Hydrogen-Based System for Storing Curtailed Solar Power

Renewable energies such as solar and wind are abundant with the potential to fully supply the power requirements of the United States and the world, thereby removing the carbon emissions and climate threats associated with fossil fuel power generation. However, there is one universal barrier that prevents this from becoming a reality; renewable energies are intermittent by nature and, unlike fossil fuels, cannot be stored in their native form to provide power generation on demand.

Our solution is to use electrolysis to convert curtailed solar power into hydrogen, which is an energy carrier that can be stored using our patented system in man-made underground chambers. Hydrogen has a high energy content and thousands of kilograms can be stored in a single chamber and reconverted into electricity using fuel cells or hydrogen rated steam turbine technologies or it can be blended with natural gas.

While our patented energy storage system is based on existing technologies and requires no technological breakthroughs, there are still challenges to be met. First and perhaps foremost, ***we need to establish credibility***. While we have confidence that our concept will work as proposed, we fully realize that validation is essential to secure investors. Unfortunately, we are in the proverbial "Catch 22" situation. Investors that we've talked to want to see a working prototype before investing in the idea, but we need the investment money to build the prototype.

Prior to construction of the working prototype, ***academic validation of the fundamental principles involved in our concept is also needed***. This includes evaluation of the following topics:

- <u>Thermodynamic Principles</u>: When a gas is pumped into a large constant volume container, the gas is compressed and heat is generated. When the gas is removed from the container, the gas expands and a cooling effect takes place. The greater the size of the container and the greater the amount of gas involved, the greater the deviations in the temperature and pressure. The regulated flow of water into and out of the SWS chamber causes the water in the chamber to act as a liquid piston which constantly adjusts the gas storage volume while maintaining a constant gas pressure. This process eliminates pressure and temperature fluctuations during the fill/empty cycle that would occur inside a constant volume storage chamber. Beyond this, the water and surrounding ground acts a heat sink which can further attenuate any temperature changes that might occur.

- <u>Hydrogen Gas & Water Interface</u>: We have done preliminary studies on possible interactions between the stored hydrogen gas and the water in the chamber, especially at the boundary where the gas and water meet. Our findings show that the amount of hydrogen absorbed into the water will be insignificant and any dissolved oxygen in the water will remain in solution under the conditions existing in the chamber. It is further noted that the SWS patent includes a "floating seal" whereby an inert liquid, or gas, floats on top of the water. This floating seal provides a barrier between the water and the gas inside the chamber and eliminates any potential problems related to direct physical contact.

One aspect that is critical to establishing credibility is ***providing convincing evidence-based analysis that our system is economically viable and analyzing how it compares with competing technologies***. We have conducted some baseline costs associated with our concept and compute a micro-grid size chamber (8.20 ft in diameter and 1,250 ft deep) can provide delivered electrical power at a cost of $0.030 per kWh if the gas is stored at 580 psi in the chamber and as low as $0.021 per kWh if the gas is filled at 5,000 psi which is within the chamber operational limits. This is a round trip cost at an overall efficiency of 30 pct. The storage costs alone are $0.122/kg for the 580-psi chamber which holds 6,164 kg of hydrogen when full. The chamber when pressurized to 5,000 psi holds 53,425 kg of hydrogen at a cost of $0.014/kg. The cost to construct the chamber is $6.1 million. The full analysis is available upon request from Solar Wind Storage.

We need to substantiate that this cost is superior to batteries and other storage methods. We also need to analyze at what baseline capacity or renewable energy penetration levels our hydrogen-based system provides a cost incentive alternative to battery storage. Ultimately, a parametric cost assessment needs to be done to determine economies of scale and how to best optimize our system to various renewable energy penetrations, duty cycles, and grid demands.

- Regeneration technologies: We anticipate using fuel cells as the primary method for converting hydrogen back into electricity. This appears to be the weakest link in our approach as the efficiency of fuel cell regeneration seems to be in the 40-50 percent range (compared to electrolyzers which have efficiencies in the 70 - 80 percent range). Two points are worth investigating: first, are there more efficient fuel cell technologies on the horizon that should be considered? Second, what is the feasibility of using a reversible electrolyzer that performs both hydrogen generation and hydrogen processing functions? We are also aware that Siemens and GE are developing hydrogen-burning steam turbine technologies, but despite our efforts we have not been able to leverage our storage concept with these developments.

- DOE research into high pressure hydrogen production: We are aware that the DOE is experimenting with high pressure (10,000 psi) hydrogen production methods and technology. It would certainly be beneficial to see if our capability to store this high-pressure hydrogen in large volumes could be leveraged in some way to include our efforts in this R&D program.

There are some "research and engineering design" elements and "proof-of-concept" component trials that would be beneficial.

- Hydrogen-resistant lining materials: We recognize that hydrogen causes embrittlement to steel and many metals. Since hydrogen is such a small molecule, the chamber (although lined with steel or concrete during construction) will need to be sealed with hydrogen-resistant material to avoid long term damage to the chamber integrity and to prevent excessive hydrogen leakage. We are aware that there are substantial hydrogen pipelines in the U.S., but we are unfamiliar with the hydrogen-resistant materials used in these applications. Hence, we can use support from a materials scientist to provide assistance in this regard. Ideally we envision a (composite) material that could be sprayed onto the chamber walls during or after construction. It would seem that laboratory testing of such materials would also be prudent.

- Leakage assessment and mitigation strategy: A baseline assessment of the hydrogen dissipation associated with leakage migration should leakage from chamber occur is one of likely pre-requisites for a first demonstration of the system. We believe that the most likely scenario would be migration of the leaked hydrogen from around the annulus of the chamber to the surface instead of lateral migration through the ground strata. The chamber is grouted in place with concrete but there could be drainage pipes or channels built into this arrangement to facilitate the drainage. Perhaps this can be modeled (numerically), or a small-scale experiment conducted to examine this behavior.

- Moisture in the Hydrogen: Hydrogen gas stored in the SWS chambers and used for certain applications, such as fuel for hydrogen powered vehicles, will need to be dried before using. This topic was discussed during our trip to Boston to visit with Giner ELX, a manufacturer of PEM electrolyzers. A Giner engineer pointed out that the hydrogen gas is normally dried when it first comes out of the electolyzer but, if using the SWS storage system, the drying stage would just need to be delayed until the hydrogen is withdrawn from storage. The same equipment could be used and the overall costs for the drying process would be unchanged.

Finally, we need marketing help!

We feel like the little fish in a big pond. We have seen investors, such as Breakthrough Energy Ventures, fund projects at tens of millions of dollars related to potential energy storage approaches that we feel are much less viable than our approach. Obviously part of this is linked to establishing our credibility overall but we could also benefit from marketing advice and the development of marketing tools. Advancing through the American-Made Solar Challenge would give us the financial resources to validate our solar energy storage concept and to build a working prototype system.