Commercial Optimization of a 100kg/day PEM based Hydrogen Generator For Energy and Industrial Applications

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ABSTRACT:
Commercial hydrogen generators using PEM water electrolysis are well proven, serving industrial applications worldwide in over 50 countries. Now, market and environmental requirements are converging to demand larger on-site hydrogen generators. North American liquid H_2 shortages, increasing trucking costs, developing economies with no liquid infrastructure, utilities, and forklift fuel cell fueling applications are all working to increase market demand for commercial on-site H_2 generation. These commercial applications may be satisfied by a 100 kg H_2/day module; this platform can be the pathway towards a 500 kg H_2/day generator desired for small forecourt hydrogen vehicle fueling stations. This paper discusses the steps necessary and activities already underway to develop a 100 to 500 kg H_2/day PEM hydrogen generator platform to meet commercial market cost targets and approach US DoE transportation fueling cost targets.

KEYWORDS: *hydrogen, generator, electrolyzer, on-site, fueling*

As we within the Hydrogen Technology Group of Proton look to understand and address our future product markets, we see economic, security and environmental drivers converging to demand larger and better on-site hydrogen generators. Applying the metric of US$ per kg of hydrogen, derived from initial capital cost, operating cost and maintenance cost of the hydrogen generator, we see the following opportunities:

- Traditional industrial hydrogen: In the traditional industrial sector, recent liquid H_2 shortages in North America, developing economies with no liquid infrastructure, site security issues, and increased gas delivery transportation costs are building market appreciation for on-site hydrogen generation involving little more than power and water infrastructure. Demand ranges from 2 to 200 kg H_2 per day for many traditional small to medium-sized industrial applications such as heat-treating and electric power turbine generator cooling.

- ForkLift fueling in distribution centers: Major warehouse distribution centers, working with fuel cell system developers and electric lift manufacturers, are actively evaluating the benefits of replacing battery boxes on their electric forklifts with hydrogen fuel cell systems that afford rapid recharge and consistent power availability throughout discharge. A distribution center with 100 forklifts may require from 100 to 400 kg of H_2 fuel per day.

- Electric utility load leveling: Progressive electric utilities are focusing on electrolysis-based projects for grid load-leveling and value creation. The smallest incremental dispatchable load of interest may be 250kW, up to a 1MW load. Modular water electrolyzers in the range of 150 to 500 kg H_2/day, capable of rapid startup and shutdown, can satisfy that requirement.

- Passenger vehicle fueling: Transportation vehicle manufacturers, driven by the need to improve both the fuel economy and the environmental performance of the passenger and freight vehicles in use today, have spent and continue to spend billions of dollars to develop fuel cell electric hybrid vehicles. These hydrogen-fueled vehicles will achieve commercial viability sometime in the next decade or so, hastened perhaps by world economic and political forces. Fueling stations for Y2010 demonstration fleets of 3 to 6 buses can be served by two 100 kg H_2/day machines; these may give way to 500 kg H_2/day capacities by Y2015 to meet near to mid-term 'small forecourt' hydrogen fueling station requirements for bus, fleet and private vehicle fueling.

Today's commercial PEM (proton exchange membrane) water electrolyzers for hydrogen are proven performers, serving industrial applications worldwide in over 50 countries. Commercially available, packaged PEM H_2 generators reliably satisfy hydrogen demands up to 12 kg/day and are competitive with delivered gaseous hydrogen in many applications. PEM-based water electrolyzers offer rapid startup, 100% turndown, excellent gas purity, low component count, ease of operation, high reliability, are scalable, produce gas at elevated pressures useful for storage and processes, and have no liquid electrolytes, only water, as a working fluid.

Proton Energy Systems, a Distributed Energy Systems company (NASDAQ: DESC) has manufactured and sold over 500 HOGEN® hydrogen generators into industrial and research applications worldwide. Proton's traditional competitors, the industrial gas suppliers and potassium hydroxide-based electrolyser manufacturers, have recently adopted PEM electrolysis for smaller scale applications, validating its technical feasibility and marketability.

Figure 1. *Proton's GC, S-series and H-series HOGEN® hydrogen generator are produced in seven models ranging from 300 ccm to 6 Nm3/h hydrogen (12 kg H_2/day)*

Yet, growth into the future markets identified herein for PEM water electrolyzers demand higher hydrogen capacities at market point pricing. What are these price points?

One projection of future market price points can be generated using market data and specific cases of the US DoE H2A model[1] for electrolysis based fueling. Figure 2 is a comparison of today's (Y2006) industrial PEM electrolyser market to price targets required to access future markets for commercial H2 fueling in Y2010 and DoE targeted electrolysis goals for Y2015. Cost per kg of H_2 is computed using the DoE H2A model. [a] Today's machines produce 12 kg H_2/day, while the Y2010 commercial electrolyser machine capacity is in the range of 100 kg H_2/day and the Y2015 electrolyser capacity approaches 500 kg H_2/day. For the Y2015 projection, manufacturing volumes of 500 units per year are assumed. With these inputs to the H2A model, cost targets reduce by about 40% every five years, achieving a target price of US$ 2.75 to 3.50 per kg H_2 delivered by the electrolyser.

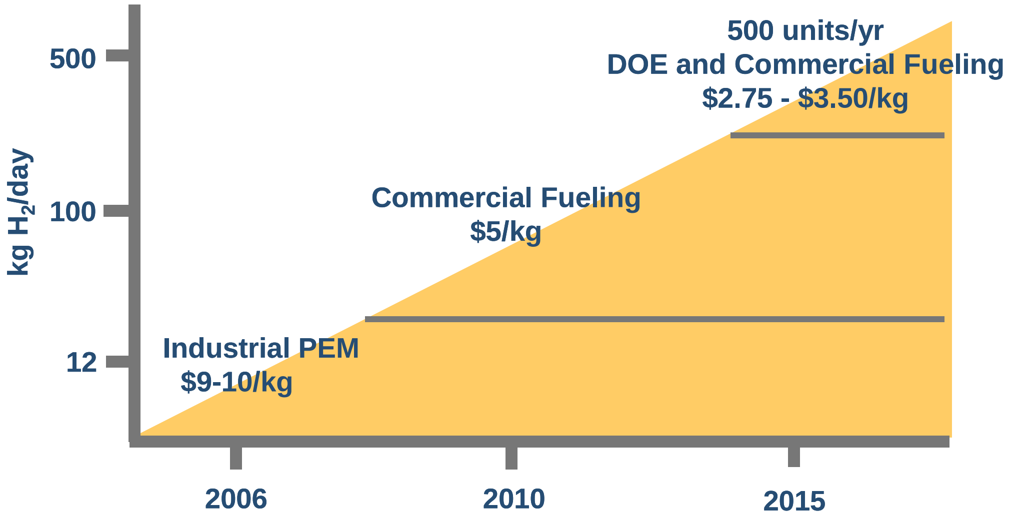

Figure 2. *Projected cost targets for Y2010 and Y2015 electrolysis opportunities*

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[a] *Assume US$ 0.04/kWh electricity, 20 year system life cycle, 90% utilization, and zero IRR for these estimates*

Given these cost targets for these market opportunities, what is the pathway to get there? Starting with a 12 kg/day product baseline produced in quantities of 100 per year, we are to attempt a 50:1 scale-up in hydrogen generation capacity and an average 3:1 reduction in delivered hydrogen cost. We assume for the balance of our discussion that we will serve a 500unit/year portion of these markets in Y2015. Power will scale from about 40kW at present to about 1 MW for the end product. Figure 3 projects required hydrogen cost per kg versus electrolyser cost per kW at several power to hydrogen conversion efficiencies, expressed as % lower heating value of H2 (% LHV). Efficiency will need to improve to meet Y2015 DoE targets, though diminishing returns are realized for incremental efficiency improvements. The higher hydrogen cost tolerated in Y2006 and Y2010 enables market acceptance of the more capital intensive and less efficient 100 kg/day units. Unit efficiency gains, scale-up and capital cost reductions are needed to meet Y2015 H_2 cost targets.

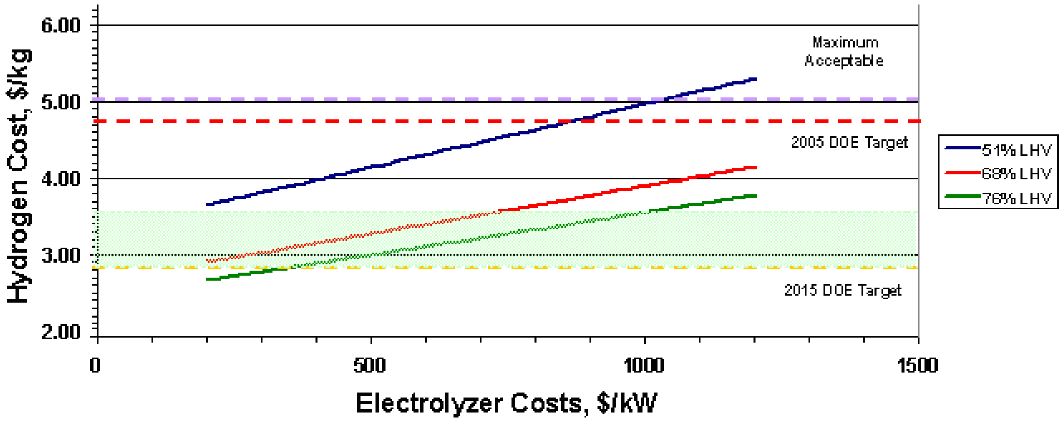

Figure 3. *H_2 costs and Capital costs at several efficiencies, compared to DoE targets.*

What innovations are required and what technology improvements are needed to complete the 500 kg/day pathway? To answer these questions, let us first consider the 'anatomy' of a modern PEM water electrolysis packaged system. As shown in Figure 4, the major components and subsystems of the packaged HOGEN H-series H6m water electrolyzer are (a) the PEM cell stacks, (b) the power conditioners that supply direct current and voltage to these cell stacks, (c) the water recirculation components that provides deionized water to feed and cool these cell stacks, (d) the hydrogen conditioning components that manage the product pressure control and water removal from the product hydrogen, (e) the safety circuit and automatic controls, and (f) the structural enclosure for the system.

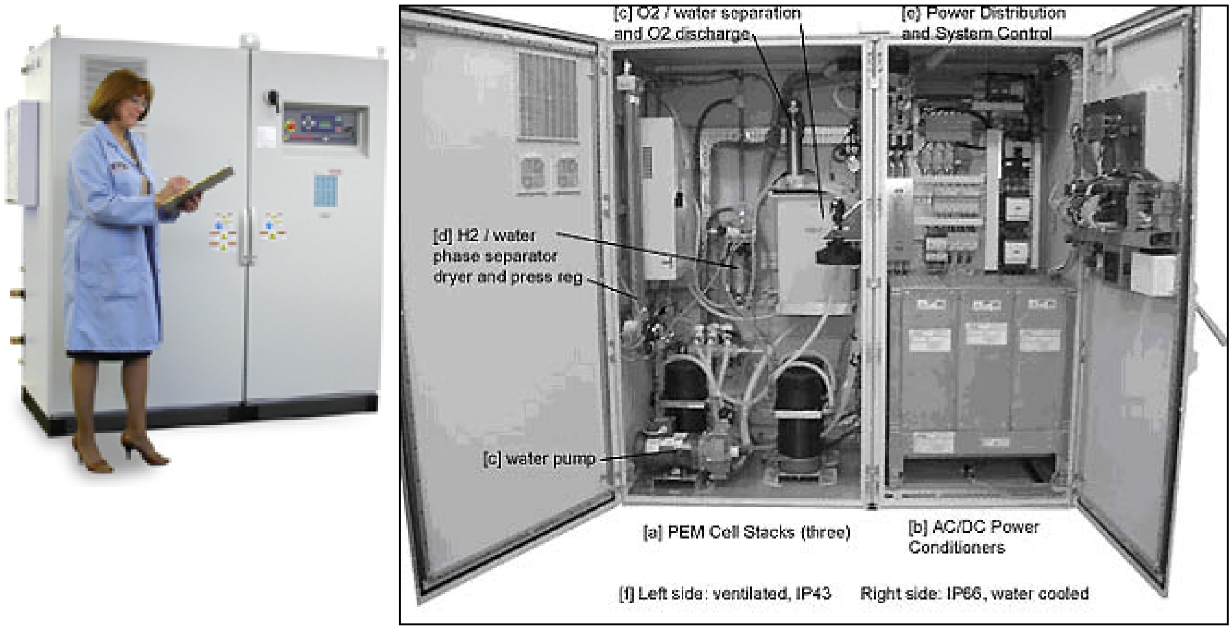

Figure 4*. The Proton HOGEN H-series hydrogen generator components and subsystems*

For the purposes of our discussion, the effects of area classification are not considered as a major cost contributor to a 500-kg/day system; also, oxygen is regarded as a byproduct only, produced at low pressure and disposed of immediately. These assumptions will need to be tested later along the product development pathway. Depending on the application area classification and applied safety engineering, system components may be located in the same enclosure or in separate enclosures in different rooms; the HOGEN H-series generator is designed for a ventilated non-classified area and is therefore economically packaged with all components within the same enclosure/skid. Unlike competitive pressure-balanced and/or liquid electrolyte systems, PEM systems may be built to only generate near-ambient oxygen pressures while producing hydrogen at full pressure; this approach affords a host of safety and cost-reducing benefits and minimizes oxygen contamination of the product hydrogen.

How do we approach components and subsystems development for the larger PEM electrolyzer? We expect the 100 and 500 kg H_2/day PEM electrolysis systems to be comprised of similar but larger versions of the HOGEN H-series generator components. What is the most costly component, and how is it affected by efficiency and target hydrogen price? Figure 5 shows the relative contribution of component and labor costs to the total. The cell stack is seen to represent about 45% of the total system cost; balance of plant (fluid components and structure) represent the next largest piece at 29%. Power electronics are not the largest contributor to system price, even though power electronics capacity must scale with the cell stack size and efficiency. This suggests that the steepest path to a cost-effective larger PEM electrolyser is through cost reduction of the cell stack and balance of plant, and that power electronics cost reductions will yield less of an overall cost reduction. In practice, power electronics and cell stack sizing are strongly interdependent.

Figure 5 illustrates the sensitivity of the required generator price to incremental reduction in market target H_2 price and incremental increases in system efficiency. A 500 kg/day hydrogen system, operating at 68% LHV, is projected to deliver US$3.50/kg H_2 at a system price of US$700,000. In the 68% LHV case shown, a 20% reduction to US$2.75/kg requires a disproportionate 10-fold decrease in electrolyser system price to achieve that lower price point. Efficiency improvements within each target hydrogen cost case also drive up system price; as seen in Figure 5, a 12% electrolysis efficiency improvement drives a disproportionate system price increase to meet the target hydrogen price. In practice, once process conditions such as cell temperature are optimized, further efficiency improvements come by reduction in cell stack current density; this in turn requires more cells at incremental cost per cell to maintain the same unit hydrogen output rate.

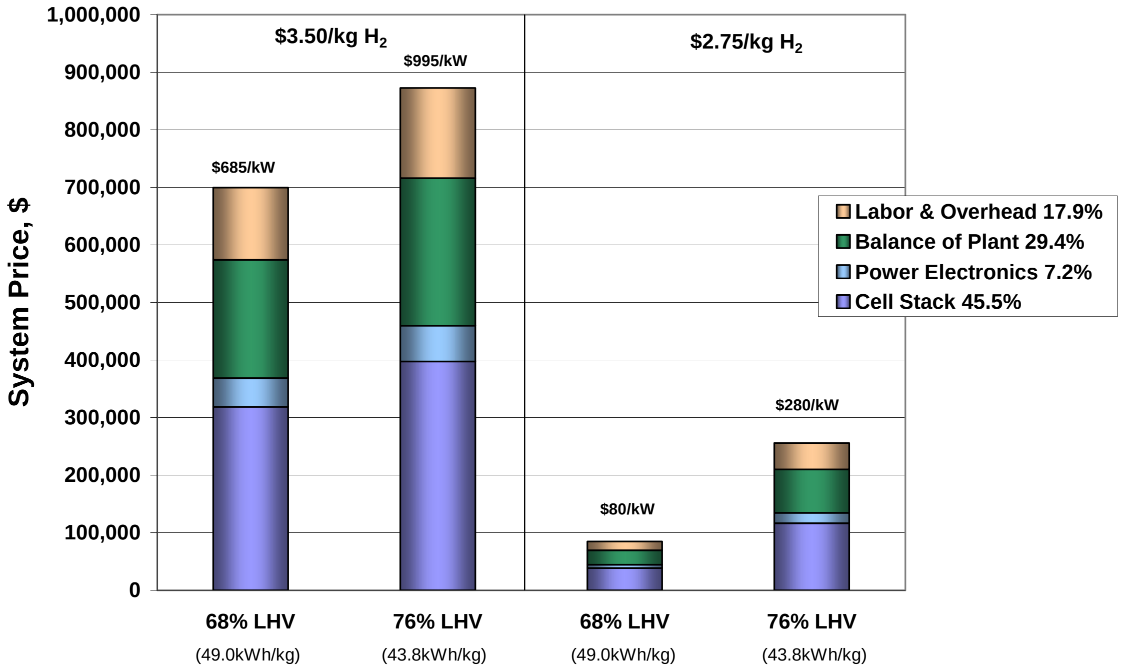

Figure 5. *Projected Cost distributions, 500 kg H_2/day, 90% utilization, US$0.04/kW*

On the development pathway to larger PEM electrolyzers, cost, durability, reliability, manufacturability and efficiency are considered at each step. This development pathway will traverse these key steps:

- Market-driven Design – determine the appropriate architecture for the target market opportunities
- Component and Process Development – identify scale-up issues and availability of raw materials components, and manufacturing processes

- Subsystem development – use analysis tools like H2A, applicable standards, and reference design and performance data to establish cost and performance targets, then develop and optimize the cell stacks, power conditioning and balance of plant to meet these targets
- Prototype Build and Field test – Obtain valuable operational data in target applications to validate design and drive improvements

Returning to the anatomy of the larger electrolyzer, a relative understanding of the subsystem cost impact to the whole, and our development pathway, what are the likely development trajectories for each major subsystem and component? We want to start with the cell stack, yet we know from lessons learned that the power conditioner that supplies DC current and volts to the stack is strongly interrelated. So, we first examine the scalability and economics of power conditioning. Figure 6 shows a desired power conditioner cost trajectory that compliments the overall system cost trajectory shown in Figure 2. If today we employ power conditioners in the 12-kg/day platforms that cost US$55/kW (50¢/watt) at the 40 kW level, what confidence do we have of achieving a requisite 5-fold reduction in cost per kW at the Y2015 goal?

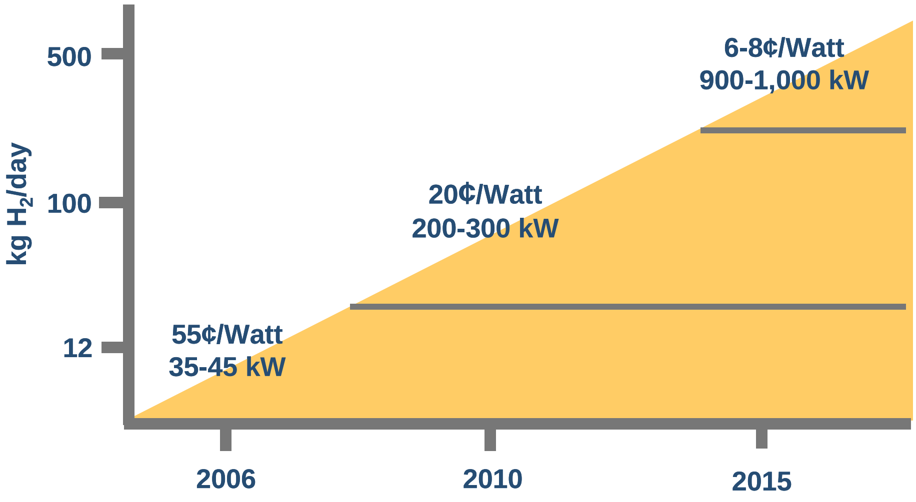

Figure 6. *Projected Cost Trajectory for Power Conditioning*

Within the operating divisions of Distributed Energy Systems, parent company of Proton Energy and Northern Power, power conditioners based on IGBT and power FET architectures are today exhibiting prototype pricing of US$20/kW at the 40kW, 480kW and 1MW power levels. These modular architectures achieve cost reductions by using multiples of smaller power components to build a larger current output. Statistically, employing many components adversely affects overall system reliability, so components have been over-specified and architectures designed to permit continued operation even when a single power component may fail. These architectures have the additional benefit of separate input stages that can be reconfigured to work from various sources and poor quality input. By selecting power conditioning architectures that are modular, multi-purpose, and adaptable to high volume circuit board type manufacturing, it is quite feasible that a two-fold reduction in cost for a three-fold increase in quantity is achievable. Field trials of both power architectures begin this fall of 2006. Possible alternate sources for lower cost power conditioning may reside in rapid battery charging equipment and other non-traditional sources of supply.

Understanding the trade space for power conditioning is one facet of larger PEM electrolysis cell stack development and optimization. What is the prime optimization path for larger capacity PEM water electrolysis stacks? The answer may already exist in the multi-million dollar financed PEM fuel cell architecture and supply chain. The legacy water electrolysis cell stack design is comprised of many separate components per cell – Proton's commercial baseline is 29 parts per unit cell. Adept leveraging of fuel cell materials, processes and bipolar plate design has shown that this part count can be reduced three-fold per unit cell. Reductions in make and assembly labor are substantial with this newer approach. Fewer components per cell results in fewer interfaces within each cell, yielding higher efficiency from lower ohmic losses and lower cost from less use of precious metal. Finally, legacy PEM water electrolysis hardware is round in design, whereas fuel cell hardware is rectangular. Many raw materials used to make metallic-based fuel cells come in rolls and sheets. Simple geometry predicts that cutting the right-size squares and rectangles instead of circles can reduce sheet stock scrap by 20%.

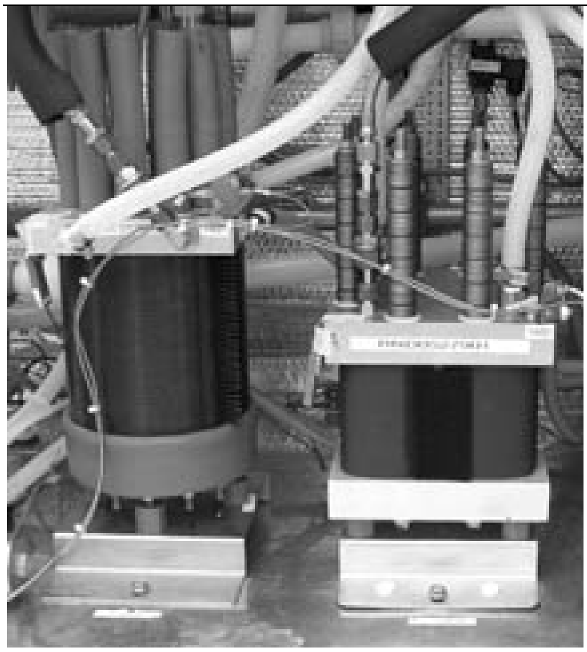

Figure 7. *Proton's round cell production stacks (left) have 29 parts per unit cell, while our next generation prototype rectangular hardware (right) has only 9 parts per cell, potentially yielding a 50% cost reduction and an efficiency improvement at the 40 kW level.*

The next-generation hardware shown under evaluation in Figure 7 intends to take advantage of the burgeoning fuel cell manufacturing base for bipolar plates. Similar advantages may also be realized for PEM membrane and electrode assemblies (MEA) as the fuel cell supply base matures. Since Y2002, Proton has been on a development path that has demonstrated means to reduce cell stack cost by 50% on a US$/kW basis. The scale-up of this rectangular architecture is easier to contemplate than the round architecture, provided cost and efficiency gains continue to be garnered. To meet the capital cost requirements of the larger PEM electrolyzer, however, a two to three-fold further reduction in cell stack cost is needed. This degree of cost reduction is consistent with the fuel cell industry's roadmap put forth by the US Department of Energy R&D targets for fuel cells. Since much of the target H_2 fueling market depends on the successful commercialization of fuel cells for transportation, riding the cost reduction curve for PEM fuel cells is synergistic with the business case for the larger PEM electrolyzer.

How may the next generation hardware, capable of 4 kg H_2/day per cell stack, scale up to meet 100 kg H_2 per day and 500 kg H_2/day requirements? Figure 8 is one possible pathway that relies on multiple cell stacks and linear scaling of production processes. Multiple cell stacks are already a feature in the HOGEN H-series platform; scale-up of processes for larger cells will need to be validated, as will the actual designs themselves. The pathway shown in Figure 8 calls for a seven-fold in crease (Step 1) in cell area to meet the 100 kg H_2/day scale; initial supply chain studies show that raw materials are available in the necessary sizes.

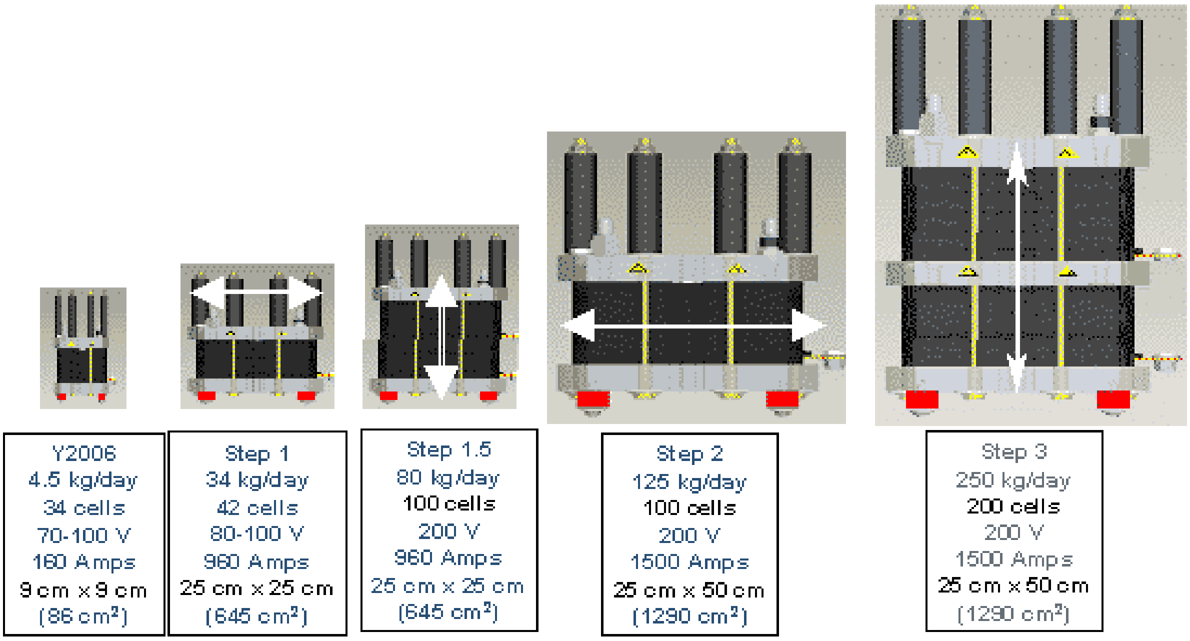

Figure 8. *A proposed scale-up pathway for PEM electrolyzer cell stacks*

The modular 100-volt power supplies discussed earlier are easily scaled to match the amperage requirements simply by installing more modules in electrical parallel. The next increment (Step 1.5) toward a 250 kg H_2/day platform may occur by introducing a higher cell count and coupling it with a next generation power conditioner designed for the higher voltage. A further two-fold scale up of cell active area in only one direction (Step 2) will not require any change in roll stock raw materials and may yield further labor cost reductions by reducing total cell count in half. A final design iteration (Step 3) of the cell stack and power supply scheme, using a common manifold, the modular 480 kW power conditioner architecture and two cell stacks, paves the remaining path to a 500 kg H_2/day platform.

What are the cell stack efficiency targets, and is there evidence of progress toward them? We have already discussed the reduction in ohmic losses by less interfacial contact area in the next generation cell stack bipolar plates. Figure 9 contrasts today's cell potential and resultant LHV efficiency performance against circa Y2001 performance against current density. Improvements since Y2001 have been garnered by catalyst and processing improvements. Based on this experience, future improvements will come through optimization of membrane, operating temperature, and further bipolar plate enhancements.

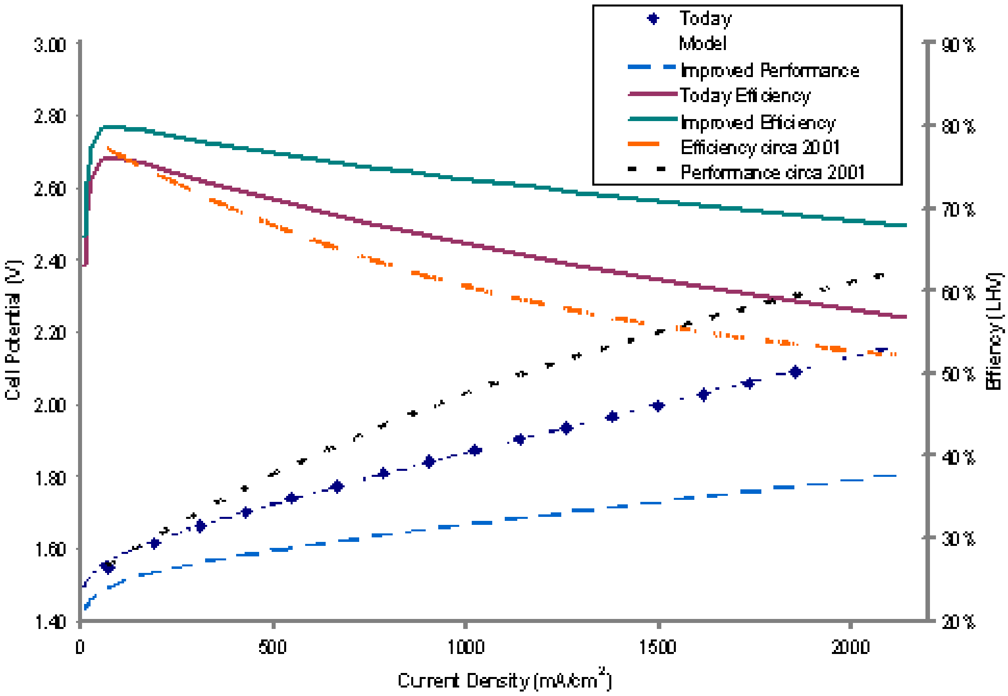

Figure 9. *Cell potentials, efficiencies for Y2001, today and projected future targets*

The pathway to the larger PEM cell stack in the larger PEM electrolyzer will focus on simpler, scalable, modular designs that are more fuel cell-like, feature lower unit cost, and rely on optimized operating conditions and materials for higher efficiency.

What improvement pathways are indicated in the balance of plant for the larger PEM electrolyzer? We can examine the parasitic losses experienced in the reference HOGEN H-series design to find areas for improvement. Dry hydrogen is a requirement for handling and storing the gas in sub-freezing temperatures; some fuel cells have narrow tolerance bands for water management on the fuel cell anode. The technology used on the 15 barg HOGEN H-series is a dual-bed pressure-swing dryer, a process that reliably reduces water vapor content to single-digit ppm_v levels. Where efficiency is not a prime design parameter, like the industrial HOGEN H-series, a simple regeneration of the "swing" bed is accomplished with a slip stream of dry product gas – up to 10% of the gross hydrogen production is lost this way. For larger PEM electrolyzers there are several ways to reduce this loss. Operation of the PEM hydrogen generator at double the pressure, 30 barg, inherently produces gas with less water content; also, the slip-stream volume required to regenerate the "swing" bed can be reduced by several percent. Reducing purge loss directly improves the PEM generator efficiency. Alternate means of regenerating the beds using dry inert gases and other techniques may also prove out as long as the otherwise excellent gas quality produced by PEM electrolysis is not compromised.

Operation of the PEM electrolyzer at elevated H_2 pressure is accomplished by back-pressuring the hydrogen outlet with a mechanical regulator and by designing the PEM cell stack to mechanically support the MEA – electrochemical compression with no mechanical pressure intensifiers. Some of our authors argue electrochemical compression is more efficient than mechanical compression through a certain pressure range[2] and 30-barg electrochemical compression can replace the initial stage of a mechanical compressor. For gaseous storage and fueling with hydrogen we know that the H_2 must be compressed; it is commonly practice to fuel vehicles at 430-barg and some are demonstrating 700-barg. This is a fueling system optimization that can yield overall efficiency benefits or result in elevated stack and balance of plant costs to meet higher-pressure requirements. For our discussion we will defer the benefits and detractors of high pressure electrochemical hydrogen compression/generation and continue to consider 15 to 30-barg as a target operating pressure for the larger PEM electrolyzer.

The PEM water electrolyzer needs a pump to circulate deionized water through each cell stack. This water circulation simultaneously supplies reactant water to the cell while removing byproduct oxygen gas and heat from the stack. This flow is not optimized in the industrial HOGEN hydrogen generators; water pumping represents up to 4% of the total input power to these small systems. With the design of fuel cell-like bipolar plates there is an opportunity to optimize the amount of recirculation water required through proper flow-field design. Increasing the cell operating temperature for voltage efficiency gains may also permit lower recirculation requirements for waste heat removal, given the larger differential temperature between process water and coolant.

Large electrolyzers are less convenient to locate indoors, where climate control can mitigate weather and freezing issues, because of physical size and concerns on area hazardous classification. The reference HOGEN H-series relies on indoor location for climate control and fresh air ventilation per code to declassify the equipment. While this is an effective and thrifty way to address these issues with the compact and low production-rate HOGEN products available today, ventilation of larger electrolyzers may require more ventilation air than practical for efficiency targets and effective thermal control. Codes and standards are finally available for packaged water electrolyzers[3], providing basis for performance and safety assessment by manufacturer and officials alike. The new standards describe traditional and newer methods to design for hydrogen and hazardous area classifications. A large PEM electrolyzer may be able to absorb the incremental cost of using classified components and wiring; this must be evaluated against more innovative techniques that may rely on compartmentalization, low volume controlled ventilation and safety rated hazardous gas monitoring to assure safety and compliance. Even so, large PEM electrolyzers promise to be relatively compact when fielded. Figure 10 is a conceptual 100 kg H_2/day factory-matched and packaged system that has a footprint of 3.9 x 1.6 x 1.8 meters, only five times the volume of the reference HOGEN H-series generator yet with nearly 10 times the hydrogen generation capacity.

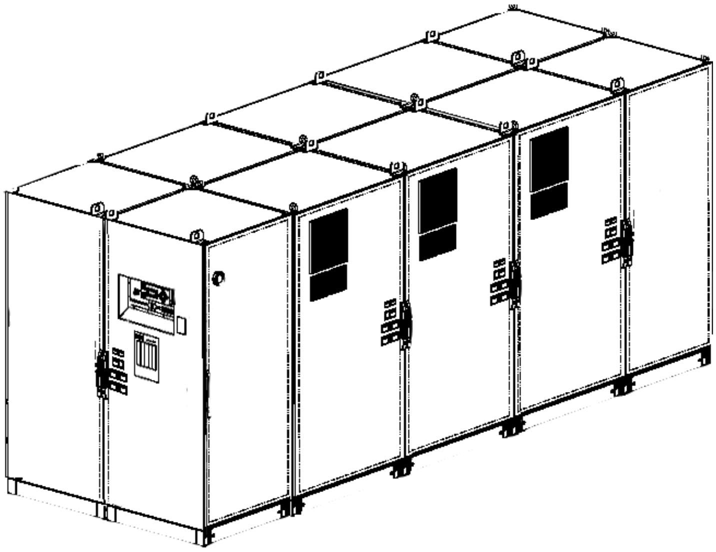

Figure 10. *A 100-kg H_2/day PEM electrolyzer platform concept*

SUMMARY AND CONCLUSIONS

Fuel cell fueling and utility management market opportunities are generating demand for larger PEM – based hydrogen generators in the 100 to 500 kg H2/day capacity range. A paced development effort can be synchronized with evolving fuel cell markets and market price points. H2A modeling and system analysis identify the components and subsystem development priorities, requirements, and challenges. Codes and standards are maturing to aid manufacturers and certification authorities make safe and compliant equipment. This development effort is feasible and can synergistically leverage the maturing PEM fuel cell technology and supply base

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