

# *Milestone Report*

## **Summary of Electrolytic Hydrogen Production**

### **Milestone Completion Report**

Johanna Ivy



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# **Summary of Electrolytic Hydrogen Production**

**Milestone Report for the Department of Energy's Hydrogen, Fuel Cells,  
and Infrastructure Technologies Program**

**Johanna Ivy  
March 19, 2004**

## 1.0 Executive Summary

This report provides a technical and economic overview of the electrolytic hydrogen production systems commercially available as of December 2003. The technical analysis focuses on five companies' electrolysis units: Stuart IMET; Teledyne HM and EC; Proton HOGEN; Norsk Hydro HPE and Atmospheric; and Avalence Hydrofiller. Cost information was obtained for three different systems, and the economics of these processes were analyzed.

The technical analysis found that currently, the largest electrolyzer unit sold produces only 380,000 kg H<sub>2</sub>/year. There are two limitations for electrolyzers of this size. If the system were to be used for forecourt production, fueling approximately 1,900 cars, 2.3 MW of electricity would be required. This electricity demand would likely preclude the purchase of cheaper industrial electricity in the forecourt scenario, thus raising the price of hydrogen. If the system were to be used in a large hydrogen generation plant, the limited hydrogen production capacity means that a significant number of electrolyzer units would be required. For example, a 500,000 kg/day hydrogen generation plant using nuclear power and electrolysis would require 500 of the largest electrolyzer units available today. In this scenario, electrolyzers 10 to 100 times the size of today's units could be utilized.

An initial cost boundary analysis was completed to determine the effects of electricity price on hydrogen costs. For each electrolyzer, the specific system energy requirement was used to determine how much electricity is needed to produce hydrogen; no capital, operating or maintenance costs are included in the calculation. At current electrolyzer efficiencies, in order to produce hydrogen at lower than \$3.00/kg, electricity costs must be lower than 4 and 5.5 cents per kWh. For an ideal system operating at 100% efficiency, electricity costs must be less than 7.5 cents per kWh to produce hydrogen at lower than \$3.00/kg. This analysis demonstrates that regardless of any additional cost elements, electricity costs will be a major price contributor.

The detailed economic analyses are based on three distinct systems for which cost and economic data were available. These data may or may not be representative of the costs and systems within each category. These three systems represent a small neighborhood (~20 kg/day), a small forecourt (~100 kg/day), and a forecourt size (~1000 kg/day). In this analysis, the hydrogen selling prices were \$31.80/kg H<sub>2</sub> for the small neighborhood size, \$13.60/kg H<sub>2</sub> for the small forecourt size, and \$6.10/kg H<sub>2</sub> for the forecourt size. The analysis was performed using year 2000 dollars, which were escalated to 2005 dollars. For the forecourt case, electricity represents 80% of the cost of the hydrogen, and the capital costs only 11%. For the small forecourt case, the electricity contribution drops to 62% while the capital costs increase to 19%. In the neighborhood case, the capital costs become the major cost factor at 43%, but electricity costs are still significant at 35%. This analysis demonstrated that for all systems electricity price is a major contributor to hydrogen price, but for small-sized electrolyzers, capital costs are more significant.

## 2.0 Introduction

The purpose of this report is to give an overview of the current state of electrolytic hydrogen production technologies, and to provide an economic analysis of the processes. The study focuses on five companies' current electrolyzer lines: Stuart IMET; Teledyne HM and EC; Proton HOGEN; Norsk Hydro HPE and Atmospheric; and Avalence Hydrofiller. The report details the state of technology as of December 2003 for all five companies' electrolysis units, and then analyzes the economics of three standard sized electrolysis processes.

## 3.0 Analysis Methodology

The technical details for each company's electrolysis systems were obtained from research on the Internet, and from personal conversations with industry representatives. The data presented are representative of systems available in December 2003. A detailed summary of each electrolysis model included in this study can be found in Appendix A.

For purposes of the analysis, the available electrolysis systems were categorized into five different size ranges: home, small neighborhood, neighborhood, small forecourt and forecourt. The term forecourt refers to a refueling station. The number of cars served and hydrogen production rate for each size are as follows:

- The home size will serve the fuel needs of 1- 5 cars with a hydrogen production rate of 200-1000 kg H<sub>2</sub>/year.
- The small neighborhood size will serve the fuel needs of 5-50 cars with a hydrogen production rate of 1000-10,000 kg H<sub>2</sub>/year.
- The neighborhood size will serve the fuel needs of 50-150 cars with a hydrogen production rate of 10,000 – 30,000 kg H<sub>2</sub>/year.
- The small forecourt size, which could be a single hydrogen pump at an existing station, will serve 150 – 500 cars with a hydrogen production rate of 30,000 – 100,000 kg H<sub>2</sub>/year.
- A full hydrogen forecourt will serve more then 500 cars per year with a hydrogen production rate of greater then 100,000 kg H<sub>2</sub>/year.

The number of cars served was determined by calculating that a car requires approximately 200 kg of hydrogen per year. This 200 kg requirement assumes that on average a car travels 12,000 miles per year, and that a vehicle will travel 60 miles/kg of hydrogen.

Table 1 below illustrates where each manufacture's electrolysis models fit into these categories.

**Table 1: Hydrogen Station Size**

| Manufacturer Model                                   | Hydrogen Production Rate |         | # of cars served | Station size       |
|--|--------------------------|---------|------------------|--------------------|
|  | kg/day                   | kg/year |                  |                    |
| Avalence Hydrofiller 15                              | 0.9                      | 315     | 1.6              | Home               |
| Proton HOGEN 20                                      | 1                        | 396     | 2.0              | Home               |
| Proton HOGEN 40                                      | 2                        | 789     | 3.9              | Home               |
| Avalence Hydrofiller 50                              | 3                        | 1182    | 6                | Small Neighborhood |
| Teledyne HM-50                                       | 6                        | 2205    | 11               | Small Neighborhood |
| Stuart IMET 300, 1 cell stack, 300 cm <sup>3</sup>   | 6                        | 2364    | 12               | Small Neighborhood |
| Stuart IMET 1000, 1 cell stack, 1000 cm <sup>3</sup> | 11                       | 3939    | 20               | Small Neighborhood |
| Avalence Hydrofiller 175                             | 11                       | 3939    | 20               | Small Neighborhood |
| Teledyne HM-100                                      | 12                       | 4410    | 22               | Small Neighborhood |
| Teledyne HM-125                                      | 15                       | 5514    | 28               | Small Neighborhood |
| Teledyne HM-150                                      | 18                       | 6615    | 33               | Small Neighborhood |
| Proton HOGEN 380 <sup>1</sup>                        | 22                       | 7875    | 39               | Small Neighborhood |
| Norsk HPE 10   | 22                       | 7875    | 39               | Small Neighborhood |
| Teledyne HM-200                                      | 24                       | 8820    | 44               | Small Neighborhood |
| Norsk HPE 12   | 26                       | 9450    | 47               | Small Neighborhood |
| Norsk HPE 16   | 35                       | 12600   | 63               | Neighborhood       |
| Norsk HPE 20   | 43                       | 15747   | 79               | Neighborhood       |
| Norsk HPE 24   | 52                       | 18897   | 94               | Neighborhood       |
| Teledyne EC-500                                      | 60                       | 22047   | 110              | Neighborhood       |
| Stuart IMET 1000, 2 cell stack, 1000 cm <sup>3</sup> | 65                       | 23622   | 118              | Neighborhood       |
| Norsk HPE 30   | 65                       | 23622   | 118              | Neighborhood       |
| Teledyne EC-600                                      | 72                       | 26457   | 132              | Neighborhood       |
| Norsk HPE 40   | 86                       | 31494   | 157              | Small Forecourt    |
| Teledyne EC-750                                      | 91                       | 33069   | 165              | Small Forecourt    |
| Stuart IMET 1000, 3 cell stack, 1000 cm <sup>3</sup> | 97                       | 35433   | 177              | Small Forecourt    |
| Norsk Atmospheric Type No.5010 (4000 Amp DC)         | 108                      | 39369   | 197              | Small Forecourt    |
| Norsk Atmospheric Type No.5010 (5150 Amp DC)         | 108                      | 39369   | 197              | Small Forecourt    |
| Norsk HPE 50   | 108                      | 39369   | 197              | Small Forecourt    |
| Stuart IMET 1000, 4 cell stack, 1000 cm <sup>3</sup> | 129                      | 47241   | 236              | Small Forecourt    |
| Norsk HPW 60   | 129                      | 47241   | 236              | Small Forecourt    |
| Stuart IMET 1000, 4 cell stack, 1000 cm <sup>3</sup> | 194                      | 70863   | 354              | Small Forecourt    |
| Norsk Atmospheric Type No.5020 (4000 Amp DC)         | 324                      | 118104  | 591              | Forecourt          |
| Norsk Atmospheric Type No.5020 (5150 Amp DC)         | 324                      | 118104  | 591              | Forecourt          |
| Norsk Atmospheric Type No.5030 (4000 Amp DC)         | 647                      | 236205  | 1181             | Forecourt          |
| Norsk Atmospheric Type No.5030 (5150 Amp DC)         | 647                      | 236205  | 1181             | Forecourt          |
| Norsk Atmospheric Type No.5040 (4000 Amp DC)         | 813                      | 296832  | 1484             | Forecourt          |
| Norsk Atmospheric Type No.5040 (5150 Amp DC)         | 1046                     | 381864  | 1909             | Forecourt          |

<sup>1</sup> Proton's HOGEN 380 has now been replaced by the HOGEN H Series. The HOGEN 380 pre-production unit was used because data on Proton's H Series Electrolyzers were not available in December 2003, which is the cutoff time for this report.

The table illustrates the production rates of current electrolysis units. Today, only Norsk Hydro makes an electrolyzer large enough to be considered a forecourt-sized system. Alkaline producers Teledyne and Stuart manufacture systems in the small neighborhood, neighborhood and small forecourt range, and Avalence's small unipolar alkaline electrolyzers are currently only sized for the home and small neighborhood. In contrast, Proton Exchange Membrane (PEM) electrolysis units, produced by Proton, are only sized for the home or small neighborhood system. This is a typical trend in the industry today as the high capital costs of PEM units limit their current viability in the large hydrogen production market, while alkaline units, with their lower capital costs, can produce across a range of hydrogen capacities.

Additionally, the categories were used to allow cost data to be generalized by system size. The economic analyses are based on three distinct systems for which cost and economic data were available. These data may or may not be representative of the costs and systems within each category. The three systems represent a small neighborhood (~20 kg/day), a small forecourt (~100 kg/day), and a forecourt size (~1000 kg/day). The specific manufacturer and model analyzed is not presented as it was agreed that specific cost data would remain confidential.

A beta version of the H2A model was used to calculate the discounted cash flow for the electrolysis process.

#### **4.0 Technology Description**

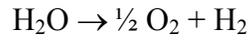
Hydrogen is produced via electrolysis by passing electricity through two electrodes in water. The water molecule is split and produces oxygen at the anode and hydrogen at the cathode.

Three types of industrial electrolysis units are being produced today. Two involve an aqueous solution of potassium hydroxide (KOH), which is used because of its high conductivity, and are referred to as alkaline electrolyzers. These units can be either unipolar or bipolar. The unipolar electrolyzer resembles a tank and has electrodes connected in parallel. A membrane is placed between the cathode and anode, which separate the hydrogen and oxygen as the gasses are produced, but allows the transfer of ions. The bipolar design resembles a filter press. Electrolysis cells are connected in series, and hydrogen is produced on one side of the cell, oxygen on the other. Again, a membrane separates the electrodes.

The third type of electrolysis unit is a Solid Polymer Electrolyte (SPE) electrolyzer. These systems are also referred to as PEM or Proton Exchange Membrane electrolyzers. In this unit the electrolyte is a solid ion conducting membrane as opposed to the aqueous solution in the alkaline electrolyzers. The membrane allows the H<sup>+</sup> ion to transfer from the anode side of the membrane to the cathode side, where it forms hydrogen. The SPE membrane also serves to separate the hydrogen and oxygen gasses, as oxygen is produced at the anode on one side of the membrane and hydrogen is produced on the opposite side of the membrane.

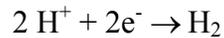
The Avalence Hydrofiller is the only unipolar electrolyzer discussed in this study. Norsk Hydro, Stuart, and Teledyne all produce bipolar electrolysis units. These units are currently capable of producing the largest amounts of hydrogen, and today are in use worldwide. The PEM electrolysis unit is the newest of the technologies discussed in this report, and Proton is the only PEM electrolyzer discussed in this study.

Regardless of the technology, the overall electrolysis reaction is the same:

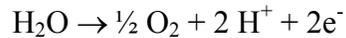


However, reaction at each electrode differs between PEM and alkaline systems. In a PEM system the reactions at the electrodes are:

PEM Hydrogen Production at the Cathode

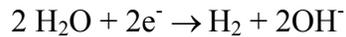


PEM Oxygen Production at the Anode

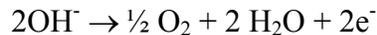


In an alkaline system the reaction at each electrode are:

Alkaline Hydrogen Production at the Cathode



Alkaline Oxygen Production at the Anode

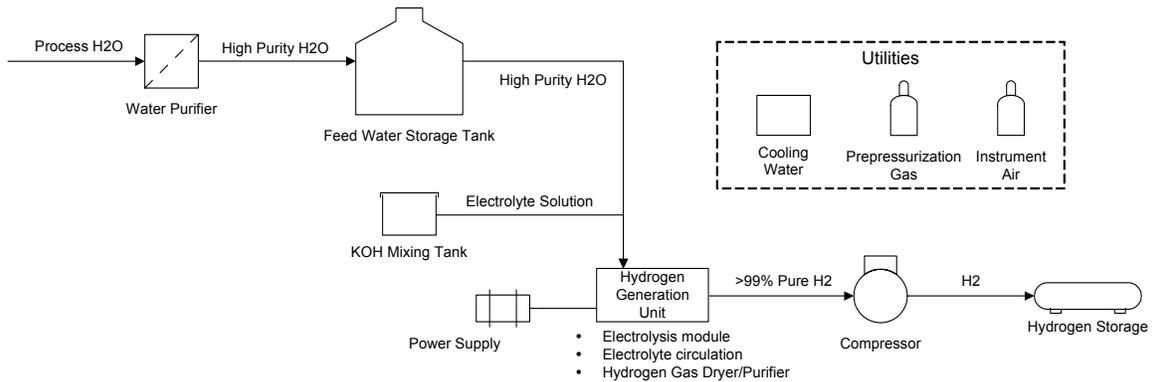


## 5.0 Process Design

A typical electrolysis process diagram is shown in Figure 1 below. Note that different processes will use different pieces of equipment. For example, PEM units will not require the KOH mixing tank, as no electrolytic solution is needed for these electrolyzers. Another example involves water purification equipment. Water quality requirements differ across electrolyzers. Some units include water purification inside their hydrogen generation unit, while others require an external deionizer or reverse osmosis unit before water is fed to the cell stacks. For systems that do not include a water purifier, one is added in the process flow. A water storage tank may be included to ensure that the process has adequate water in storage in case the water system is interrupted. Each system has a hydrogen generation unit that integrates the electrolysis stack, gas purification and dryer, and heat removal. Electrolyte circulation is also included in the hydrogen generation unit in alkaline systems. The integrated system is usually enclosed in a container or is installed as a complete package. Oxygen and purified hydrogen are

produced from the hydrogen generation unit. If desired, a compressor and hydrogen storage can be added to the system. Although hydrogen storage and compression are included in the process diagram below, for purposes of this analysis, hydrogen storage is not included. It is assumed that as the hydrogen is produced it is fed directly into a pipeline or truck. In addition, note that there is no oxygen compression and storage. For the purposes of this analysis, oxygen production is not considered.

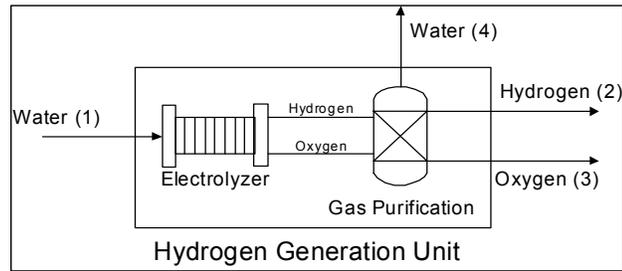
Typical utilities that the electrolysis systems need include electricity for electrolysis and other peripheral equipment; cooling water for the hydrogen generation unit; pre-pressurization gas; and inert gas.



**Figure 1: Process Flow Diagram**

### 5.1 Mass Balance Results

A simplified process flow is displayed in Figure 2 below to help illustrate the mass balance of the electrolysis system. The mass balance data provided are based on each of the manufacturers' largest electrolysis system: the Stuart IMET 1000, the Teledyne EC-750, the Proton Hogen 380, the Norsk Hydro Atmospheric Type No.5040 (5150 Amp DC) and the Avalence Hydrofiller 175.



|             | Stream (1)<br>Water |       |          | Stream (2)<br>Hydrogen Product |       |          | Stream (3)<br>Oxygen Product |        |          | Stream (4)<br>Water Removal |       |          |
|-------------|---------------------|-------|----------|--------------------------------|-------|----------|------------------------------|--------|----------|-----------------------------|-------|----------|
|             | l/hr                | kg/hr | kmole/hr | Nm3/hr                         | kg/hr | kmole/hr | Nm3/hr                       | kg/hr  | kmole/hr | l/hr                        | kg/hr | kmole/hr |
| Stuart *    | 60                  | 60    | 3.3      | 60                             | 5.4   | 2.7      | 30                           | 43     | 1.3      | 11.80                       | 11.80 | 0.7      |
| Teledyne    | 42                  | 42    | 2.3      | 42                             | 3.77  | 1.9      | 21                           | 30.01  | 0.9      | 8.21                        | 8.21  | 0.5      |
| Proton      | 8.4                 | 8.4   | 0.47     | 10                             | 0.90  | 0.45     | 5.0                          | 7.1    | 0.22     | 0.40                        | 0.40  | 0.02     |
| Norsk       | 485                 | 485   | 26.9     | 485                            | 43.59 | 21.6     | 242.5                        | 346.51 | 10.8     | 94.82                       | 94.82 | 5.3      |
| Avalance ** | 4.5                 | 4.5   | 0.2      | 5                              | 0.45  | 0.2      | 2.5                          | 3.57   | 0.1      | 0.48                        | 0.48  | 0.03     |

\* Assumes stoichiometric production of oxygen

\*\* Assumes stoichiometric production of oxygen and 1 L of water input per kg of hydrogen produced.

**Figure 2: Mass Balance**

The product streams are assumed to be 100% oxygen or hydrogen because typically the amount of contaminant in the product streams is so small as to be considered negligible. The hydrogen purities for the above systems range from 99.9 - 99.9998%, and the oxygen purities, where provided, range from 99.2-99.9993%. The difference in gas purities depend on the gas purification technology used in each system.

## 5.2 Energy Balance Results

The energy balance in Table 2 details the energy required for hydrogen production by each manufacturer's largest hydrogen generation system. Note that only Stuart and Norsk Hydro provide the actual energy requirement of the electrolyzer. Stuart also provided the energy requirement of the entire system, while Norsk Hydro's system energy requirement was calculated by using the power requirements of the system and the hydrogen generation rate. Avalance's system energy requirement was calculated in the same manner. Proton and Teledyne both provide energy requirement data based on the entire hydrogen production system. Only Norsk Hydro's system energy requirements include compression: one water injected screw compressor followed by a reciprocating compressor to bring the gas to 33bar (480 psi).

**Table 2: Energy Balance**

| Manufacturer Model                                  | Energy Required: System |        | Energy Required: Electrolyzer | Hydrogen Production | System Power Requirement |
|---|-------------------------|--------|-------------------------------|---------------------|--------------------------|
|   | kWh/Nm3                 | kWh/kg | kWh/Nm3                       | Nm3/hr              | kW                       |
| Stuart: IMET 1000                                   | 4.8                     | 53.4   | 4.2                           | 60                  | 288                      |
| Teledyne: EC-750                                    | 5.6                     | 62.3   | -                             | 42                  | 235.2                    |
| Proton: HOGEN 380                                   | 6.3                     | 70.1   | -                             | 10                  | 63                       |
| Norsk Hydro: Atmospheric Type No.5040 (5150 Amp DC) | 4.8                     | 53.5   | 4.3                           | 485                 | 2330                     |
| Avalence: Hydrofiller 175                           | 5.0                     | 55.6   | -                             | 5                   | 25                       |

## 6.0 Efficiency Results

Efficient conversion of water and electricity to hydrogen is critical to the electrolytic hydrogen production technology.

### 6.1 Conversion Efficiency

The conversion efficiency of water to hydrogen is shown in Table 3. Overall, the conversion efficiency is high, ranging from 80-95%.

**Table 3: Conversion Efficiency**

|   | Reactants | Product H2 | Product O2 | Conversion efficiency |
|---|-----------|------------|------------|-----------------------|
|   | kg/hr     | kg/hr      | kg/hr      | %                     |
| Stuart: IMET 1000                                   | 60        | 5.4        | 43         | 80%                   |
| Teledyne: EC-750                                    | 42        | 3.8        | 30         | 80%                   |
| Proton: HOGEN 380                                   | 8.4       | 0.9        | 7.1        | 95%                   |
| Norsk Hydro: Atmospheric Type No.5040 (5150 Amp DC) | 485       | 434        | 347        | 80%                   |
| Avalence: Hydrofiller 175                           | 4.5       | 0.45       | 3.6        | 89%                   |

### 6.2 Energy efficiency

Energy efficiency is defined as the higher heating value (HHV) of hydrogen divided by the energy consumed by the electrolysis system per kilogram of hydrogen produced. The justification for using HHV can be seen in Appendix B. The energy efficiency of the electrolysis process is shown in Table 4. The energy efficiency ranges from 56-73%. Proton’s PEM process has the lowest efficiency at 56% and both Stuart’s and Norsk Hydro’s bipolar alkaline efficiencies are the highest at 73%. An efficiency goal for electrolyzers in the future has been reported to be in the 50 kWh/kg range, or a system

efficiency of 78%. However, this 78% includes compression of the hydrogen gas to 6000 psi. Currently, these electrolyzers, other than Avalence's, reach a pressure ranging from 60-435 psig for the power requirements presented. These efficiencies would decrease if additional compression up to 6000 psig were included. Only Avalence's energy requirement of 55.6 kWh/kg includes reaching hydrogen pressures in the 6000 psig range.

Note that in this study the energy requirement of the entire electrolysis system is used to calculate the efficiency, not just the efficiency of the electrolyzer. As an example, the electrolyzer alone for the Stuart IMET 1000 requires 46.8 kWh/kg (4.2 kWh/Nm<sup>3</sup>), which corresponds to 83% efficiency when you divide the HHV of hydrogen by the electrolyzer power requirement. However, when you include the rectifier and auxiliaries the energy requirement becomes 53.5 kWh/kg or 73% efficient. As a result, when referring to the "System Energy Required" in this study, the value refers to the entire electrolysis system, not just the electrolyzer itself.

**Table 4: Energy Efficiency**

|  | <b>Energy Required System</b><br>kWh/kg | <b>HHV of Hydrogen (equivalent to 142 MJ/kg)</b><br>kWh/kg | <b>System Efficiency</b><br>% | <b>Production Pressure</b><br>psig |
|--|---|--|-------------------------------|------------------------------------|
| <b>Stuart: IMET 1000</b>                                   | 53.4                                    | 39   | 73                            | 360                                |
| <b>Teledyne: EC-750</b>                                    | 62.3                                    | 39   | 63                            | 60-115                             |
| <b>Proton: HOGEN 380</b>                                   | 70.1                                    | 39   | 56                            | 200                                |
| <b>Norsk Hydro: Atmospheric Type No.5040 (5150 Amp DC)</b> | 53.5                                    | 39   | 73                            | 435                                |
| <b>Avalence: Hydrofiller 175</b>                           | 55.6                                    | 39   | 70                            | up to 10,000                       |

## 7.0 Capital and Operating Cost Results

An initial boundary analysis was completed to determine the effects of electricity price on hydrogen costs, and the results are shown in Figure 3. For each electrolyzer, the specific system energy requirement is used to determine how much electricity is needed to produce hydrogen; no capital, operating or maintenance costs are included in the calculation. The system energy requirement used is the lowest energy requirement reported for each manufacturer. This graph shows that, at current electrolyzer efficiencies, in order to produce hydrogen at lower than \$3.00/kg, electricity costs must be between 4 and 5.5¢/kWh. In order to produce hydrogen for less than \$3.00/kg with a system that is 100% efficient, electricity prices must be less than 7.5¢/kWh. The U.S. Department of Energy's Energy Information Administration (EIA) reports 2002 industrial, commercial, and residential electricity prices at 4.83, 7.89, and 8.45¢/kWh, respectively. Thus, if only electricity costs were incurred, current electrolyzers could produce hydrogen for \$3.00/kg at industrial electricity prices; an ideal system could produce hydrogen for \$3.00/kg at slightly lower than commercial prices. This analysis

shows that regardless of any additional cost elements, electricity costs will be a major price contributor.

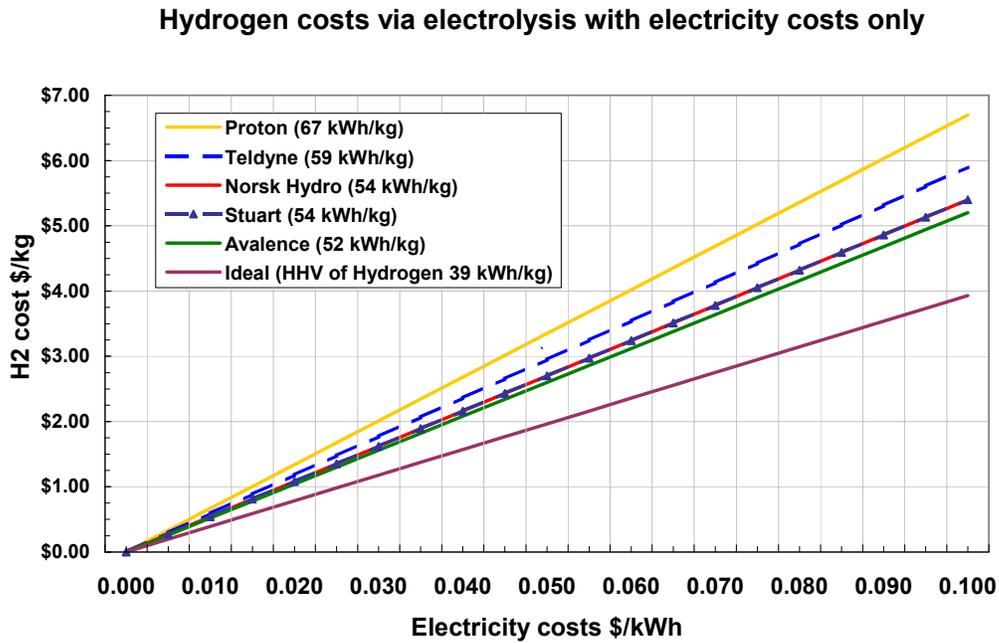


Figure 3<sup>2</sup>

## 8.0 Discounted Cash Flow Results

The discounted cash flow analysis was completed using the H2A model. The specifics for each of the three systems analyzed will not be presented here, as each vendor requested that the detailed economic data they provided remain confidential. Non-confidential data and parameters are provided in Table 5, and show the cost assumptions that were used in the analysis which are common between all three systems analyzed. These parameters are included to help provide transparency in the analysis.

Table 5: DCF Parameters

| Parameter                   | Assumption             |
|-----------------------------|------------------------|
| <b>Process Parameters</b>   |                        |
| Primary Feedstock           | Electricity and Water  |
| Electricity Used            | Industrial Electricity |
| Conversion Technology       | Electrolysis           |
| <b>Financial Parameters</b> |                        |
| Start-up Year               | 2005                   |
| After-Tax Real IRR (%)      | 10                     |

<sup>2</sup> The Proton efficiency is based on the HOGEN 380 series, which is no longer available. Current efficiencies of Proton systems are in the 62-70 kWh/kg range

| <b>Parameter</b>   | <b>Assumption</b> |
|--|-------------------|
| Depreciation Type  | MACRS             |
| Depreciation Schedule Length (No. of Years)              | 7                 |
| Analysis Period (years)                                  | 40                |
| Plant Life (years)                                       | 40                |
| Assumed Inflation Rate (%)                               | 2                 |
| State Income Taxes (%)                                   | 6                 |
| Federal Income Taxes (%)                                 | 35                |
| Effective Tax Rate (%)                                   | 39                |
| Operating Capacity Factor (%)                            | 97                |
| % Equity Financing                                       | 100               |
| Length of Construction Period (years)                    | 1                 |
| % of Capital Spent in 1st Year of Construction           | 100               |
| Start-up Time (years)                                    | 1                 |
| % of Revenues During Start-up (%)                        | 75                |
| % of Variable Operating Costs During Start-up (%)        | 75                |
| % of Fixed Operating Costs During Start-up (%)           | 75                |
| Salvage Value of Capital (% of Total Capital Investment) | 10                |
| Decommissioning Costs (% of Total Capital Investment)    | 10                |
| <b>Replacement Capital Parameters</b>                    |                   |
| Electrolyzer cell stack lifetime (years)                 | 5-15              |
| <b>Indirect Depreciable Capital Parameters</b>           |                   |
| Buildings (% of fixed capital investment)                | 14                |
| Yard Improvements (% of fixed capital investment)        | 3.5               |
| Construction (% of fixed capital investment)             | 9                 |
| Engineering and design (% of fixed capital investment)   | 8                 |
| Contingency (% of fixed capital investment)              | 25-30             |
| <b>Non Depreciable Capital Parameters</b>                |                   |
| Land (\$/acre)   | 5,000             |
| <b>O&amp;M Parameters</b>                                |                   |
| Burdened Labor (\$/hour)                                 | 50                |
| Overhead and G&A (% of labor cost)                       | 20                |
| Property Tax (% of depreciable capital costs)            | 1                 |
| Insurance Rate (% of depreciable capital costs)          | 1                 |

2005 was chosen as the startup year for this analysis because the study focuses on currently available technology. Presently, the electrolysis industry meets a smaller market demand than would exist if hydrogen were in use as a transportation fuel. As the demand for hydrogen increases, capital costs will come down due to mass production. The economic results of this study should be considered representative of the electrolysis market as it stands today and in the near future, but not representative of long term costs and prices.

The three systems represented in the discount cash flow (DCF) analysis were the only three systems for which cost and economic data were available. These data may or may not be representative of the costs and systems within each category.

Electricity prices for this analysis come from the H2A model, which projects electricity prices through 2070. The projections from 2001 through 2025 come from the latest Annual Energy Outlook (AEO 2004) recently published by EIA. The projections between 2025 and 2035 are extrapolations of the EIA projections. The projections past 2035 are derived from growth rates that came from a Pacific Northwest National Laboratory long-term energy model called Climate Assessment Model (M-CAM).

Industrial electricity prices, reported as 4.83¢/kWh for 2002 by EIA, were used for all base case economic analyses. While electrolyzers may be too small to obtain the cheaper electricity prices usually available to industrial users, using such prices in this analysis sets the boundary for research goals on other parameters such as capital costs and efficiency. Additionally, sensitivity analyses were run to determine the impact of higher electricity prices on the hydrogen selling price results.

The results of the base case discounted cash flow analyses are shown in Table 6. The hydrogen selling price ranges from \$31.80/kg for the small neighborhood size to \$6.13/kg for the forecourt size. The analysis was performed using year 2000 dollars, which were escalated to 2005 dollars. The after-tax real IRR was fixed at 10% and the hydrogen selling price was varied until the NPV equaled zero.

**Table 6: DCF Outputs**

| <b>DCF CALCULATION OUTPUTS:</b>                                       | <b>Small Neighborhood</b> | <b>Small Forecourt</b> | <b>Forecourt</b> |
|---|---------------------------|------------------------|------------------|
| <b>Required Hydrogen Selling Price (Year 2000 Real Dollars)</b>       | \$28.94                   | \$12.39                | \$5.58           |
| <b>Required Hydrogen Selling Price (Nominal Startup Year Dollars)</b> | \$31.80                   | \$13.60                | \$6.10           |
| <b>After-Tax Real IRR</b>   | 10.0%                     | 10.0%                  | 10.0%            |
| <b>Pre-Tax Real IRR</b>   | 14.6%                     | 14.7%                  | 14.8%            |
| <b>After-Tax Nominal IRR</b>  | 12.1%                     | 12.1%                  | 12.1%            |
| <b>Pre-Tax Nominal IRR</b>  | 16.8%                     | 16.8%                  | 16.9%            |

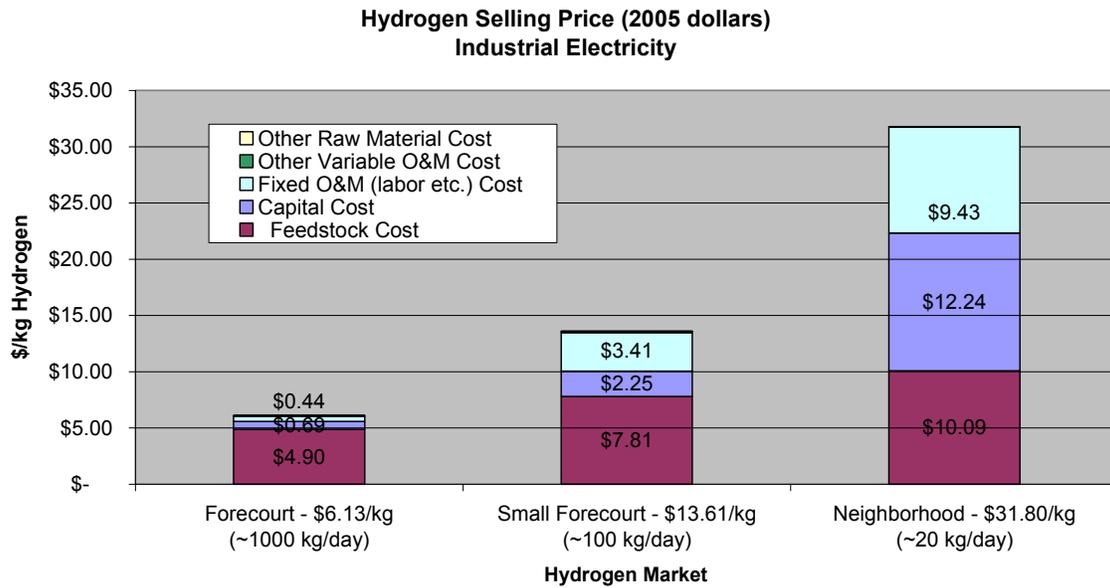
The above DCF calculations yielded the specific item costs for each of the systems, and are shown in Table 7. The feedstock cost contribution includes only the cost of electricity for the system. Although it can be argued that electricity is not a feedstock, it was entered as such so that the electricity cost contribution can be easily distinguished from other utilities such as the process water, cooling water and inert gas contribution, which can be seen in the variable O&M cost contribution row. As anticipated, the cost of electricity is a major factor in all three of the cases. Only in the small neighborhood case does the capital cost contribution outweigh the electricity cost contribution.

**Table 7: DCF Item Costs**

| <b>Specific Item Costs</b>                          | <b>Small Neighborhood</b> | <b>Small Forecourt</b> | <b>Forecourt</b> |              |
|---|---------------------------|------------------------|------------------|--------------|
| <b>Item</b>   | <b>Cost</b>               | <b>Cost</b>            | <b>Cost</b>      | <b>Units</b> |
| <b>Capital Cost Contribution</b>                    | \$12.239                  | \$2.25                 | \$0.690          | /kg of H2    |
| <b>Feedstock Cost Contribution</b>                  | \$10.090                  | \$7.81                 | \$4.900          | /kg of H2    |
| <b>Other Raw Material Cost Contribution</b>         | \$0.000                   | \$0.00                 | \$0.040          | /kg of H2    |
| <b>Fixed O&amp;M (labor etc.) Cost Contribution</b> | \$9.432                   | \$3.41                 | \$0.444          | /kg of H2    |
| <b>Variable O&amp;M Cost Contribution</b>           | \$0.038                   | \$0.13                 | \$0.051          | /kg of H2    |
| <b>Byproduct Credit Cost Contribution</b>           | \$0.000                   | \$0.00                 | \$0.000          | /kg of H2    |

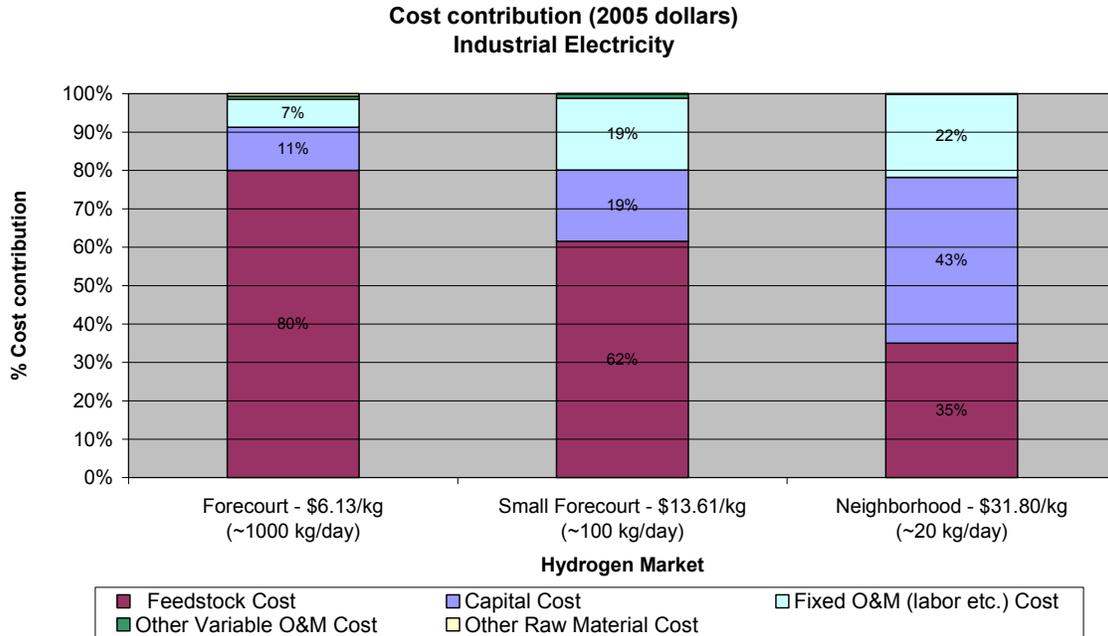
Note that a few factors differ between electrolysis cases, which will vary the cost numbers. First, each system has different electrolyzer system efficiencies. As a result, the systems will need different amount of electricity to make the same amount of hydrogen. Second, different electrolyzers have different system lives. This analysis had an analysis period and plant life of 40 years. This time was chosen to be consistent with the H2A guidelines. However, electrolyzers have a stack life of 5-15 years, so different manufacturers stacks will need to be replaced at different intervals. The systems with the shorter system life will have higher capital costs.

The graph in Figure 4 better illustrates the different cost contributions for all three cases, along with the difference in cost contributions across the cases. For all three cases, the other raw material cost contribution and variable O&M cost contribution are negligible. The other raw material cost contribution includes the KOH electrolyte, when applicable. The variable O&M costs include utility costs: process or de-mineralized water, cooling water and inert gas. The inert gas is needed for instruments and initial system pressurization. For the small neighborhood size electrolysis unit, capital costs are the largest cost contributor, but even without that cost, the hydrogen cost would still be \$19.51 in year 2005 dollars, higher than the small forecourt or forecourt case.



**Figure 4**

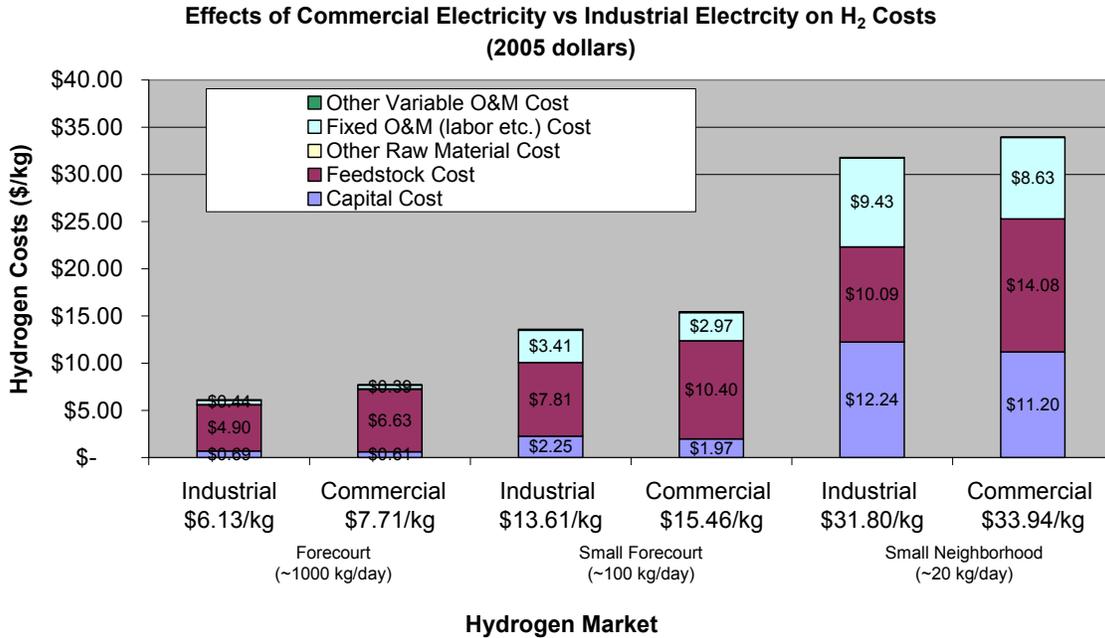
Figure 5 illustrates the driving cost for each of the three cases. For the forecourt case, electricity represents 80% of the cost of the hydrogen, and the capital costs only 11%. For the small forecourt case, the electricity contribution drops to 62% while the capital costs increase to 19%. In the neighborhood case, the capital costs become the major cost factor at 43%, but electricity costs are still significant at 35%. This graph shows that the small neighborhood case must focus on capital cost reductions in order to be competitive with either of the forecourt cases. All three cases need to consider electricity cost as a major driving factor and look to minimize those costs.



**Figure 5**

The previous graph shows how dependent the electrolysis hydrogen costs are on electricity price. The price of electricity is important, and, as stated earlier, all of these costs are based on industrial electricity cost. In order to better determine the relationship between hydrogen price and electricity cost, a sensitivity analysis was run using higher commercial electricity prices.

The graph in Figure 6 illustrates how an increase in electricity price to commercial levels increases the price of hydrogen.



**Figure 6**

Obviously, an increase in electricity costs leads to an increase in hydrogen costs. For the forecourt case, the price of hydrogen increases from \$6.13/kg to \$7.71/kg, an increase of 26%. The price of hydrogen from the small forecourt case increases from \$13.61/kg to \$15.46, an increase of 14%. Finally, the small neighborhood case increases from \$31.80/kg to \$33.94/kg, an increase of 7%. As the electricity price represents a smaller percentage of the hydrogen price contributions in the small neighborhood and small forecourt cases, the effect of using commercial electricity is decreased. However, as the technology improves capital costs will become less of a factor, and the effect of higher electricity costs will be significant for all systems, regardless of size.

## 9.0 Conclusions

The cost of producing hydrogen via current electrolytic processes is largely dependent on the cost of electricity, the efficiencies of the systems, and the capital costs of the systems.

The cost of electricity and the system efficiencies are interrelated because either an increase in efficiency or a decrease in electricity costs will bring down the overall electricity cost contribution. However, the amount the system efficiency can be increased is limited, and current industry goals are to reduce the energy requirement of the system to around 50 kWh/kg of hydrogen (a system efficiency of 78%), including compression of the hydrogen gas to 6000 psig. While this increased efficiency will bring down the electrical cost contribution, it will not reduce the cost as much as a significant reduction in electricity price. If forecourt systems can use industrial priced electricity as opposed to commercial priced electricity, hydrogen prices can be reduced by 26%. If even lower priced electricity alternatives are available they should be evaluated for electrolytic hydrogen production.

The smaller home systems have a two-fold challenge. First the capital costs of such systems need to be reduced so that those costs are no longer a major cost contribution. All electrolysis systems will benefit from a reduction in capital results as the hydrogen economy grows and these systems are mass produced, but the smaller systems will benefit the most, as the largest percentage of their hydrogen cost contribution comes from capital costs. Second, a scenario must exist where systems that require 15-300kW of electricity can negotiate for industrial electricity prices, as opposed to the costly commercial or residential prices. Such a scenario may require a shift in the price policies of the power companies.

Another challenge of the electrolysis industry is the limited hydrogen production rates of the current units. Electrolysis units are sized to meet the demands of today's hydrogen markets, but in a world where a hydrogen economy exists, today's systems are too small to take advantage of the potential low cost, high volume electricity production methods such as wind and nuclear power. In order to effectively use the large amounts of electricity produced from such systems, electrolyzers 10 to 100 times the size of today's units could be utilized.

## **10.0 Future Work**

Several opportunities for further analysis exist, and are briefly described.

### **10.1 Sensitivity Analyses**

Monte Carlo sensitivity analysis and tornado diagrams need to be completed for the next phase of this study to better understand the relationship between parameters included in the study and hydrogen price.

### **10.2 Future electrolysis**

The purpose of this study was to develop an understanding of the electrolytic hydrogen production technology today. However, it may be years before this technology becomes an important player in the transportation fuel arena. The future costs of hydrogen production via electrolysis need to be researched and analyzed.

### **10.3 Distributed generation and H<sub>2</sub> production**

In order for electrolysis to produce low cost hydrogen, low cost electricity must be available. Scenarios need to be researched under which electricity could be available to forecourt sized electrolyzers for prices equal to or less than current industrial electricity prices. One of the scenarios that may be of particular interest in longer-term models is distributed hydrogen generation and its relationship to distributed power.

### **10.4 "Off Peak" Electricity**

Oftentimes off peak electricity prices are used as a scenario by which electrolytic hydrogen production can become more economical. However, a better understanding of the off peak pricing and the effect that large-scale hydrogen production would have on off peak pricing is needed.

### **10.5 Oxygen credits**

Oxygen by-product credits are another way electrolytic hydrogen is also made more economical. A better understanding of the current and future oxygen market is needed to justify such a credit.

### **10.6 Power requirements**

The power requirements of electrolysis systems are not insignificant. The largest forecourt system requires 2.3 MW of power. A better understanding of the current power infrastructure needs to be understood, so the feasibility of delivering 2.3 MW of power to a forecourt station can be validated. The chart in Appendix A shows the power requirements for each size of electrolyzer in this study.

### **10.7 Additional scenarios for small neighborhood and home**

The market for small neighborhood and home transportation fuel production does not currently exist. Additional analysis could be done to better understand how electrolysis units would have to function in such a market. As an example, in this analysis, the fixed O&M costs include the labor, general and administrative (G&A), property tax and insurance costs required for an electrolysis plant. For the small neighborhood size, it was assumed that these units would serve 5 to 50 cars a year, and would resemble a typical filling station, but smaller. However, the validity of this assumption needs to be examined for the small neighborhood and also for home refueling units. These electrolysis units may be different from the filling stations today and require less land, labor, insurance and property tax charges. Particularly with home electrolysis, the refueling units would need to operate as an appliance; the homeowner would do any maintenance with occasional expert help brought in for repairs. As a result, insurance and property taxes would not be assessed, and labor and G&A costs should be greatly reduced. This would lead to an overall reduction in the hydrogen costs for these smaller units. A better understanding of the needs and associated costs of hydrogen production in the home and neighborhood market is needed.

## 11.0 Appendix

### 11.1 Appendix A: Overview of Current Electrolysis Systems

| Manufacturer Model                           | Technology        | Hydrogen Production Rate |     |       |      | Hydrogen product pressure | Energy Requirement |                     | Power required for max H <sub>2</sub> production | H <sub>2</sub> Purity | Lifetime |
|--|-------------------|--------------------------|-----|-------|------|---------------------------|--------------------|---------------------|--|-----------------------|----------|
|  |                   | Nm <sup>3</sup> /hr      |     | kg/hr |      |                           | psig               | kWh/Nm <sup>3</sup> |  |                       |          |
|  |                   | Min                      | Max | Min   | Max  |                           |                    |                     |  |                       |          |
| Avalence Hydrofiller 15                      | Unipolar Alkaline |                          | 0.4 |       | 0.04 | up to 10,000 psig         | 5.0 <sup>3</sup>   | 55.6                | 2  | 99.7                  |          |
| Avalence Hydrofiller 50                      | Unipolar Alkaline |                          | 1.5 |       | 0.1  | up to 10,000 psig         | 4.7 <sup>3</sup>   | 51.9                | 7  | 99.7                  |          |
| Avalence Hydrofiller 175                     | Unipolar Alkaline |                          | 5   |       | 0.4  | up to 10,000 psig         | 5.0 <sup>3</sup>   | 55.6                | 25   | 99.7                  |          |
| Norsk Atmospheric Type No.5010 (4000 Amp DC) | Bipolar Alkaline  | 0                        | 50  | 0     | 4.5  | 0.3                       | 4.8                | 53.4                | 240  | 99.9 ± 0.1            | 7-10     |
| Norsk Atmospheric Type No.5010 (5150 Amp DC) | Bipolar Alkaline  | 0                        | 50  | 0     | 4.5  | 0.3                       | 4.8                | 53.4                | 240  | 99.9 ± 0.1            | 7-10     |
| Norsk Atmospheric Type No.5020 (4000 Amp DC) | Bipolar Alkaline  | 50                       | 150 | 4.5   | 13.5 | 0.3                       | 4.8                | 53.4                | 720  | 99.9 ± 0.1            | 7-10     |
| Norsk Atmospheric Type No.5020 (5150 Amp DC) | Bipolar Alkaline  | 50                       | 150 | 4.5   | 13.5 | 0.3                       | 4.8                | 53.4                | 720  | 99.9 ± 0.1            | 7-10     |
| Norsk Atmospheric Type No.5030 (4000 Amp DC) | Bipolar Alkaline  | 150                      | 300 | 13.5  | 27.0 | 0.3                       | 4.8                | 53.4                | 1440   | 99.9 ± 0.1            | 7-10     |
| Norsk Atmospheric Type No.5030 (5150 Amp DC) | Bipolar Alkaline  | 150                      | 300 | 13.5  | 27.0 | 0.3                       | 4.8                | 53.4                | 1440   | 99.9 ± 0.1            | 7-10     |

<sup>3</sup> This energy requirement was calculated using the input power value in kW provided by Avalence

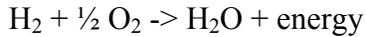
| Manufacturer Model                                   | Technology       | Hydrogen Production Rate |     |       |      | Hydrogen product pressure | Energy Requirement |                     | Power required for max H <sub>2</sub> production | H <sub>2</sub> Purity | Lifetime |
|--|------------------|--------------------------|-----|-------|------|---------------------------|--------------------|---------------------|--|-----------------------|----------|
|  |                  | Nm <sup>3</sup> /hr      |     | kg/hr |      |                           | psig               | kWh/Nm <sup>3</sup> |  |                       |          |
|  |                  | Min                      | Max | Min   | Max  | kW                        |                    |                     | %  | years                 |          |
| Norsk Atmospheric Type No.5040 (4000 Amp DC)         | Bipolar Alkaline | 300                      | 377 | 27.0  | 33.9 | 0.3                       | 4.8                | 53.4                | 1810   | 99.9 ± 0.1            | 7-10     |
| Norsk Atmospheric Type No.5040 (5150 Amp DC)         | Bipolar Alkaline | 300                      | 485 | 27.0  | 43.6 | 0.3                       | 4.8                | 53.4                | 2328   | 99.9 ± 0.1            | 7-10     |
| Norsk HPE 10   | Bipolar Alkaline |                          | 10  |       | 0.9  | 232                       | 4.8 <sup>4</sup>   | 53.4                | 48   | 99.8                  | 7-10     |
| Norsk HPE 12   | Bipolar Alkaline |                          | 12  |       | 1.1  | 232                       | 4.8 <sup>4</sup>   | 53.4                | 58   | 99.8                  | 7-10     |
| Norsk HPE 16   | Bipolar Alkaline |                          | 16  |       | 1.4  | 232                       | 4.8 <sup>4</sup>   | 53.4                | 77   | 99.8                  | 7-10     |
| Norsk HPE 20   | Bipolar Alkaline |                          | 20  |       | 1.8  | 232                       | 4.8 <sup>4</sup>   | 53.4                | 96   | 99.8                  | 7-10     |
| Norsk HPE 24   | Bipolar Alkaline |                          | 24  |       | 2.2  | 232                       | 4.8 <sup>4</sup>   | 53.4                | 115  | 99.8                  | 7-10     |
| Norsk HPE 30   | Bipolar Alkaline |                          | 30  |       | 2.7  | 232                       | 4.8 <sup>4</sup>   | 53.4                | 144  | 99.8                  | 7-10     |
| Norsk HPE 40   | Bipolar Alkaline |                          | 40  |       | 3.6  | 232                       | 4.8 <sup>4</sup>   | 53.4                | 192  | 99.8                  | 7-10     |
| Norsk HPE 50   | Bipolar Alkaline |                          | 50  |       | 4.5  | 232                       | 4.8 <sup>4</sup>   | 53.4                | 240  | 99.8                  | 7-10     |
| Norsk HPE 60   | Bipolar Alkaline |                          | 60  |       | 5.4  | 232                       | 4.8 <sup>4</sup>   | 53.4                | 288  | 99.8                  | 7-10     |
| Proton HOGEN H Series                                | PEM              | 0                        | 6   | 0     | 0.5  | 218                       | 6.3                | 70.1                | 38   | 99.999                |          |
| Proton HOGEN 20                                      | PEM              |                          | 0.5 |       | 0.04 | 200                       | 5.6                | 62.3                | 3  | 99.999                | 5-7      |
| Proton HOGEN 40                                      | PEM              |                          | 1   |       | 0.1  | 200                       | 5.6                | 62.3                | 6  | 99.999                | 5-7      |
| Proton HOGEN 380                                     | PEM              |                          | 10  |       | 0.9  | 200                       | 6.3                | 70.1                | 63   | 99.999                | 5-7      |
| Stuart IMET 1000, 1 cell stack, 1000 cm <sup>3</sup> | Bipolar Alkaline | 3                        | 5   | 0.3   | 0.4  | 360                       | 4.8                | 53.4                | 24   | 99.997                | 10       |
| Stuart IMET 1000, 2 cell stack, 1000 cm <sup>3</sup> | Bipolar Alkaline | 16                       | 30  | 1.4   | 2.7  | 360                       | 4.8                | 53.4                | 144  | 99.997                | 10       |

<sup>4</sup> This energy requirement was calculated using the total plant energy requirement in kW provided by Norsk Hydro

| Manufacturer Model                                   | Technology       | Hydrogen Production Rate |      |       |     | Hydrogen product pressure | Energy Requirement |                     | Power required for max H <sub>2</sub> production | H <sub>2</sub> Purity | Lifetime |
|--|------------------|--------------------------|------|-------|-----|---------------------------|--------------------|---------------------|--|-----------------------|----------|
|  |                  | Nm <sup>3</sup> /hr      |      | kg/hr |     |                           | psig               | kWh/Nm <sup>3</sup> |  |                       |          |
|  |                  | Min                      | Max  | Min   | Max | kW                        |                    |                     | %  | years                 |          |
| Stuart IMET 1000, 3 cell stack, 1000 cm <sup>3</sup> | Bipolar Alkaline | 31                       | 45   | 2.8   | 4.0 | 360                       | 4.8                | 53.4                | 216  | 99.997                | 10       |
| Stuart IMET 1000, 4 cell stack, 1000 cm <sup>3</sup> | Bipolar Alkaline | 64                       | 60   | 5.8   | 5.4 | 360                       | 4.8                | 53.4                | 288  | 99.997                | 10       |
| Stuart IMET 1000, 6 cell stack, 1000 cm <sup>3</sup> | Bipolar Alkaline |                          | 90   |       | 8.1 | 360                       | 4.8                | 53.4                | 360  | 99.997                | 10       |
| Stuart IMET 300, 1 cell stack, 300 cm <sup>3</sup>   | Bipolar Alkaline | 1                        | 3    | 0.1   | 0.3 | 360                       | 4.9                | 54.5                | 15   | 99.997                | 10       |
| Teledyne EC-500                                      | Bipolar Alkaline |                          | 28   |       | 2.5 | 60-115                    | 5.6                | 62.3                | 157  | 99.9998               | 15       |
| Teledyne EC-600                                      | Bipolar Alkaline |                          | 33.6 |       | 3.0 | 60-115                    | 5.6                | 62.3                | 188  | 99.9998               | 15       |
| Teledyne EC-750                                      | Bipolar Alkaline |                          | 42   |       | 3.8 | 60-115                    | 5.6                | 62.3                | 235  | 99.9998               | 15       |
| Teledyne HM-50                                       | Bipolar Alkaline |                          | 2.8  |       | 0.3 | 100                       | 6.1                | 67.9                | 17   | 99.9998               | 15       |
| Teledyne HM-100                                      | Bipolar Alkaline |                          | 5.6  |       | 0.5 | 100                       | 5.7                | 63.4                | 32   | 99.9998               | 15       |
| Teledyne HM-125                                      | Bipolar Alkaline |                          | 7    |       | 0.6 | 100                       | 5.7                | 63.4                | 40   | 99.9998               | 15       |
| Teledyne HM-150                                      | Bipolar Alkaline |                          | 8.4  |       | 0.8 | 100                       | 5.7                | 63.4                | 48   | 99.9998               | 15       |
| Teledyne HM-200                                      | Bipolar Alkaline |                          | 11.2 |       | 1.0 | 100                       | 5.3                | 59.0                | 59   | 99.9998               | 15       |

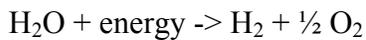
## 11.2 Appendix B: Higher Heating Value Justification

The reaction of the formation of water is:



At 25 C and 1 atm, the heat of formation of liquid water, or the energy released when water is formed in the reaction above is 39 kWh/kg of hydrogen. This value is the higher heating value (HHV) of hydrogen. The heat of formation of steam is 33 kWh/kg of hydrogen, and is the lower heating value (LHV) of hydrogen.

The electrolysis reaction is the opposite of the formation of water reaction:



For purposes of electrolysis in this report liquid water, and not steam, is electrolyzed to produce hydrogen. So the reaction above is the reverse of the formation of liquid water. As a result, the amount of energy needed to create hydrogen from water using electrolysis is 39 kWh/kg. In order to determine the efficiency of the electrolysis process, the theoretical amount of energy needed, 39 kWh/kg of hydrogen, needs to be divided by the actual amount of energy used by the electrolysis unit to create hydrogen.

The reason this distinction is important is because by using the lower heating value, we misrepresent the efficiency of electrolyzers. If you use LHV, to calculate the efficiencies, the efficiencies are low. For example, the Stuart IMET 1000 series electrolyzers are calculated to be 33 kWh/kg (LHV) ÷ 53.4 kWh/kg (the energy required to produce 1 kg of hydrogen using Stuart electrolyzer) which equals 64%. Using the HHV of 39 kWh/kg yields an efficiency of 73%. Another way to look at it is if the actual energy required to create 1 kg of hydrogen, 39 kWh/kg, is divided into the LHV value, the maximum efficiency of the electrolysis process is 33.3/39.4 = 84.5%. That is to say, that an electrolyzer that converts every kWh of input energy into hydrogen energy will have only 84.5% efficiency, even though there are no losses<sup>5</sup>.

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<sup>5</sup> Merer, Rupert. "RE: H2A Update." Personal e-mail. 17 Mar. 2004.

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