WHITE PAPER

Distributed hydrogen production

Lowering the global cost and carbon footprint of hydrogen production

By: Tony Leo

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Distributed hydrogen production benefits

An emerging approach to generating hydrogen can serve markets at lower cost and with lower environmental impact than existing alternatives. Hydrogen can be provided locally to users at a distributed scale while producing high-value power, water, and heat products. The technology uses an ultra-clean fuel cell that converts natural gas or renewable hydrocarbon fuels to hydrogen as part of the power generation process. The system can produce extra hydrogen at lower cost and with much lower emissions. The carbon footprint for hydrogen production from this system is much smaller than when conventional methods are used.

Hydrogen production is driven by waste energy from the fuel cell process, rather than the conventional burning of fuel. The hydrogen production rate is about 1,200 kg/day, which is a good scale to be sited near industrial hydrogen users and fuel cell vehicle filling stations, eliminating the need to truck hydrogen long distances in polluting vehicles. The systems can also be sited near renewable fuel sources, such as wastewater treatment plants, to produce renewable hydrogen. Larger systems can be configured with multiple units. Distributed scale hydrogen production has been attempted before, but high cost due to economies of scale has limited the commercial impact.

By co-producing hydrogen with other value streams (power, water, and heat), this approach solves the scale problem in many markets. The fuel cell plant modified for hydrogen production is called a tri-generation system because it produces power, water, and hydrogen.

Industrial hydrogen use *is an existing market.*

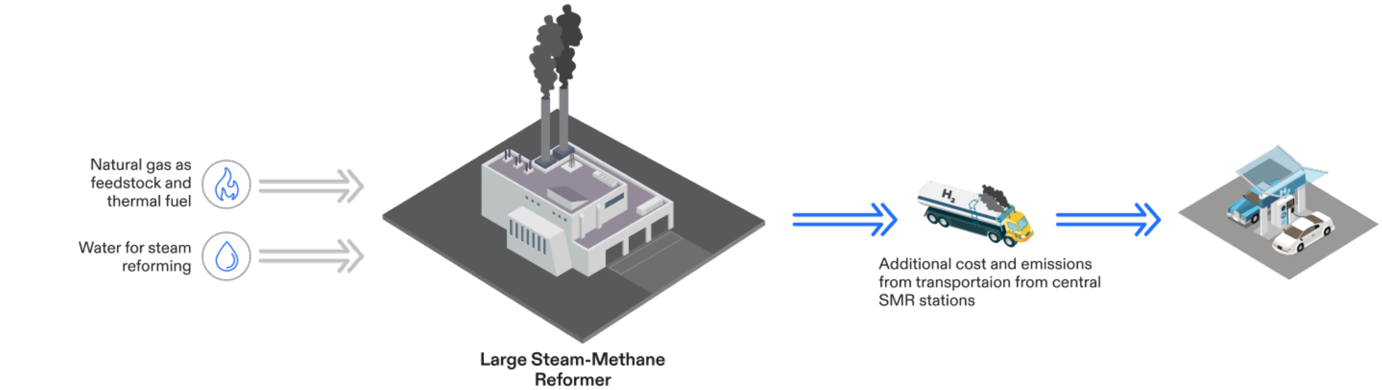
Vehicle fueling *is an emerging market.*

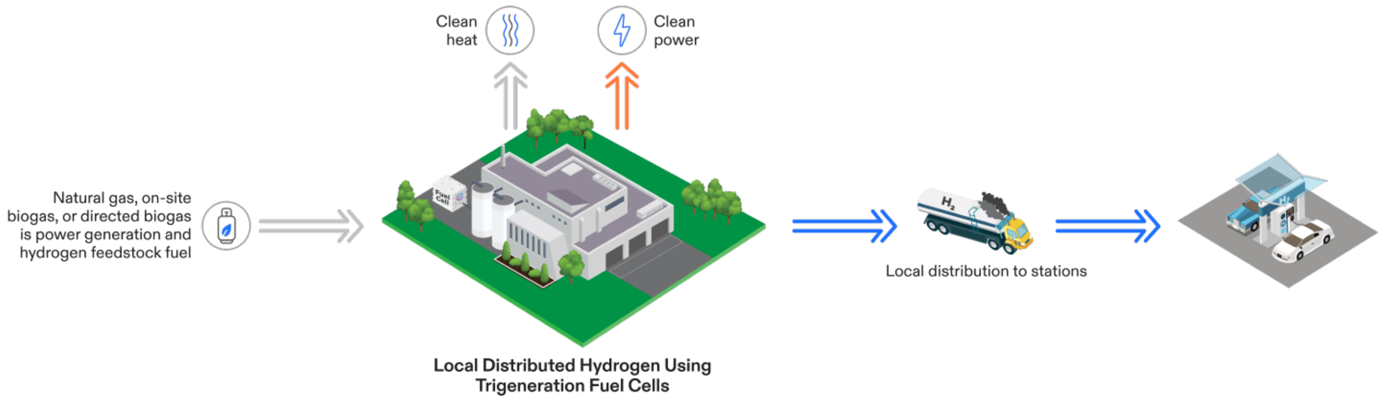
Distributed hydrogen applications

Significant near-term and emerging markets exist for distributed hydrogen production.

Hydrogen is typically produced from natural gas (which is mostly methane) in large plants that produce hydrogen from a reaction of steam and methane called reforming. These plants, called Steam-Methane Reformers (SMR), burn additional fuel to produce heat for the reforming reaction and steam production. Hydrogen produced in these large plants is distributed to users in trucks as liquid or pressurized gas. Fuel cell vehicles using this fuel emit much less greenhouse gas and NOX than a conventionally fueled vehicle. Additional emissions reductions are possible using locally produced hydrogen in tri-generation fuel cell systems, which are inherently lower in emissions than conventional hydrogen production methods and can produce green hydrogen from renewable fuels.

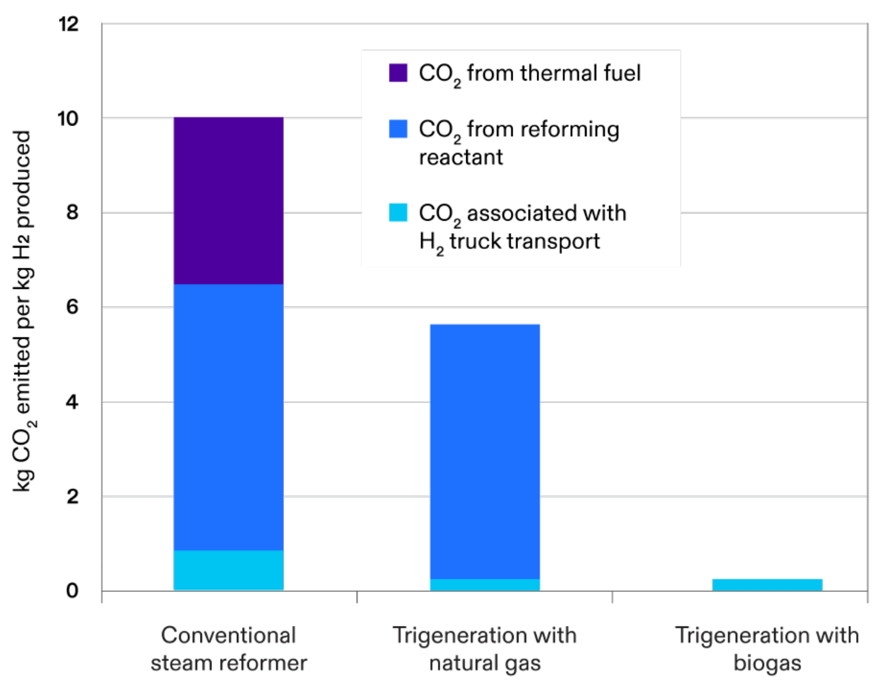
Tri-generation systems also produce hydrogen through a reforming reaction, but the heat and steam needed for the reforming process come from the fuel cell power generation reaction, so no additional fuel is burned, and no water is consumed. NOX emissions are negligible, and GHG emissions per kg of hydrogen produced are about 40% less than conventional SMR production when using natural gas fuel. The hydrogen is carbon-free when using biogas fuel. The price of the hydrogen is reduced by the revenue from the fuel cell system's co-production of power and heat. While producing clean hydrogen, tri-generation systems provide clean power, water, and heat in projects that can provide power savings, improve grid reliability, and support microgrid systems.





Central and distributed hydrogen comparison

Tri-generation is inherently cleaner than conventional production, and production closer to point-of-use reduces the emissions and costs associated with transportation. The tri-generation concept has significant advantages over conventional reforming when it comes to carbon footprint considerations. In the natural gas reforming reaction, hydrogen is removed from methane (CH_4) in the fuel, and the carbon component of the methane combines with oxygen to produce CO_2. In the theoretical complete reforming reaction, 5.4 kg of CO_2 are emitted for every kg of hydrogen produced. In addition to providing the reaction feedstock, extra natural gas is also burned to provide the thermal energy required by the reforming reaction. Considering the extra fuel that is burned in a typical large-scale reformer, about 9 kg of CO_2 are emitted for every kg of hydrogen produced. In the tri-generation system, the thermal energy required to drive the reforming reaction is provided entirely by fuel cell waste heat, so the carbon footprint of hydrogen production is driven down to the theoretical 5.4 kg CO_2 per kg of hydrogen. Since these systems can be deployed near renewable fuel sources, such as wastewater treatment digesters, they can be fueled with biogas, essentially driving the carbon footprint to zero (or negative, if waste heat is used to offset natural gas burner fuel in digester heaters). Many of FuelCell Energy's fuel cell plants deployed in the U.S. are operating on renewable fuels at wastewater treatment plants. The first tri-generation field demonstration system provided zero carbon hydrogen from renewable fuel at the Orange County Sanitation District wastewater treatment plant in Fountain Valley, California, in a project supported by the U.S. Department of Energy.



Hydrogen production carbon footprint comparison

Thermal energy required for the reforming process is produced by burning fuel in conventional reforming but driven by fuel cell waste heat in FuelCell Energy's tri-generation systems.

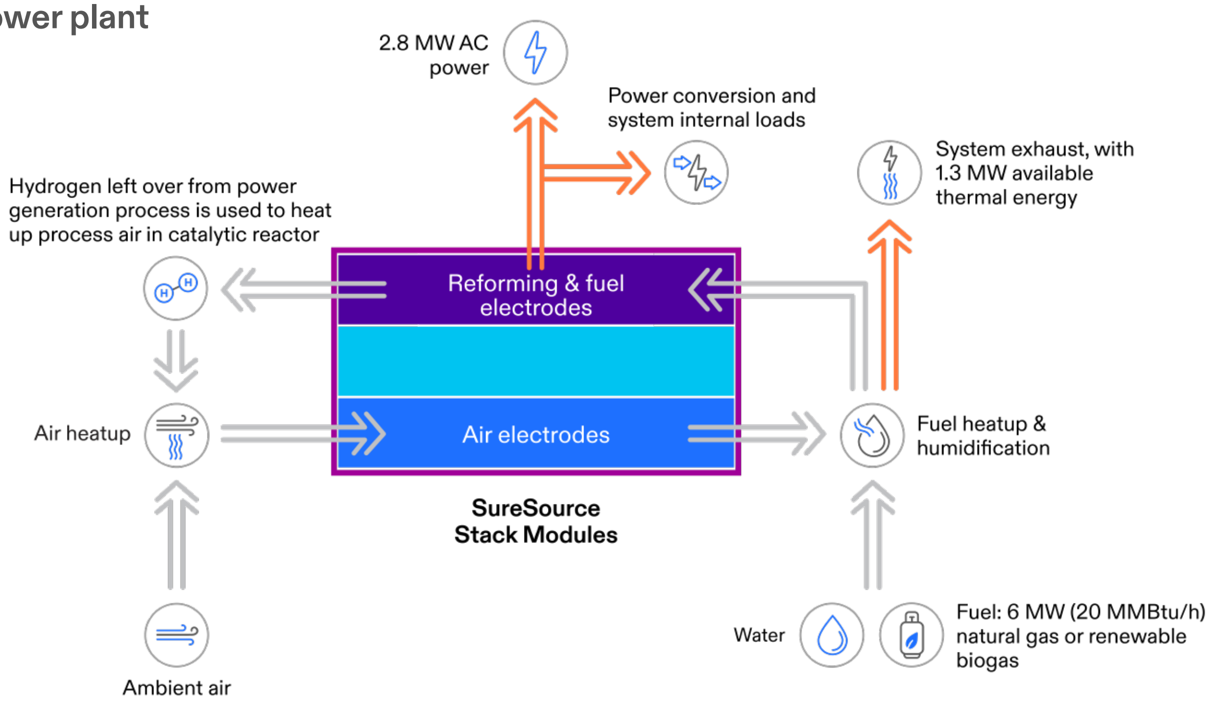
The tri-generation system is based on FuelCell Energy's proven fuel cell products. A major advantage of these products is internal reforming. Hydrocarbon fuels such as natural gas or biogas can be sent directly to the fuel cell stacks, where they will be reformed to hydrogen before reacting electrochemically to make power. The thermal energy required by the reforming process is provided by fuel cell waste heat, eliminating the need to burn additional fuel. This makes internal reforming a low-cost and extremely efficient way to produce hydrogen. The tri-generation system concept is an extension of the standard FuelCell Energy system design.

In standard FuelCell Energy power plants, the power generation reactions consume about 70% of the internally reformed hydrogen. The remaining 30% is used in a catalytic reactor to pre-heat incoming process air. In the tri-generation system, excess hydrogen produced by the internal reforming reactions is separated from the system and the pre-heat energy is provided by heat exchange with other process streams. The additional equipment which separates and purifies the hydrogen relies on conventional process engineering technology for hydrogen purification.

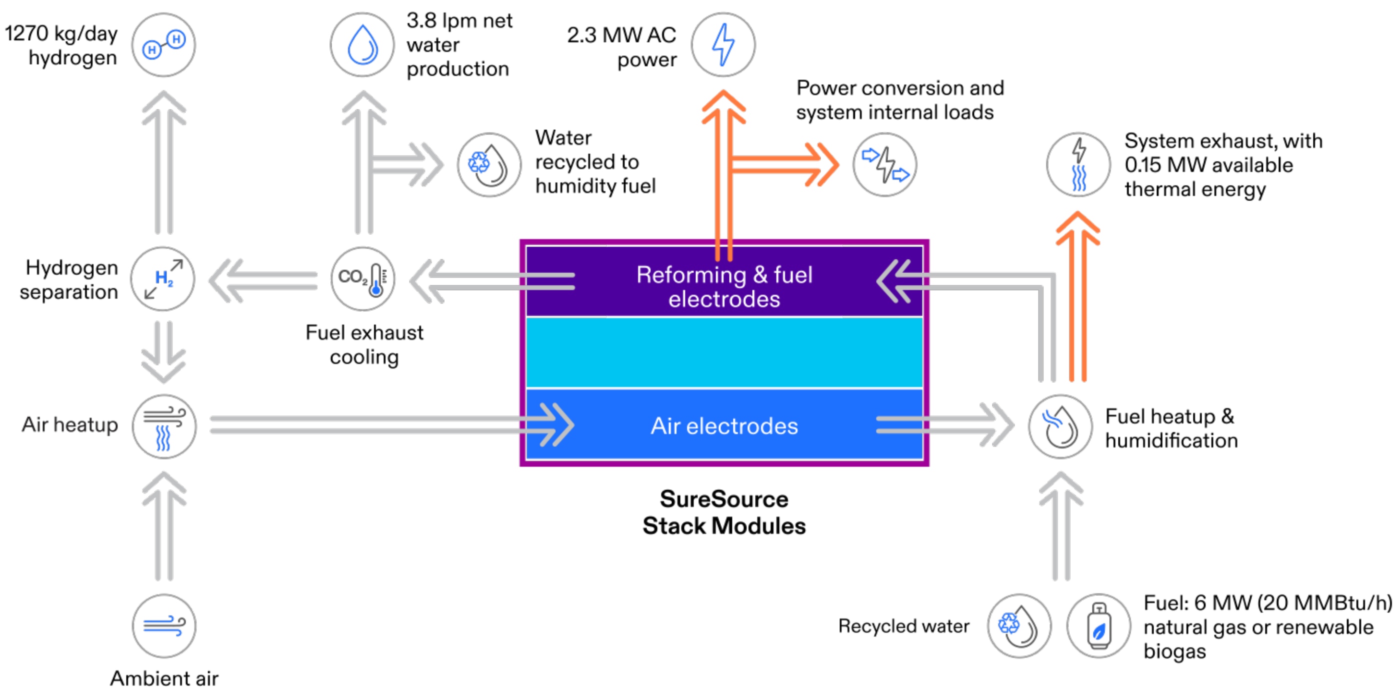
Tri-generation simplified system schematic

A standard FuelCell Energy power plant is modified to include equipment to extract residual hydrogen from the stack anode exhaust stream.

Standard power plant



Tri-generation system



The power output and hydrogen-generation profile for the standard FuelCell Energy 3000 and tri-generation systems are shown in the following table. Power output levels in tri-generation mode reflect the additional parasitic power needed for hydrogen separation and purification. A layout of the system is shown in the figure below.

3000 Output, kW	2,800
Tri-generation Configuration Output, kW	2,350
Hydrogen Production, kg/day	1,270
Water Production, liters/day	5,300

FuelCell Energy tri-generation

***FuelCell Energy** hydrogen tri-generation system.*

Hydrogen production rates are a good fit for industrial hydrogen users and emerging vehicle filling stations.

The first commercial-scale tri-generation project is underway with Toyota at the Port of Long Beach, California. This port facility is where Toyota is importing their Mirai fuel cell vehicles, which need to be fueled before being delivered to dealers. Toyota is also demonstrating the use of hydrogen fueled heavy-duty trucks at this location, which they are developing with the Kenworth division of Paccar. The tri-generation system being installed at the port will use directed renewable biogas and produce up to 2.3 MW of renewable power to meet Toyota's power needs. Excess power will be sold to the local utility under a biogas feed in tariff. The system will also produce up to 1,200 kg/day of renewable hydrogen for Toyota's vehicle fueling operations. As an added benefit, the system will produce up to 5,300 liters/day of clean water, which Toyota will use for car washing. This is especially valuable as Long Beach is impacted by the continuing drought situation in California.