FastOx™ Gasification & Renewable Hydrogen

Demonstration and Analysis Plan for FastOx Syngas to Hydrogen Fuel Cell

Sierra Energy, March 2014
**Introduction**

Hydrogen fuels from renewable sources are considered some of the most promising for reducing oil consumption, greenhouse gas emissions, and air pollution. Municipal solid waste (MSW) represents a distributed, renewable source of hydrogen capable of addressing multiple environmental concerns associated with energy generation while remaining cost competitive with conventional sources of H₂ (current models predict production costs of $1.94 per gallon gasoline equivalent, even at very small scales). Making use of this resource to produce hydrogen requires further integration development and real-world operation. Funding for technology demonstration and analysis funding is fundamental to acquire the data and experience needed to understand the full techno-economic potential of these fuels.

**Our solution**

Sierra Energy’s FastOx™ gasification technology allows the complete conversion of MSW and other waste resources into a sustainable synthetic fuel gas (“syngas”) and safe, vitrified slag/glass and recyclable metals. The FastOx syngas primarily composed of hydrogen (H₂) and carbon monoxide (CO) is a flexible, low cost fuel source and:

- It displaces natural gas and other conventional fossil fuels,
- Is generally ‘carbon negative’ or ‘carbon neutral’ due to avoiding the emissions from transportation and landfiling the waste,
- Can be converted into a variety of fuels, the most efficient and economical is hydrogen.

This demonstration will utilize an existing gasifier already producing syngas by adding a syngas-to-hydrogen pathway. A fully-funded gasification-to-electricity project is underway at U.S. Garrison Fort Hunter Liggett to generate electricity and Fischer Tropsch diesel substitute from locally generated waste. **Sierra Energy is seeking funding to build an additional pathway for syngas-to-hydrogen fuel cell at this site** to provide real-world validation and bring to market a novel hydrogen production approach that facilitates the Fuel Cell Technology Office goals.

After making progress with hydrogen, Sierra Energy is also seeking funding for a second phase of this project: the addition of equipment that will take CO₂ off-gas from the hydrogen generating process and convert these emissions to transportation fuels, closing the loop and maximizing the potential outputs on the system.

**Potential Benefits**

The production of hydrogen from waste materials via the FastOx technology can be deployed in small-scale, distributed production plants that could be located to solve multiple local municipal problems:

- Sourcing low-cost alternative distributed primary or peak shaving power where waste is generated
- Demonstrate alternative H₂ source in real-world conditions
- Reduction in transportation of waste materials and associated greenhouse gas emissions;
• Elimination and potential remediation of existing landfills and the associated greenhouse gas emissions
• Production of carbon negative hydrogen source (avoidance of methane emissions from landfill)
• Generation of local energy products that reduce dependence on foreign oil.
• Exposure of hydrogen power technologies to a potential early-adopter: the U.S. Department of Defense

Technical Description
The FastOx gasifier is able to produce low-cost hydrogen using the following systems in series:

1. The FastOx gasifier (funded and under construction at Fort Hunter Liggett)
2. Gas Cleaning, Water Gas Shift and H₂ Purification
3. Hydrogen Fuel Cell

Figure 1 above is a rendering of the major system components currently under construction for Fort Hunter Liggett, shown with the potential addition of the equipment within the two modules on the right - gas cleaning and preparation specific to hydrogen fuel cell requirements, and the fuel cell itself (far right). A process flow diagram for the hydrogen pathway is below in Figure 2.
The FastOx Gasifier

Sierra's FastOx Pathfinder under construction at U.S. Garrison Fort Hunter Liggett is a 10-tonne-per-day ("MTPD") waste-gasification system that efficiently converts virtually any form of waste into renewable energy. The feedstock at Fort Hunter Liggett will be MSW generated within the facilities of the garrison that would otherwise go to landfill.

Sierra's compact and integrated Pathfinder consists of containerized modules including a waste pre-processing unit, an air-separation unit ("ASU") for oxygen generation, a FastOx gasifier, gas conditioning equipment, a control/utility skid, and an electrical genset. Sierra's patented high-temperature thermochemical conversion process breaks down waste at the molecular level. The process begins with feeding waste into the top of the refractory-lined gasifier, while oxygen and steam are injected at the bottom. The design allows the entire process to occur within a single vessel, with no internal moving parts, minimizing maintenance and increasing up-time.

Gravity pulls waste through four reaction zones in the FastOx gasifier as shown in Figure 3:
1. **Drying Zone:** The hot syngas produced lower in the FastOx gasifier rises and passes through incoming wet waste in the top zone of the unit, driving off any free moisture.

2. **Devolatization Zone:** The majority of organic matter is converted into syngas through pyrolysis (heating in the absence of free oxygen).

3. **Partial Oxidation Zone:** Remaining organic materials in the waste react with injected oxygen and steam, creating temperatures of 2,000°C and converting any residual carbon into syngas.

4. **Melting Zone:** Any inorganic compounds melt due to the high temperatures in the partial oxidation zone, producing liquid metal and a non-leaching inert stone ("slag"), both of which are recovered for use or sale.

Syngas produced by the FastOx gasifier flows to a gas cleaning and preparation module where any trace contaminants are removed to meet fuel cell requirements.

While Sierra's Pathfinder is a 10 MTPD unit, shown in Figure 1 above, Sierra expects that its FastOx technology can easily scale-up to extremely large capacities equal to the largest blast furnaces in the world – many thousands of tonnes per day in a single vessel – because they share the same basic design. This flexibility allows for sizing of a system to match a site's specific feedstock amounts. Sierra's FastOx technology has a lower parasitic load, a higher specific throughput capacity, a greater ability to consume high-moisture feedstocks, no leftover toxic ash, and lower air emissions.

Sierra built its most recent Mk4.2 gasifier in September 2010 to test the conversion of multiple waste streams, determine the composition of the resulting syngas, and troubleshoot operational logistics. In a second Renewable Energy Testing Center (RETC) whitepaper written in September 2012, preliminary Mk4 data satisfied the following technical objectives:

- Verification of the Mk4.2’s operability with numerous waste materials, all varying in ash and moisture content.
- Validation of increased syngas quality through real-time gas analysis, demonstrating a 118% increase in the dry syngas energy density when compared with conventional air-blown operations.
• Confirmation of the non-leaching character of produced slag, in accordance with EPA TCLP and TTLC standards, qualifying the slag to be sold as a construction material to replace cement clinker and road-base.
• Analysis of the Mk4.2’s performance metrics, indicating a 116% increase in operational productivity and a 185% increase in oxidant productivity.

Gas Cleaning, Water Gas Shift and H₂ Purification
Additional gas conditioning and preparation is required for the production of hydrogen. This additional equipment is not required for the production of electricity using gas turbines, or reciprocating internal combustion engines. After additional cleanup, the syngas moves on to the gas conditioning and preparation unit, where it is compressed and mixed with high-pressure saturated steam and fed into the Water-Gas Shift (WGS) reactor where the following reaction takes place to maximize H₂ production:

\[ \text{CO} + \text{H}_2\text{O} \rightarrow \text{H}_2 + \text{CO}_2 \]

The amount of steam injected into the WGS reactor will be continuously controlled to maximize the H₂ production. The WGS reaction is mildly exothermic, and excess heat is removed from the shifted syngas with a waste-heat boiler (heat exchanger) that makes high-pressure steam.

A hydrogen membrane module is used to remove the hydrogen from the post-WGS gas stream, before sending that hydrogen stream to a pressure swing adsorption (PSA) module to purify the hydrogen product stream to the very high purity requirements.

• Syngas compressor - used to raise the pressure of the syngas from 2 barA to the pressures required by the downstream equipment;
• WGS reactor for conversion to H₂;
• Hydrogen membrane - for the separation of the excess hydrogen from the post-WGS syngas; and
• PSA module - for final purification of the separated hydrogen to meet the hydrogen purity requirements of the final consumer, in this case 99.99% volume pure hydrogen for a fuel cell.

Hydrogen Fuel Cell
The purified hydrogen produced by the system is fed into a hydrogen fuel cell. A proton exchange membrane (PEM) fuel cell is an established, low temperature hydrogen-fueled technology with proven operational abilities converting conventional hydrogen sources into electricity. PEMs have a variety of end use applications (stationary, transportation), high electrical efficiency ranging from 40-60%, and no emissions other than heat and water.

This project would provide essential integration and logistical control strategies, input and output data, and analysis parameters of waste-to-syngas-to-hydrogen, and allow for conjecture on economic viability and associated quantifiable environmental benefits.
**CO₂ Recovery: Phase II Project Addition**

After the syngas goes through the water gas shift and hydrogen membrane, a system upgrade can be added to include enhanced CO₂ recovery. Gas treatment to the off-gas at this point in the process (gases other than the hydrogen) can be installed to generate a purified stream of CO₂. At this stage, one of the several methods of converting CO₂ to transportation fuels becomes viable. The addition of this capability to a FastOx system will maximize the energy output and leave no wasted emissions. Phase II of this project will demonstrate this process and capture data for future system inclusion.

**Hydrogen Economics with FastOx**

The US Department of Energy (DOE) has developed a detailed Excel-based program to calculate the unit cost of producing hydrogen from various processes. The H2A model allows the user to enter the process mass balance for a given example project size, along with key assumptions (such as land, labor, utilities and the costs of borrowing) and calculates financial metrics, most notably being the present-value Specific Hydrogen Production cost in $/kg(H₂).

Sierra Energy used the H2A model to calculate key metrics for the FastOx process and worked with experts at NREL’s ‘Hydrogen Technologies & Systems Center’ to refine the assumptions and model settings. The results are displayed in the chart above.

In comparison, the cost of producing hydrogen via conventional methods:

- H₂ from natural gas (produced via steam reforming at fueling station) $4 – $5 per kg(H₂)
- H₂ from natural gas (produced via steam reforming off-site and delivered by truck) $6 – $8 per kg(H₂)
• H₂ from wind (via electrolysis) $8 – $10 per kg(H₂)
• H₂ from solar (via electrolysis) $10 – $12 per kg(H₂)

The Proton Exchange Membrane (PEM) fuel cell technologies that utilize hydrogen gas are significantly more efficient compared to internal combustion (IC) engines (less energy is wasted as heat and noise). For transportation, a fuel cell would power a vehicle approximately 2.5 times as far as a gallon of gasoline in an IC engine. Therefore, even though 1 kg of hydrogen (120.2 MJ(LHV)/kg(H₂)) coincidentally has the same energy content as 1 gallon of gasoline (120.2 MJ(LHV)/gal(California reformulated gasoline), the 1 kg(H₂) has the potential to replace 2.5 gallons of gasoline, and thus a hydrogen production cost of $5.00/kg(H₂) is equivalent to $2.00/gal(gasoline) or $2.00/GGE where GGE is “Gallon of Gasoline Equivalent”.

Therefore, even at the smallest commercially-deployable FastOx scale (12.5MTPD gasifier size) hydrogen can be produced an industry-leading $1.94/GGE.

Coupled with the benefits the FastOx technology can provide for solid waste authorities (increasing the volume of recyclable materials recovered, and eliminating landfills), this distributed FastOx-to-H₂ system is a paradigm shift from conventional operations.

**DOE H2A MODEL** The DOE’s H2A model can be downloaded here:
http://www.hydrogen.energy.gov/h2a_production.html

**Demonstration Plan**

**Timeline**

Construction of the FastOx gasification system is expected to be complete by the end of 2014. If funded, a hydrogen pathway will be designed and installed accordingly:

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<thead>
<tr>
<th>Task No</th>
<th>Task Name</th>
<th>2015</th>
<th>2016</th>
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<tr>
<td>0</td>
<td>Project Initiation</td>
<td>Jan - Mar</td>
<td>Apr-Jun</td>
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<tr>
<td>1</td>
<td>Engineering and Permitting</td>
<td>Apr-Jun</td>
<td>Jul - Sep</td>
</tr>
<tr>
<td>2</td>
<td>Construction and System Installation</td>
<td>Oct - Dec</td>
<td>Jan - Mar</td>
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<tr>
<td>3</td>
<td>Commissioning</td>
<td>Apr - Jun</td>
<td>Jul - Sep</td>
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<tr>
<td>4</td>
<td>Demonstration</td>
<td></td>
<td></td>
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</tbody>
</table>

**Project Initiation**: This task includes all contracting, initial reporting and other requirements of the funding. This task will also include the establishment of technical project objectives in order to deliver quantifiable success criteria useful for techno-economic analysis and environmental benefit studies.

**Engineering and Permitting**: The detailed design, equipment selection, final cost estimates, and equipment acquisition will result from this task, commencing with a final equipment list and site engineering requirements. Any permitting requirements are also included in this task.
Construction and System Installation: Site engineering and preparation of the new equipment will begin while the final equipment acquisition is taking place as some items have long lead-times for manufacturing.

Commissioning: As equipment is installed, shakedown subsystem testing and sampling of gases produced to qualify the gas cleaning and preparation module will take place to ensure the hydrogen produced meets the stringent specifications of the fuel cell downstream.

Demonstration: Hydrogen production using testing parameters determined in the Project Initiation task which result in reporting of results from Sierra Energy and a third party. The National Renewable Energy Lab (NREL) will conduct a greenhouse gas lifecycle analysis, and analyze the viability of hydrogen electricity produced from waste with FastOx gasification in the existing and emerging market. Depending on funding during this task, Phase II of the project will take place following successful demonstration of electrical generation via hydrogen fuel cell.

Budget Estimate
The following is a rough estimate of the costs required to install and demonstrate a hydrogen fuel cell pathway using the already constructed gasification equipment at Fort Hunter Liggett:

<table>
<thead>
<tr>
<th>Description</th>
<th>Cost</th>
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<tbody>
<tr>
<td>Engineering/Permitting/Procurement</td>
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<tr>
<td>Site Preparation Construction (utilities, foundations, electrical)</td>
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<tr>
<td>Gas Cleaning and Compression</td>
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<td>Water Gas Shift</td>
<td>$60,000</td>
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<td>H2 Membrane and PSA Purifier</td>
<td>$430,000</td>
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<td>Hydrogen Fuel Cell (250kW_e)</td>
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<td>Commissioning, Operation, and Maintenance Costs</td>
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<tr>
<td>Reporting, Internal and Third Party</td>
<td>$150,000</td>
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<td><strong>Total</strong></td>
<td><strong>$2,480,000</strong></td>
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Additional funding would be necessary to design, purchase and install the CO₂ recovery equipment as a Phase II of this project. Costs depend on the technologies selected for the gas treatment and conversion to transportation fuels.