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Milestone Report

Summary of Electrolytic Hydrogen Production

Milestone Completion Report

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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 H2/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 then 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 $19.01/kg H_2 for the small neighborhood size, $8.09/kg H_2 for the small forecourt size, and $4.15/kg H_2 for the forecourt size. The analysis was performed using year 2000 dollars, which were escalated to 2005 dollars. For the forecourt case, electricity represents 58% of the cost of the hydrogen, and the capital costs only 32%. For the small forecourt case, the electricity contribution drops to 35% while the capital costs become the major cost factor at 55%. In the neighborhood case, the capital costs increase to 73%, but electricity costs are not insignificant at 17%. This analysis demonstrated that for all systems electricity price is a 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_2/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_2/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_2/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_2/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_2/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 cm3	6	2364	12	Small Neighborhood
Avalence Hydrofiller 175	10	3622	18	Small Neighborhood
Stuart IMET 1000, 1 cell stack, 1000 cm3	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[1]	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 cm3	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 cm3	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 cm3	129	47241	236	Small Forecourt
Norsk HPW 60	129	47241	236	Small Forecourt
Stuart IMET 1000, 4 cell stack, 1000 cm3	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

[1] 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.

The initial version of this analysis, published March 19, 2004, used a beta version of the H2A model to calculate the discounted cash flow for the electrolysis process. In this version of the analysis, an updated version of the H2A model was used.

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+ 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:

$$H_2O \rightarrow \frac{1}{2} O_2 + H_2$$

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

$$2 H^+ + 2e^- \rightarrow H_2$$

PEM Oxygen Production at the Anode

$$H_2O \rightarrow \frac{1}{2} O_2 + 2 H^+ + 2e^-$$

In an alkaline system the reaction at each electrode are:

Alkaline Hydrogen Production at the Cathode

$$2 H_2O + 2e^- \rightarrow H_2 + 2OH^-$$

Alkaline Oxygen Production at the Anode

$$2OH^- \rightarrow \frac{1}{2} O_2 + 2 H_2O + 2e^-$$

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.

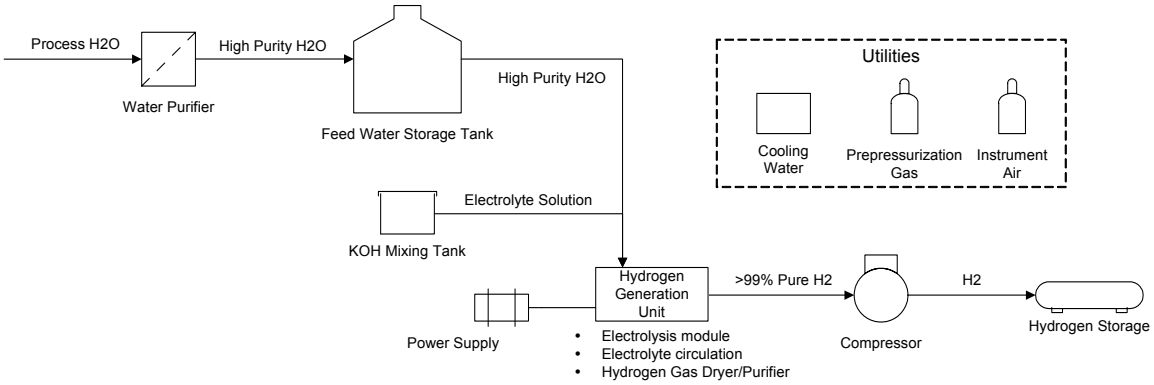
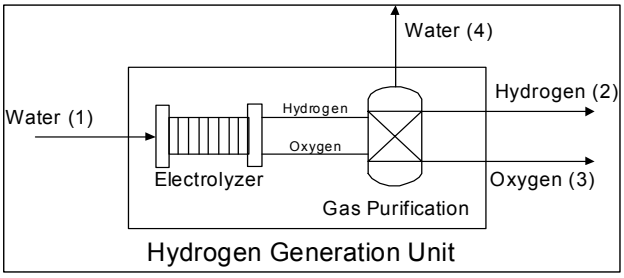


Figure 1: Process Flow Diagram

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) Water			Stream (2) Hydrogen Product			Stream (3) Oxygen Product			Stream (4) 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. Avalence'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

	Energy Required: System		Energy Required: Electrolyzer	Hydrogen Production	System Power Requirement
Manufacturer Model	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	5.4	60.5	-	4.6	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 then 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 60.5 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^3), 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

	Energy Required System kWh/kg	HHV of Hydrogen (equivalent to 142 MJ/kg) kWh/kg	System Efficiency %	Production Pressure psig
Stuart: IMET 1000	53.4	39	73	360
Teledyne: EC-750	62.3	39	63	60-115
Proton: HOGEN 380	70.1	39	56	200
Norsk Hydro: Atmospheric Type No.5040 (5150 Amp DC)	53.5	39	73	435
Avalence: Hydrofiller 175	60.5	39	64	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 then commercial prices. This analysis

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

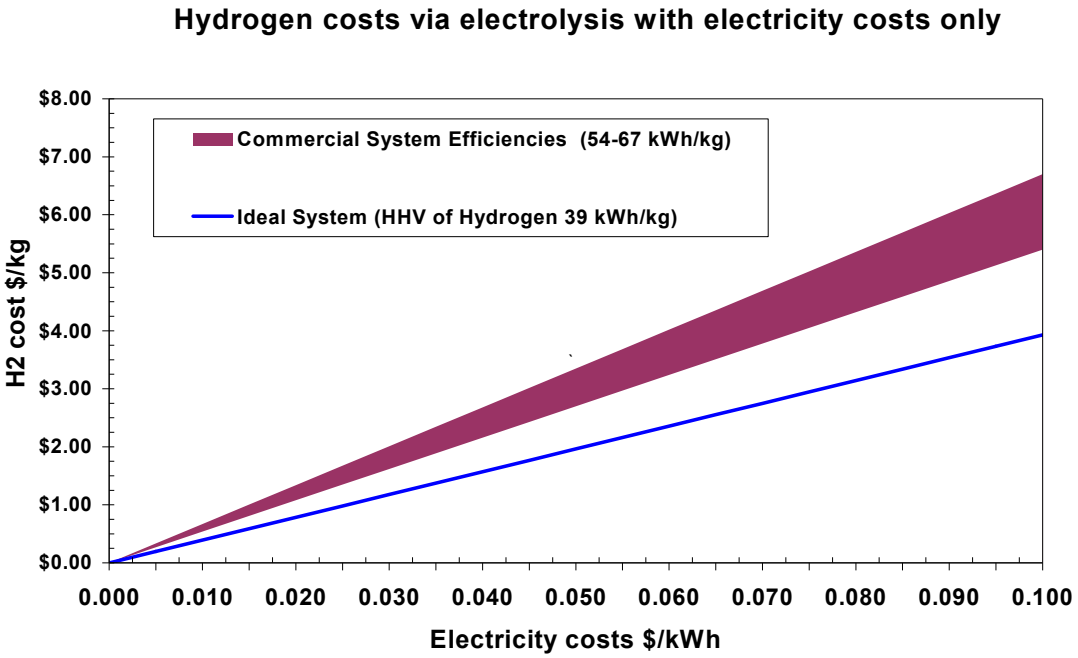


Figure 3[2]

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
Process Parameters	
Primary Feedstock	Electricity and Water
Electricity Used	Industrial Electricity
Conversion Technology	Electrolysis
Financial Parameters	
Start-up Year	2005
After-Tax Real IRR (%)	10
Depreciation Type	MACRS

[2] 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

Parameter	Assumption
Depreciation Schedule Length (No. of Years)	7
Analysis Period (years)	40
Plant Life (years)	40
Assumed Inflation Rate (%)	1.9
State Income Taxes (%)	6
Federal Income Taxes (%)	35
Effective Tax Rate (%)	38.9
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 (%)	100
Salvage Value of Capital (% of Total Capital Investment)	10
Decommissioning Costs (% of Total Capital Investment)	10
Replacement Capital Parameters	
Electrolyzer cell stack lifetime (years)	5-15
Indirect Depreciable Capital Parameters	
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
Non Depreciable Capital Parameters	
Land ($/acre)	5,000
O&M Parameters	
Burdened Labor ($/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 then 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 $19.01/kg for the small neighborhood size to $4.15/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

DCF CALCULATION OUTPUTS:	**Small Neighborhood**	**Small Forecourt**	**Forecourt**
Required Hydrogen Selling Price (Year 2000 Real Dollars)	$19.01	$8.09	$4.15
Required Hydrogen Selling Price (Nominal Startup Year Dollars)	$20.88	$8.89	$4.56
After-Tax Real IRR	10.0%	10.0%	10.0%
Pre-Tax Real IRR	13.0%	12.5%	12.7%
After-Tax Nominal IRR	12.1%	12.1%	12.1%
Pre-Tax Nominal IRR	15.1%	14.6%	14.9%

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 factor in all three of the cases.

Table 7: DCF Item Costs

Specific Item Costs	Small Neighborhood	Small Forecourt	Forecourt	
Item	Cost	Cost	Cost	Units
Capital Cost Contribution	$13.90	$4.43	$1.32	/kg of H2
Feedstock Cost Contribution	$3.15	$2.80	$2.41	/kg of H2
Other Raw Material Cost Contribution	$0.00	$0.00	$0.02	/kg of H2
Fixed O&M (labor etc.) Cost Contribution	$1.93	$0.80	$0.37	/kg of H2
Variable O&M Cost Contribution	$0.01	$0.05	$0.03	/kg of H2
Decommissioning Costs	$0.02	$0.01	$0.00	/kg of H2
Byproduct Credit Cost Contribution	$0.00	$0.00	$0.00	/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, decommissioning 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 all electrolysis units, capital costs and feedstock costs are the two largest cost contributors, and fixed O&M costs are the third largest contributor.

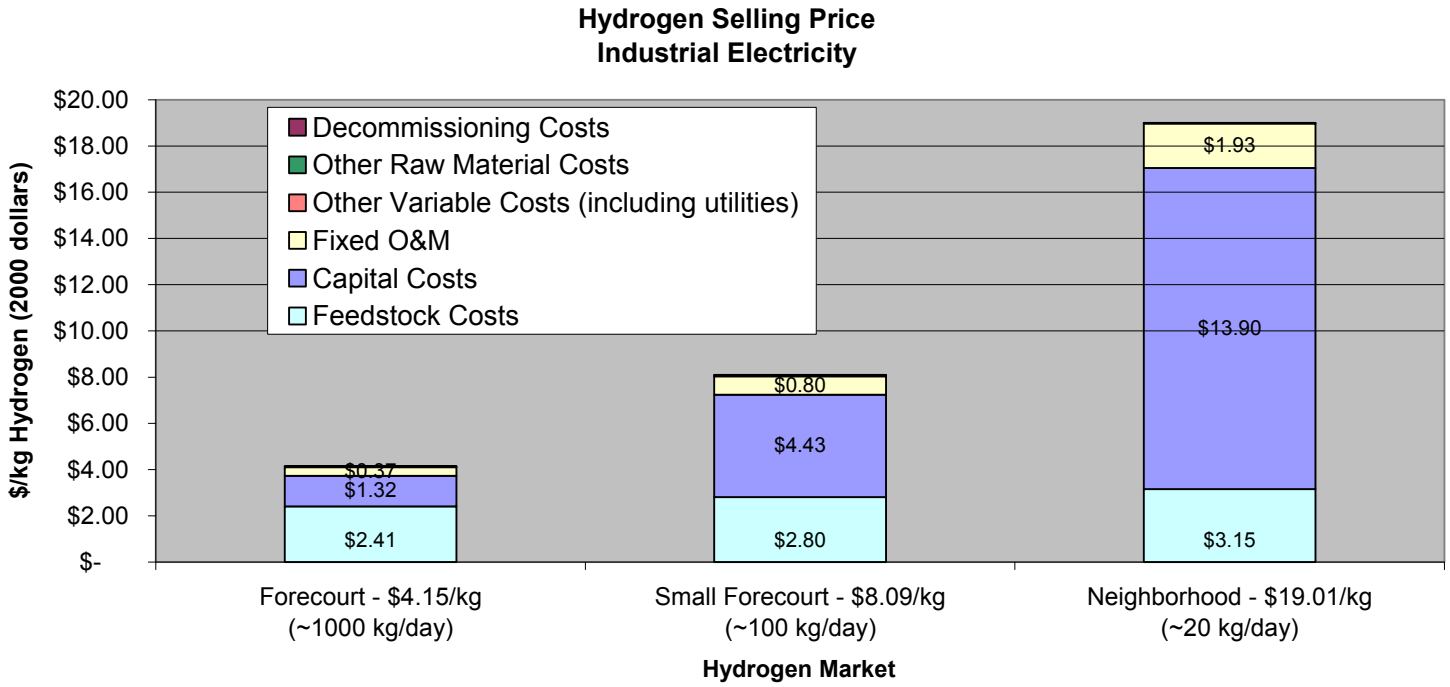


Figure 4

Figure 5 illustrates the driving cost for each of the three cases. For the forecourt case, electricity represents 58% of the cost of the hydrogen, and the capital costs only 32%. For the small forecourt case, the electricity contribution drops to 35% while the capital costs become the major cost factor at 55%. In the neighborhood case, the capital costs increase further to 73%, but electricity costs are not insignificant at 17%. This graph shows that the small neighborhood case and small forecourt cases must focus on capital cost reductions in order to be competitive with the forecourt cases. All three cases need to consider electricity cost as a factor and look to minimize those costs.

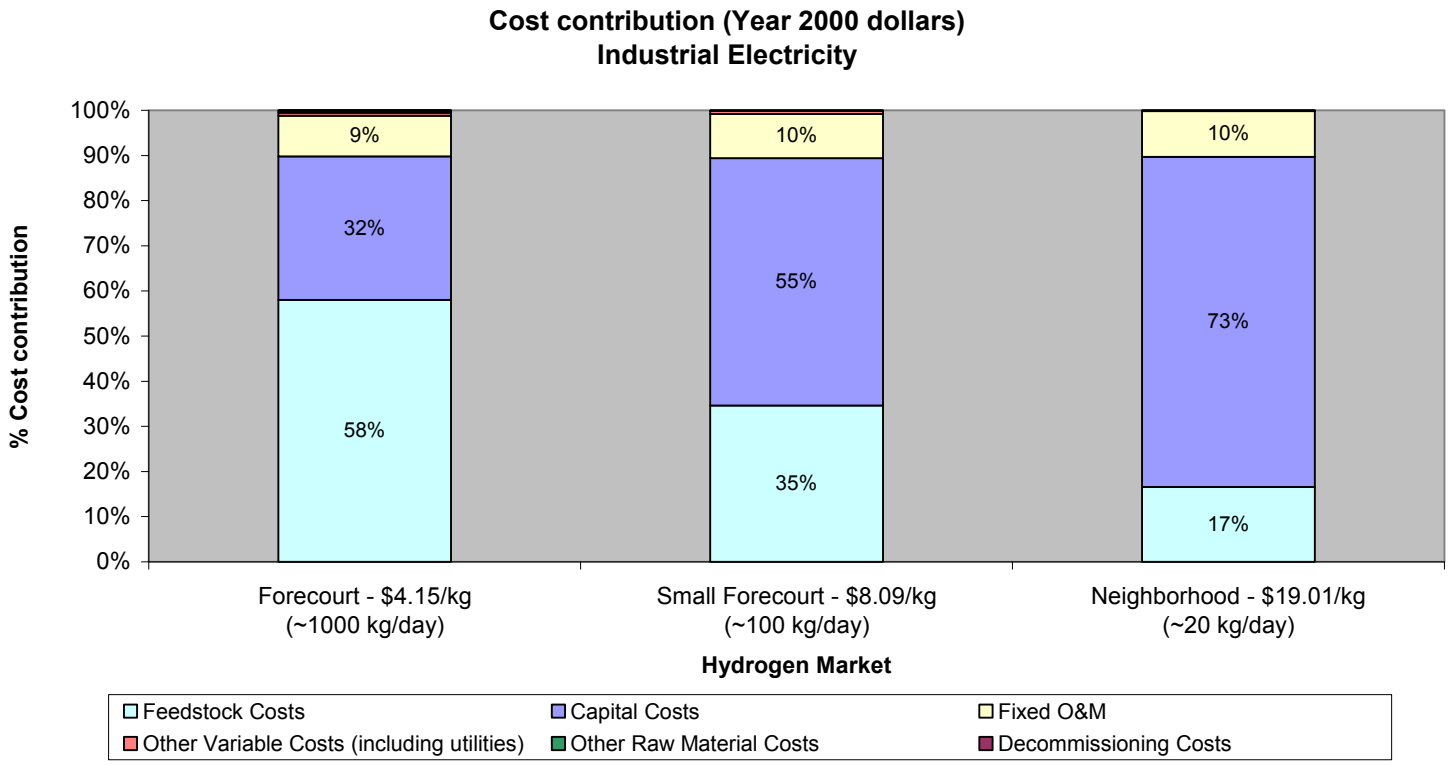


Figure 5

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.

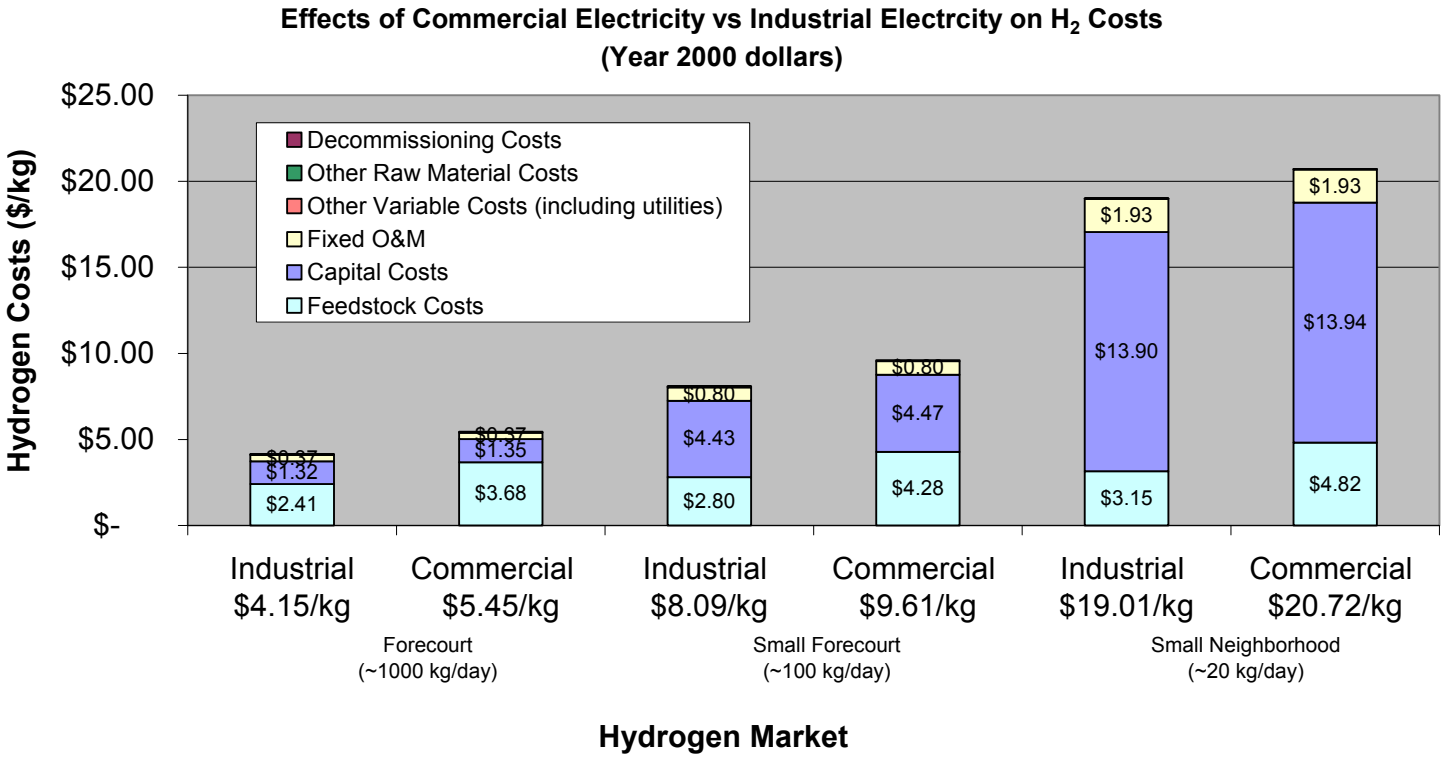


Figure 6

Obviously, an increase in electricity costs leads to an increase in hydrogen costs. For the forecourt case, the price of hydrogen increases from $4.15/kg to $5.45/kg, an increase of 31%. The price of hydrogen from the small forecourt case increases from $8.09/kg to $9.61/kg, an increase of 19%. Finally, the small neighborhood case increases from $19.01/kg to $20.72/kg, an increase of 9%. 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 31%. If even lower

priced electricity alternatives are available they should be evaluated for electrolytic hydrogen production.

The smaller 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 H2 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_2 production	H_2 Purity	Lifetime
		Nm3/hr		kg/hr		psig	kWh/Nm3	kWh/kg	kW	%	years
		Min	Max	Min	Max						
Avalence Hydrofiller 15	Unipolar Alkaline		0.4		0.04	up to 10,000 psig	5.1[3]	56.4	2	99.7	
Avalence Hydrofiller 50	Unipolar Alkaline		1.3		0.1	up to 10,000 psig	5.3[3]	59.2	7	99.7	
Avalence Hydrofiller 175	Unipolar Alkaline		4.6		0.4	up to 10,000 psig	5.4[3]	60.5	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

[3] 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_2 production	H_2 Purity	Lifetime
		Nm3/hr		kg/hr		psig	kWh/Nm3	kWh/kg	kW	%	years
		Min	Max	Min	Max						
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[4]	53.4	48	99.8	7-10
Norsk HPE 12	Bipolar Alkaline		12		1.1	232	4.8[4]	53.4	58	99.8	7-10
Norsk HPE 16	Bipolar Alkaline		16		1.4	232	4.8[4]	53.4	77	99.8	7-10
Norsk HPE 20	Bipolar Alkaline		20		1.8	232	4.8[4]	53.4	96	99.8	7-10
Norsk HPE 24	Bipolar Alkaline		24		2.2	232	4.8[4]	53.4	115	99.8	7-10
Norsk HPE 30	Bipolar Alkaline		30		2.7	232	4.8[4]	53.4	144	99.8	7-10
Norsk HPE 40	Bipolar Alkaline		40		3.6	232	4.8[4]	53.4	192	99.8	7-10
Norsk HPE 50	Bipolar Alkaline		50		4.5	232	4.8[4]	53.4	240	99.8	7-10
Norsk HPE 60	Bipolar Alkaline		60		5.4	232	4.8[4]	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 cm3	Bipolar Alkaline	3	5	0.3	0.4	360	4.8	53.4	24	99.997	10
Stuart IMET 1000, 2 cell stack, 1000 cm3	Bipolar Alkaline	16	30	1.4	2.7	360	4.8	53.4	144	99.997	10

[4] 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_2 production	H_2 Purity	Lifetime
		Nm3/hr		kg/hr		psig	kWh/Nm3	kWh/kg	kW	%	years
		Min	Max	Min	Max						
Stuart IMET 1000, 3 cell stack, 1000 cm3	Bipolar Alkaline	31	45	2.8	4.0	360	4.8	53.4	216	99.997	10
Stuart IMET 1000, 4 cell stack, 1000 cm3	Bipolar Alkaline	64	60	5.8	5.4	360	4.8	53.4	288	99.997	10
Stuart IMET 1000, 6 cell stack, 1000 cm3	Bipolar Alkaline		90		8.1	360	4.8	53.4	360	99.997	10
Stuart IMET 300, 1 cell stack, 300 cm3	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:

$H_2 + ½ O_2 \rightarrow H_2O + \text{energy}$

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:

$H_2O + \text{energy} \rightarrow H_2 + ½ O_2$

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[5].

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14. ABSTRACT *(Maximum 200 Words)*

This report provides an overview of the current state of electrolytic hydrogen production techonologies and an economic analysis of the processes and systems available as of December 2003. The operating specifications of commercially available electrolyzers from five manufacturers, i.e., Stuart, Teledyne, Proton, Norsk Hydro, and Avalence, are summarized. Detailed economic analyses of three systems for which cost and economic data were available were completed. The contributions of the cost of electricity, system efficiency, and capital costs to the total cost of electrolysis are discussed.

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