- **High efficiency electrolysis**, which is so called as it leverages steam, rather than water, to extract the hydrogen molecule from the H_2O. One such system uses a solid oxide electrolyzer cell (SOEC), such as a ceramic, instead of a liquid electrolyte as a next generation. The benefit of using an SOEC is its high efficiency rate.

Toshiba has researched and developed hydrogen extraction systems that leverage renewable energy to create hydrogen at 30% greater efficiencies than previous solutions. Therefore depending on the customer site and power needs, either system can be deployed to provide an efficient, and clean, hydrogen production solution.

Creating an End to End System

Whether a large capacity or high efficiency technology is used, a hydrogen system that uses water or alkali solution for fuel still needs electricity to separate the water bonds in the first place. Renewable energy, whether solar photovoltaic (PV) or wind power, can create the electricity that is then used to extract the hydrogen.

Fuel Cells and Renewable Energy

It may seem more efficient to use renewable energy directly for on-site power needs, instead of rerouting it to extract hydrogen to fuel a fuel cell, and then create power—and historically this is how solar and wind have been used. However as both solar and wind provide intermittent power that is difficult to use directly with a building or to feed into the grid, they are usually combined with some form of energy storage. As electricity itself cannot be stored, batteries are often used with a PV rooftop or installed at a wind turbine site to mitigate the fluctuations generated by renewable power.

Hydrogen Storage

Hydrogen storage for industrial uses typically involves transportation from where it is generated to where it is used. This may be by pipeline, over the road in gaseous tube trailers or cryogenic liquid tanker trucks, or via rail or ship. This also requires the hydrogen to be compressed or liquefied—which requires additional energy—so as to increase the volume of hydrogen that can be transported per mile.

Absorbtion is the Key

A more advanced system is one that employs materials that "absorb" the hydrogen, such as a metal hydride system. With metal hydride hydrogen storage, the system absorbs hydrogen as though it were in a sponge, and at densities that almost rival liquid hydrogen storage, but without the high cost of compressing the fuel. These systems tend to be heavier than other forms of storage, which makes them less apt for the transportation of hydrogen, but this is not a hindrance for on-site storage.

While much of the activity in recent years around hydrogen has been in regards to extraction, the storage aspect is critical to both the technical feasibility and improving the economics of the system. Toshiba has looked at all aspects of the on-site hydrogen ecosystem and is able to deploy both simple tanks as well as metal hydride storage on-site in its H_2One™. The company is taking storage a step further as it develops its large capacity hydrogen energy storage system, a five megawatt solution that will propel hydrogen solutions from building systems and into campus and community-scale power.

Fuel Cells for Generation

Hydrogen is clearly a clean and abundant fuel for power generation, which can be generated in a manner that is environmentally responsible and stored in a way that is safe and efficient. The next step in the process is using hydrogen for electricity production.

Quiet, Clean, and Easily Maintained

The concept of fuel cells is not new—it has been around since the mid-1800s, and even predates the roll out of the power-plant-and-grid system in the US. Fuel cells are often compared to batteries, as they are quiet and the main process does not contain moving parts, as an engine does. However they are, more accurately, a generation, rather than storage, technology. Like any power generator, they require fuel, and will continue to generate electricity as long as that fuel is present. They do so with chemical, rather than mechanical, forces, but the outcome of fuel-in/ electricity-out is the same. Fuel cells tend to have low service and repair costs, as fewer moving parts means there is less that can break down due to friction or wear. Fewer moving parts also means fuel cells are very quiet and do not cause excessive vibration. Fuel cells also are very efficient, in particular when considering that high quality heat (i.e., stable, high temperature heat) and water are byproducts that can be used to reduce energy needs for related systems in a building.

Fuel cells have low service and repair costs

University campuses, for instance, are one scenario that highlights the benefits from fuel cells. Universities will have buildings such as labs and data centers that require constant, high-quality power. On-site power is advantageous in this situation as grid power can be unreliable. Universities will also want quiet, clean power, and dormitories and cafeterias would leverage the heat and hot water generated from a fuel cell. The same conditions could be applied to hospitals, or in the hospitality industry. In an industrial setting, high quality power is also needed for sensitive manufacturing and production, and the excess heat can again be leveraged for purposes such as generating steam or industrial drying processes.

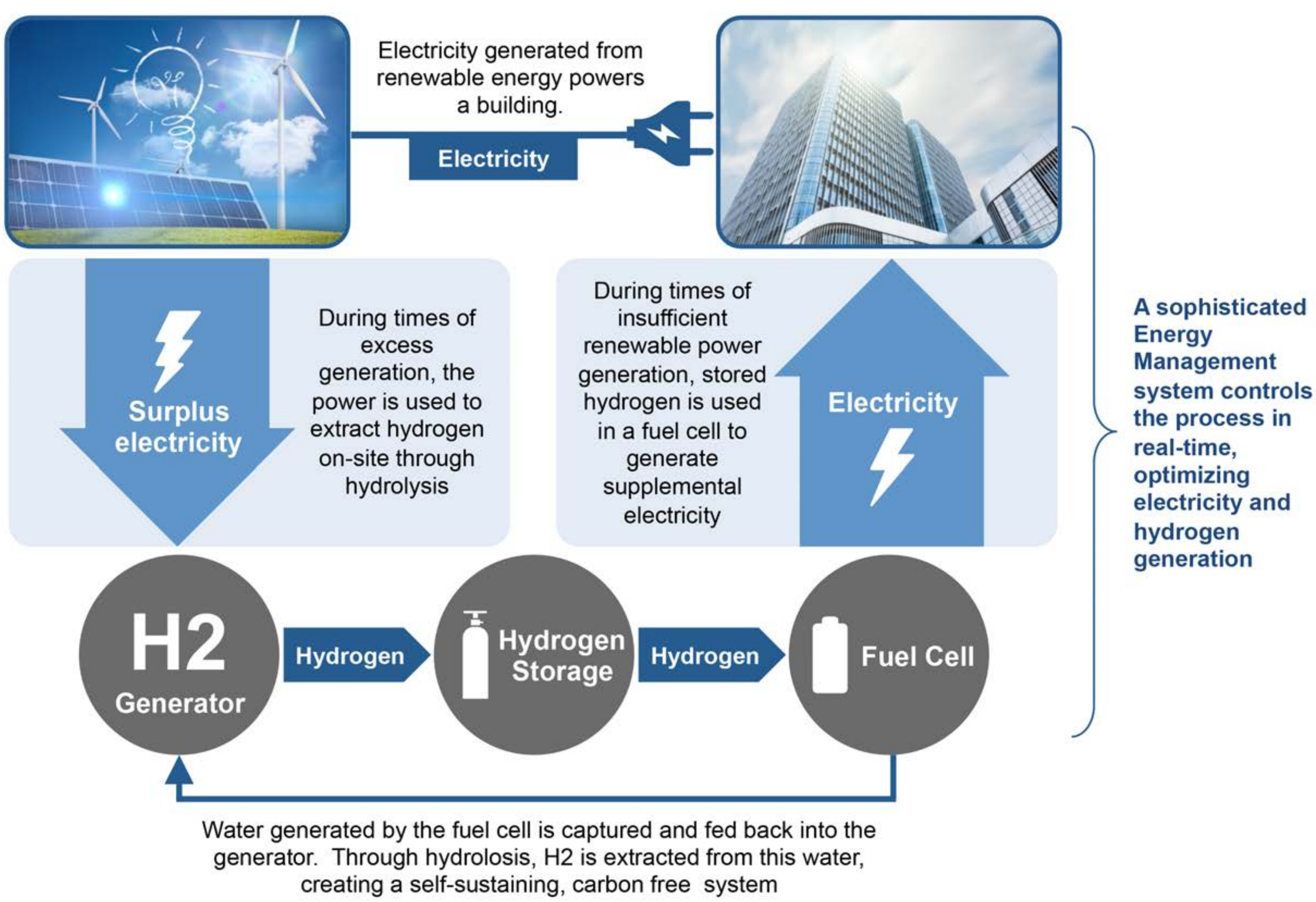
Coming Full Circle

A truly clean and efficient source of power also needs be plentiful to be effective, and the best way to ensure an on-going source of energy is to have that system be cyclical. In the hydrogen system, hydrogen is extracted from water to power a fuel cell, then the fuel cells recombines the hydrogen with oxygen to generate pure water.

Figure 1 illustrates this process, in which:

- Solar panels, in this example, generate fuel-free and emission-free electricity. Some of the electricity goes to power a building and the remaining electricity is routed to the hydrogen generator.
- The hydrogen generator uses this electricity to extract hydrogen from water. The hydrogen then moves to a storage tank.
- When power is needed in addition to what the solar panels can provide, such as at night, this stored hydrogen is used in a fuel cell, which generates electricity for the building.

FIGURE 1: THE HYDROGEN SYSTEM



Source: Toshiba

Toshiba's system is both practical and revolutionary in that it incorporates all the aspects needed for a self-sufficient on-site clean energy system. It turns the challenges of renewable energy—intermittent and poorly-timed electricity generation—into a benefit by "time shifting" energy usage. For example, Toshiba had an H_2One™ located in southern Japan, a region that receives plentiful sunshine during the summer. At the Henn na Hotel in Nagasaki, long summer days generate ample electricity through the system's PV panels. This electricity goes to power the hotel, but also generate enough power in excess to fuel the on-site hydrogen extraction process. A highly sophisticated energy management system allows the electricity to toggle between powering the hotel and generating hydrogen in real-time.

The hydrogen is stored on-site safely and with no degradation over time. During evening hours and in the winter when the solar panels are not able generate the full building's load of power, the hydrogen is used in the fuel cell—automatically and with near-perfect timing due to the energy management system—to supplement or replace the solar-generated electricity, along with heat, a byproduct of the fuel cell, that further helps reduce the building's energy needs.

The system is hence fully, and automatically, responsive to the phases of day and night and cycle of the seasons, in a closed-loop system.

The Potential of Carbon Free Future

Such a system can be scaled up as needed. It can incorporate additional renewable energy sources such as wind allowing for even greater volumes of hydrogen to be extracted and stored. A wide-spread renewable energy/hydrogen extraction and fuel cell system could be therefore used at a much broader scale than just one building.

Long-term, could have the potential to disrupt the century-old power plant and grid system, with its inefficiencies and growing complexities. This may not happen overnight, however in the short term, the solutions already exist to provide buildings, campuses, and even communities with a clean, efficient, self-sustained and infinite power solution.

WHAT NEXT?

Learn more about Toshiba's innovative energy solutions:

toshiba.com/power

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This is the fourth in a series of Frost & Sullivan white papers on the future of energy in the US, the series will dive deeper into the following subjects:

- Energy in America
- Energy Storage
- Hydropower

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Silicon Valley
3211 Scott Blvd
Santa Clara, CA 95054

Tel 650 475 4500
Fax 650 475 1571

San Antonio
7550 West Interstate 10
Suite 400
San Antonio, TX 78229

Tel 210 348 1000
Fax 210 348 1003

London
Floor 3 - Building 5,
Chiswick Business Park,
566 Chiswick High Road
London W4 5YF

Tel +44 (0)20 8996 8500
Fax +44 (0)20 8994 1389

877.GoFrost
myfrost@frost.com
www.frost.com

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