AN ASSESSMENT OF THE CAPACITY AND COSTS OF ELECTROLYTIC HYDROGEN PRODUCTION FROM SURPLUS HYDROELECTRICTY IN THE PACIFIC NORTHWEST

by

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ABSTRACT

An Assessment of the Capacity and Costs of Electrolytic Hydrogen Production from Surplus Hydroelectricity in the Pacific Northwest

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Transitioning to the hydrogen economy is inhibited by the inability to produce electrolytic hydrogen at a competitive costs and substantial volumes. The Pacific Northwest's capacity to generate large amounts of low cost surplus hydroelectricity provides an opportunity to produce hydrogen gas at competitive costs through forecourt scale electrolysis. This research analyzes Pacific Northwest surplus hydroelectric capacity and models the production of electrolytic hydrogen from a single Norsk Hydro Atmospheric Type 5040 (5150 Amp DC) electrolyzer unit. Modeling projects production of more than 300,000 kilograms of electrolytic hydrogen gas annually, at approximately $3.88 per kilogram. The results of this study suggest that hydroelectricity utilities in the Pacific Northwest have the capacity to produce substantial amounts of electrolytic hydrogen at costs competitive with conventional hydrogen production.

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Acronyms:

$/kg : Dollars per kilogram
aMW: Average Megawatts
BPA: Bonneville Power Administration
HLH: Heavy Load Hours
HHV: Higher Heating Value
IR: Industrial Firm Rates
kWh: Kilowatt Hours
MMBtu: Million British Thermal Unites
PF: Priority Firms
WY: Water Year

Helpful Conversions:

1 MMBtu = 293.1 kWh
1 kWh = 0.003412 MMBtu
1 kg = 11.0921 m^3
1mill= 0.1¢ /kWh
MW = 1,000 kW

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Section I: Introduction

A critical challenge to building a clean energy future has been the inability to produce substantial quantities of clean burning fuel derived from clean energy sources, at a cost that is competitive with dirtier conventional fossil fuels. For the past several decades, hydrogen has been targeted as potential energy game-changer that could drastically reduce dependence on fossil fuels. In its H_2 form, hydrogen has been praised for its high energy density, versatility, storability, lack of pollutants, absence of greenhouse gas emissions, and ability to be produced from renewable energy sources. Although it is the most abundant element in the universe, hydrogen rarely naturally exists in its H_2 form. Without natural H_2 deposits, H_2 must be produced by separating it from hydrogen compounds. water molecules can be split into hydrogen and oxygen through the simple process of electrolysis. Requiring substantial amounts of feedstock electricity, electrolysis can be a very expensive process, largely giving fossil fuel production economic advantage over electrolytic hydrogen. Low electricity prices, such as those of Pacific Northwest hydroelectricity, create an opportunity to produce electrolytic hydrogen at reduced costs, that could potentially elevate the region as a leader in clean and efficient hydrogen production.

Problem Statement:

Producing a universal energy carrier from renewable and cleaner sources could alleviate economic, social and environmental burdens engendered from fossil fuel production and consumption. Hydrogen, in its H_2 form, has the ability to perform all the duties of conventional fossil fuels and has several additional advantages over fossil fuels including: higher energy efficiency, lack of emissions and ability to be produced through renewable energy sources. Marred by a large demand for costly feedstock electricity inputs, electrolytic hydrogen as an energy carrier and transportation fuel has been largely shelved until there is production efficiency and capacity improvement and/or significant increase in the cost of petroleum products.

Maturation of electrolytic technologies have allowed for more efficient large scale electrolysis, potentially allowing the opportunity to produce economically viable electrolytic H_2. With constant production, today's largest electrolyzer units can produce more than 1,000 kg of hydrogen a day. This high level of production comes at a high electricity consumption, demanding more than two megawatts (MW) of constant electricity. That is enough energy to power roughly 1,600 homes.

This thesis intends to determine whether a tipping point has been reached that would allow Pacific Northwest power utilities to use inexpensive surplus hydroelectric resources to produce economically viable electrolytic hydrogen on a large (forecourt) scale that is cost competitive with conventional hydrogen production and gasoline.The economic viability of electrolytic hydrogen production will be assessed through an analysis of regional surplus hydroelectricity availability, establishment of fixed production costs of electrolytic hydrogen, and calculation of electrolysis feedstock electricity demand and its associated variable costs. With establishment and validation of total production costs, an assessment of the price per kilogram of raw electrolytic hydrogen gas can be made. This research represents a pilot study for the Pacific Northwest's capacity to produce a clean, storable energy carrier that can serve as back up energy supply or be sold as a merchantable commodity or fuel.

Hypothesis and Rationale:

The following subsection exhibits the working research hypothesis and supporting rationale for this thesis. The null hypothesis is represented as H_o and the alternative hypothesis is represented as H_o.

H_o: Despite the abundance of low cost surplus hydroelectricity in the Pacific Northwest region, maturation of electrolysis technology and escalation of fossil fuel costs, large scale production of electrolytic hydrogen is not an economically viable use of hydropower resources.

H_α: Because of the abundance of low cost surplus hydroelectricity in the Pacific Northwest region, the maturation of electrolysis technology, and the escalation of fossil fuels costs, large scale production of electrolytic hydrogen is an economically viable use of hydropower resources.

Rationale for utilization of hydroelectric resources to produce electrolytic hydrogen stems from three advantages of hydroelectricity:

(1) Hydropower has ahigh capacity to produce large volumes of electricity, allowing for high production electrolyzers to produce hydrogen at economies of scale.

(2) Hydropower resources have the greatest ability to produce large amounts of low cost surplus electricity.

(3) Hydropower is an existing installed energy resource, very little infrastructure would have to be built and carbon costs of hydroelectric plants have been largely mitigated over their longoperating lifetime.

Thesis Organization

Prior to an assessment of the availability, capacity and costs of electrolytic hydrogen production utilizing surplus hydropower in the Pacific Northwest, validation of study background and parameters first must be established. Once study foundations are established then research transitions to an analysis of electrolysis cost variables after which, overall production capacity and costs can be calculated.

Proceeding from this point, this thesis is organized into several larger sections. First is the articulation of the study scope and design. Then the thesis progresses to a foundational discussion of hydrogen energy and hydrogen production. The next portion reports on the preexisting hydroelectricity-to-hydrogen studies which influence, support and guide this research. After the review of the preexisting studies, this research transitions to establish Pacific Northwest surplus hydroelectric availability, and validate fixed and variable production costs. Finally, analysis of total production cost is made, overarching conclusions are drawn and opportunities for further research are suggested.

Section II: Study Scope, Parameters and Design

Assessment of electrolytic hydrogen production from surplus Pacific Northwest hydropower requires establishment of foundational study parameters. This section addresses the selection of the Pacific Northwest for the study site, sets appropriate scale of electrolysis production, addresses the selection of the appropriate electrolyzer unit and details necessary foundational study assumptions.

Selection of Pacific Northwest for Hydroelectricity to Hydrogen Production:

Natural resources have finite quantities and extraction locations. Since natural resources have limits, ultimately the goal is to more efficiently and sustainably use these resources. Hydropower represents the most advantageous methods of producing high capacity, non-intermittent electricity with only marginal greenhouse gas emissions. Single hydro dams can constantly generate several thousands of megawatts of power, but have maximum capacities and finite locations that are technologically and economically viable for energy extraction. Nearly all of these locations have been exploited in North America. (Altinbilek, Seelos and Taylor 2005) The Pacific Northwest is fortunate to have the highesthydroelectric capacity in the United States, but as we have installed the practicable the maximum of hydroelectric capacity, it becomes increasingly important to most efficiently use this valuable resource.

To sustainability manage power resources, it is essential to forecast energy consumption demand. Bonneville Power Administration forecasts demand loads ten years in advance to ensure it has the capacity supply the demanded energy resources Figure 1 displays anticipated regional monthly load demand for 2011-2012, 2015-2016, and 2020-2021, illustrating the regional energy supply requirements each month for an entire year.

Figure 1: Monthly Power Load Demand in the Pacific Northwest

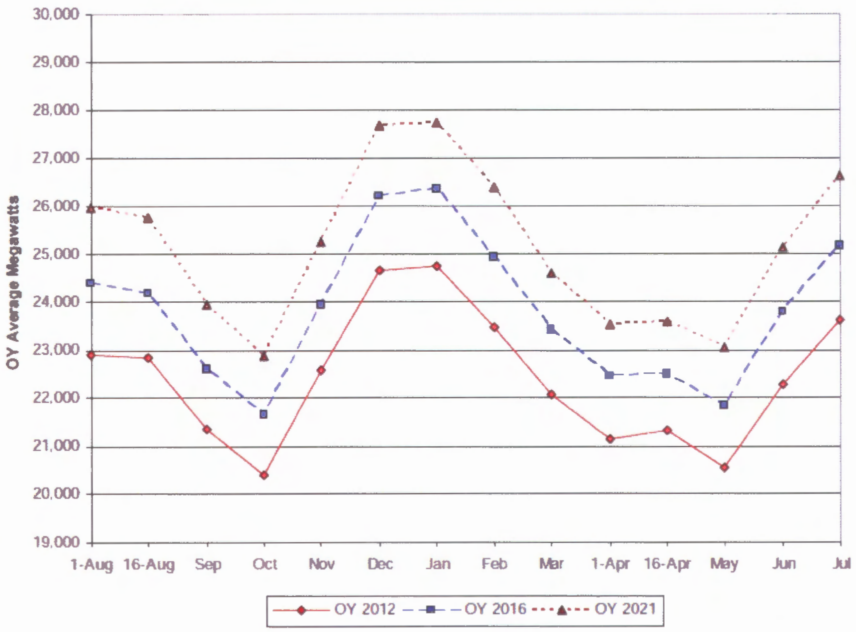

Figure 1 displays projected electricity load demand in megawatts for the Pacific Northwest region in the 2012, 2016, and 2021 operating years.
Source: Bonneville Power Administration *2011 Pacific Northwest Loads and Resource Study* p.64

Figure 1 displays the minimum energy supply necessary to fill the electricity demands of the Pacific Northwest region. Figure 1 demonstrates the cyclical annual energy demand in the Pacific Northwest region, depicting highest demand in the coolest months. Anticipated regional growth generates sizeable energy demand increase over the next ten years. Whereas energy demand can be forecasted with reasonable accuracy, energy supply is widely variable. The Pacific Northwest's energy supply is dominated by hydroelectricity and hydropower's production capacity is directly dictated by water year conditions. Water year conditions are historic records of river levels resulting from annual precipitation and snow melt levels. Table 1 displays the wide range in Pacific

Northwest electricity resource in average megawatts for years 2012-2021 under variable water year conditions.

Table 1: Projected Pacific Northwest Load Resources for the Years 2012 – 2012 Under Variable Water Year Conditions in Average Megawatts

Operating Year	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Top 10% Water Year	33,121	33,064	33,061	32,979	33,054	32,850	33,105	32,857	33,003	32,272
Middle 80% Water Year	29,785	29,778	29,819	29,755	29,825	29,660	29,885	29,667	29,774	29,082
Bottom 10% Water Year	26,434	26,509	26,588	26,537	26,603	26,435	26,669	26,442	26,555	25,857

Table 1 displays the forecasted electricity supply in average megawatts (aMW) for the Pacific Northwest under variable water year conditions
Source: Bonneville Power Administration *2011 Pacific Northwest Loads and Resource Study* p.67

Furthermore, Table 1 demonstrates the potentially wide range in electricity supply water year conditions generate. The difference in electricity supply between a Top 10% and Bottom 10% water year is greater than 6000 aMW, enough electricity to power roughly 4.8million homes.Comparison of Figure 1 and Table 1 reveals that even in critical water years, there is typically ample electricity supply to meet regional demand. Power generated above regional demand is considered surplus and is eligible to fill supplemental regional energy demands or is exported out of region. Figure 2, demonstrates projected surplus through 2021 under critical water year conditions, representing the most conservative annual average energy surplus.

Figure 2: Projected Pacific Northwest Electricity Surplus Under Critical Water Year Conditions

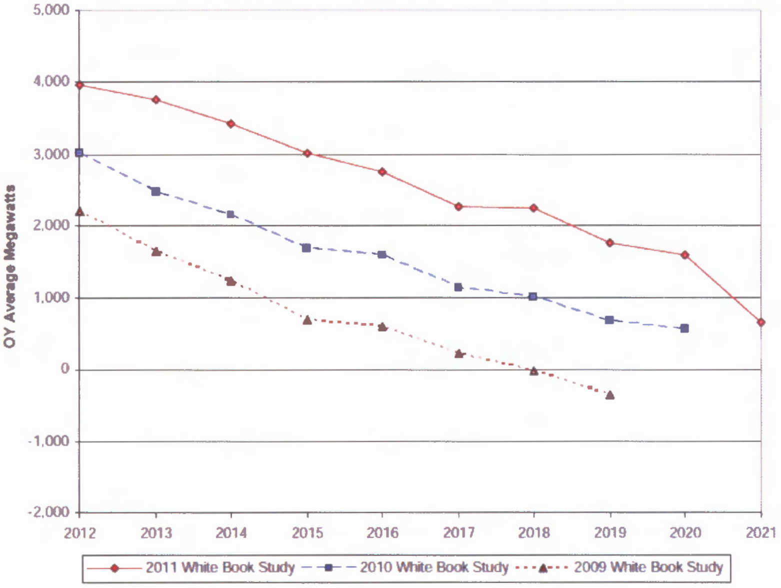

Figure 2 displays projected electricity surplus produced by Pacific Northwest energy firms for the years 2012 through 2021 under critical water year conditions.
Source: Bonneville Power Administration *2011 Pacific Northwest Loads and Resource Study* p.70

Cursory examination of Figure 2 suggests that projected electricity surplus derived from the Pacific Northwest's large hydroelectricity capacity is ample electricity supply to utilize surplus electricity to produce electrolytic hydrogen. Even under the lowest of water years, as seen in Figure 2, annual surplus appears ample to support electrolytic hydrogen production, exposing the Pacific Northwest's suitability for this study. Further analysis of surplus electricity resources are discussed later in Section V, but initial outlooksuggests Pacific Northwest hydroelectric dominated power resources make the region attractive for electrolytic hydrogen production.

Selection of Electrolysis Production Scale:

There are numerous companies currently producing commercially available electrolyzer units. Available in differing sizes, designs and production capacities, there are primarily five scales of electrolytic hydrogen production capacity. Although there is variance in the design of electrolyzer technology, all electrolyzers fundamentally function the same way, with the application of direct electric current to a hydrogen compound and then the collection of separated gases. Table 2 displays the five scales of electrolytic production and the corresponding number of cars such could potentially fuel.

Table 2: Scales of Electrolyzer Production

Scale	Kg. of H_2 Produced Annually	Number of vehicles served
Home	200 – 1,000	1 – 5
Small Neighborhood	1,000 – 10,000	5 – 50
Neighborhood	10,000 – 30,000	50 – 150
Small Forecourt	30,000 – 100,000	150 – 500
Forecourt	➢ 100,000	➢ 500

Table 2 displays the five scales of hydrogen production from commercially available electrolyzers
Source: (Ivy, 2004)

In order to make the most sizable impact in clean hydrogen production, this study selectsthe largest scale electrolytic production, known as forecourt electrolysis. A forecourt hydrogen production plant has the capacity to produce greater than 100,000kg of hydrogen annually. (Ivy 2004)A plant of this capacity requires substantial feedstock electricity input, and has a sizeable physical footprint. Selection of forecourt scale is paramount to economic feasibility. The large capital cost of electrolysis requires the selection of forecourt scale so that economies of scale are reached, resulting in the least expensive price per kilogram of H_2 produced.

Selection of Electrolyzer Unit:

Selection of an electrolyzer unit is closely married to desired production scale. For the scale considered in this analysis, only a forecourt scale electrolyzer is considered because of its production output. Ideally electrolyzers would operate with a level of input power yielding the highest production rate. But, as availability of surplus hydroelectricity can change rapidly, the electrolyzer must have the ability to quickly adapt to varying current loads. (Ouellette, Rogner and Scott 1997)

The electrolyzer selected for this study is the Norsk Atmospheric Type No. 5040 (5150 Amp DC). It is the largest commercially available electrolyzer; a single unit has the production capacity of 1,046 kg of H_2 daily, enough to supply fuel for 1909 cars annually, on the assumption of approximately 200 kg of H_2 annually at 60 miles per kg of hydrogen. (Ivy 2004)The Norsk Atmospheric Type No. 5040 (5150 Amp DC) is a bipolar electrolyzer, employing a filter press and alkaline electrolyte. This design clamps stacks alternating layers of electrodes, separated by support diaphragms. The stacked electrode cells are connected in series, generating higher voltage. Bipolar electrolyzers have the advantage of a smaller footprint, higher current density, and the ability to produce higher pressure gas. (Kroposki, et al. 2006) The Norsk Atmospheric Type No. 5040 (5150 Amp DC) is amongst the most efficient electricity-to-hydrogen electrolyzers current available. Requiring 2.328 MW to operate at optimal production levels, it produces a single kilogram of hydrogen for every 53.5kW input, generating roughly 43.6 kilograms an hour. Its overall electricity to hydrogen efficiency is 73% and has the ability to compress gas to 435psi. (Ivy 2004) Further discussion and explanation of the electrolysis process can be found below in Section III.

Study Assumptions:

This study asserts several key assumptions in order to produce consistent results. Any given year's specific water year (WY) condition dictates surplus power availability. Reflecting the recorded historical 70 year water levels, water year conditions are the strongest determinant of how much surplus hydropower can be generated and how a power utility would consider using its water resources. Along with determining availability, specific water year conditions dictate the price surplus hydropower commands. The unpredictable nature of water year conditions and corresponding unpredictable energy supply drives the following assumptions, which are made to provide predictable study parameters and a reduction of exogenous variables.

Today, the electrical grid in the United States is constructed as a patchwork of smaller regional electricity grids. Electricity is sold as a commodity and is transmitted from region to region in times of power deficit and surplus. Electricity transmission is governed by Regional Transmission Organizations (RTO) and Independent System Operators (ISO).Currently, the majority of surplus electricity generated in the Pacific Northwest is sold to the California ISO and British Columbia. This study assumes that any existing contracts and agreements that may bind Pacific Northwest hydroelectric utilities to sell to inter-regional energy exchanges are disregarded. This assumption enables any regionally generated hydropower above the load demand to be consumed by electrolytic hydrogen production. Participation in inter-regional energy exchanges is voluntary, and the quantity ofsurplus electricity sold on the exchanges is variable and difficult to ascertain. This assumption does not preclude surplus hydropower to be transmitted out of region, it is simply a caveat giving electrolytic hydrogen production the first priority to surplus power. Furthermore, Bonneville Power Administration's Pacific Northwest surplus electricity forecasts through the year 2021 anticipate only extreme occurrences, consisting of the poorest of water years and during the coldest months, which surplus power is so marginal that there would be insufficient surplus for both electrolytic hydrogen production and out transmission out of region. Additional discussion of Pacific Northwest surplus electricity capacity is addressed in Section V.

The Pacific Northwest has a substantial amount of Independent Power Producers (IPPs) that contribute 3,287 aMW to the power grid, enough electricity to power more than roughly 2.4 million homes. IPPs constitute roughly 10% of BPA total generating capacity. Generating power by wind, biomass, natural gas, and coal the IPPs assist BPA filling base-load power requirement. Independent Power Producers have the option of selling electricity out of region to ISOs and RTOs, but this study assumes that all IPP electricity would stay within the Pacific Northwest Region. Regardless of water year conditions, this study assumes that all 3,287 aMW are available to the Pacific Northwest base-load demand. Delivering all IPP electricity to the regional grid allows for a more consistent measure of base-load power resources. Counting all 3.287 aMW non-hydropower resources as delivering regional base-load power, it can then be assumed that all electricity generated beyond base-load demand is surplus generated through hydroelectricity.

Determination of the price of surplus electricity is difficult because of large amounts ofdaily, monthly and annual variance. Surplus electricity prices and availability reflect seasonal river conditions and overall specific water year conditions. For this study the price of surplus power is assumed to be equal to or below the lowest contracted electricity rates offered by Bonneville Power Administration. Currently, the lowest contracted electricity rates are paid by Priority Firms at prices that vary monthly, reflecting historical seasonal river flow rates. Calculations in this study that employ Priority Firm Rates, will represent conservative surplus electricity rates.

Climate change poses a potential challenges to hydroelectricity generating utilities. Changes in precipitation rates, seasonal conditions, stream lengthand annual freeze and melt events represent potential disruption of traditional power generation timing and capacity. Although potentially having substantial impact on surplus availability and timing, this study does not take in to consideration impacts of climate change on water year conditions, population change, precipitation, river flow change, and changes inenergy demand. Climate change represents an intriguing consideration for future hydroelectricity producers, which has the potential to increase, decrease or cause no change to availability of surplus electricity, but this consideration is beyond the scope of this study.

The several assumptions addressed above are established to provide a standard and predictable baseline of power resources in the Pacific Northwest, and reduce ambiguity of what power is available and its dispersion. As available power is consistently in flux in this region, it is important to account for all the consistently predictable power resources.

These assumptions allow more predictable allocation of regional electricity resources, which will allow a more accurate forecast of regionally available surplus hydropower and price.

Section III: Foundations of Hydrogen Energy and Hydrogen Production

The most basic and lightest of all elements, hydrogen has a host of uses which makes hydrogen production enticing. Beyond its potential role in the energy field, hydrogen is used in a multitude of manufacturing processes, and is an essential part of chemical, metal and glass production. Hydrogen's versatility keeps demand for production high and as hydrogen energy continues to gain interest, there is increasingly more demand to produce larger quantities. This section highlights hydrogen energy and discusses the two common methods of hydrogen production.

The Hydrogen Economy:

The term 'hydrogen economy' arose amidst the energy crisis of the 1970s and constitutes the replacement of the petroleum-based transportation and energy infrastructure with hydrogen produced from non-fossil fuel based sources. (Balat and Kirtay 2010) Essentially transitioning to the hydrogen economy entails three steps: (1) large scale production of hydrogen fuel; (2) storage, transportation, and distribution of hydrogen fuel; and lastly (3) wide-scale implementation and utilization of hydrogen fuel. (Tomczyk 2009) Certainly, the hydrogen economy is a drastic overhaul of our existing energy and transportation infrastructure that would generate a complex array of transitional strife to a host of interconnected industries. A large scale of energy transition would potentially render currently crucial products and services obsolete, but a transition to a hydrogen economy has the widely appealing possibility of energy independence, virtually devoid of greenhouse emissions.

Transitioning to the hydrogen economy requires the clearance of substantial obstacles. The United States consumes roughly 140 billion gallons of gasoline annually, which would need to be replaced with roughly the same amount of kilograms of hydrogen. (Kroposki, et al. 2006) Today's hydrogen production does not yet approach 140 billion kg. In 2009 world hydrogen production accounted for roughly 45 million kg (500 billion m^3) and nearly 96% of all hydrogen was produced with fossil fuel based feedstocks. (Tomczyk 2009) This hydrogen would be inappropriate forbuilding thehydrogen economy, as producing hydrogen from fossil fuel based feedstock contradicts the foundation of thehydrogen economy's fossil fuel-free energy and transportation fuel. The roughly 1.8 million kg of hydrogen not produced with fossil fuel feedstocks are generated through electrolysis. Utilizing electrolysis to produce hydrogen is the ideal method of producing hydrogen for transition to the hydrogen economy and detailed explanation of the electrolytic process can be found in the "Electrolytic Hydrogen Production" subsection below.

The complete transition to the hydrogen economy would require electrolytic hydrogen production to exponentially increase. To generate enough electrolytic hydrogen to replace fossil fuels would require the US to "... double its current electricity capacity." (Kroposki, et al. 2006, p. 20) Not only would electricity capacity need to double, but the new electricity would have to come from non-fossil fuel energy sources such as wind, solar, hydro, biomass, nuclear and other renewables. Although a full transition to the hydrogen economy requires a dramatically large increase in electricity capacity, incremental steps towards the hydrogen economy can be made with more efficient and sustainable management of the electric resources already in place.

This pilot study, which analyzes electrolytic hydrogen production potential from surplus hydroelectricity resources, is an attempt to make more efficient and sustainable management of currently available resources. If there is ample surplus capacity and low enough production costs, electrolytic hydrogen from surplus hydropower could represent a model for potential energy conservation through hydrogen production.

Hydrogen's Benefits Over Petroleum:

The consequences of modern dependence upon fossil fuels have far reaching negative economic, social and environmental impacts. As conveniently accessible fossil fuels continue to diminish, we are faced with exerting increased energy inputs in order meet our energy demand. The increased exertion of input energyto fill the same energy demand depicts the growing inefficiency of fossil fuel based energy. Unless substantial new deposits are discovered, fossil fuels' life-cycle efficiency will continue to decline, generating increasingly higher costs to the consumer. This does not account for the host environmentally harmful by-products producing and burning fossil fuels generates, nor the social strife generated as a cost of conducting business in the fossil fuel industry.

Hydrogen is a proven and viable fuel, directly comparable with gasoline. A single kilogram of hydrogen contains the energy capacity of 33999.6 kWh (122398.56 MJ or 116MMBtu) which is approximately the same energy capacity as a gallon of gasoline 31676.1- 36368.9 kWh (108-124MMBtu or 11403.4 – 130928 MJ). (Levene, Kroposki and Sverdrup 2006) Although a gallon of gasoline and a kilogram of hydrogen have the same potential energy capacity, when consumed hydrogen fuel delivers superior energy performance, losing far less potential energy to heat than gasoline.

Half the global oil production is consumed by motor vehicles. Burning fossil fuels in motor vehicles accounts for more than 70% carbon monoxide (CO) emissions, 17% of carbon dioxide (CO_2) emissions, and a host of other pollutants including: nitrogen oxides, hydrocarbons, lead and particulates. (Balat and Kirtay 2010) As fossil fuel energy sources are rapidly becoming scarcer with increased global petroleum demand, there is the need to procure a storable, transportable energy supply derived from non-fossil fuel sources. Hydrogen has received significant endorsements as the fuel of the future. When burnt, hydrogen emits pure water and only a marginal amount of nitrous oxide (approximately 1/200 of diesel's $N0_3$ by-product) (Balat and Kirtay 2010) Hydrogen is more efficient energy carrier than petroleum products, storing more than 2.5 times the energy per unit of mass than gasoline. Hydrogen's better efficiency performance equates to a vehicle traveling further on the same mass unit of fuel and less energy lost as heat. Hydrogen burns at a rapid rate and at high octane. Hydrogen has more versatile flammability in air 4% - 75% by volume opposed to gasoline's 1 – 7.6%. Hydrogen has a very low minimum ignition energy of .02 mJ and is easy to ignite at low temperatures. (Balat and Kirtay 2010) Hydrogen can be compressed, stored and transported efficiently and inexpensively (Rifken, 2002). Much of the infrastructure built for petroleum transport, and delivery can be used with hydrogen fuel.

Hydrogen outperforms petroleum in energy efficiency, is cleaner for the environment and has potentially limitless production capacity from renewable electricity. Petroleum's advantage over hydrogen is chiefly economical. The long term investments made to access reserves, allows fossil fuels to be less expensive to produce on a large scale. As the cost to produce fossil fuels increases, we must consider whether continuing to make large investments in fuels that are increasing less economical and exacerbate negative environmental and social conditions are a better use of our resources than beginning to make investments into hydrogen and start a transition to an energy carrier that offers more long term sustainability than petroleum.

Hydrogen can be produced from domestic energy sources. Production is well suited for alternative and renewable energy resources. The intermittence of renewables can cause hard to predict spikes and declines in electricity generation. Sudden changes in energy output from renewables generate issues balancing regional energy supply and demand. The potential to take surplus electricity and store it for use in times of increased demand constitutes a major leap forward in energy conservation and efficiency. Once stored, hydrogen has the versatility to be used as either a transportation fuel or electrical power source.

Hydrogen has a host of social, environmental, and fuel performance advantages over fossil fuels, but the problem that persists is the unavailability of a large source of cheaply produced hydrogen. Until large quantities of hydrogen can be produced at prices competitive with petroleum, the economics of petroleum will continue outcompete hydrogen.

Conventional Hydrogen Production:

As aforementioned, hydrogen is the most abundant element in the universe, but rarely exists naturally in its H_2 state. The H_2 compound is the form required forhydrogen's use as an energy carrier, meaning H_2 has to be produced through separating hydrogen fromother elements withina compound. H_2 is an 'energy carrier,' rather than an energy source. This is an important distinction as it implies that hydrogen (H_2) is not a natural harvestable energy resource. Energy inputs are required to generate the H_2, which has the capacity to store a substantial portion of imputed energy, and then can be consumed as fuel.

The conventional method for producing hydrogen is a process called stream reformation, in which stream reacts with natural gas, liquefied coal or another fossil fuel in a catalytic convertor. The reaction between steam and fossil fuel strips away H_2 from the steam molecules, which then can be collected. Steam reformation production costs range from \$1.00-5.00 per kg of hydrogen and is the current least expansive method of H_2 production. Fossil fuel feedstock price volatility contributes to this wide ranging cost scale. (Kroposki, et al. 2006) The process of steam reformation has the unfortunate byproduct of large amounts of greenhouse gasemissions. Fossil fuel based hydrogen generation, "...produces at least the same amount of CO_2 as the direct combustion of the fossil fuels." (Balat and Kirtay 2010, p. 865) Additionally, steam reformation hydrogen commonly has high levels of impurities. (Kroposki, et al. 2006) Hydrogen that has higher rates of impurities reduces fuel cell performance. Despite this, steam reformation is still the hydrogen production method of choice, representing 96% of all hydrogen production as of 2010 (Balat and Kirtay 2010)

Steam reformation has several advantages that make it the current hydrogen production method of preference. Primarily, steam reformation has economic advantage over non-fossil fuel based hydrogen production. Steam reformation is versatile. Any fossil fuel can be used as a feedstock in the process. Steam reformation has the ability to produce substantial amounts of hydrogen on a smaller physical footprint and has a better input energy to hydrogen conversion efficiency. Opposed to electrolysis, steam reformation has the ability to produce economical hydrogen at smaller scale production output.

The advantages of steam reformation production are reduced with consideration of steam reformation's long-term sustainability, and potential role in the hydrogen economy. As global fossil fuel deposits decline, steam reformation's hydrocarbon based feedstock costs will continue to increase. Geopolitical strife is perpetuated through the reliance on steam reformation, as it continues the need to conduct business in volatile fossil fuel producing nations. Steam reformation necessary use of fossil fuel feedstocks, releases greenhouse gases and other pollutants, ruling out steam reformation hydrogen fuel in the potential hydrogen economy. The hydrogen economy fundamentally prohibits hydrogen produced through fossil fuel based energy. Steam reformation's associated greenhouse gas emissions could be mitigated with carbon capture systems, but the current application of carbon sequestration technology to conventional hydrogen production has not proven itself economical. (Balat and Kirtay 2010) Steam reformation will likely continue to serve the industrial needs of hydrogen, as the method performs efficiently producing economical supplies of hydrogen, but its poor sustainability and dependence on fossil fuel feedstocks, does not make the steam reformation a long term-viable solution towards advancing to the hydrogen economy.

Electrolytic Hydrogen Production:

It is well established that there is another hydrogen production methods without the undesirable consequences of the steam reformation process. Electrolysis, discovered more than two centuries ago by William Nicholson and Sir Anthony Carlisle, is a rather simple process in which the application of direct current to water splits the atoms into its two basic elements, Hydrogen (H_2) and oxygen (O_2). Electrolysis generates these gases as electricity is introduced to an electrolyzer, which consists of four basic components: an electrolyte, electrodes, a separator, and container. The electrolyte is a highly conductive solution or polymer, most commonly an alkali, which supplies atoms to be exchanged. The electrodes are the actual interaction point between electric current and electrolyte. Consisting of a positive charged anode and negative charged cathode, electrodes are highly conductive metals which facilitate the exchange of atoms. Oxidation occurs at the anode site, which entails stripping away electrons. Reduction, or the gain of electrons, occurs at the cathode. The anode facilitates the generation of oxygen, while the cathode generates hydrogen. The electrode is the most variant component between electrolyzer designs and facilitates different levels of efficiency and productivity. A separator is the corrosive resistant buffer between anode and cathode which prevents the mixture of gases within the electrolytic cell. Lastly, the container is simply the vessel which holds the electrolyte and allows for flow of current. (Pratt, et al. 1984) Regardless of individual electrolyzer unit, the same fundamental reaction occurs with the application of direct current to water. The process of electrolysis can be expressed by the following reaction equation, representing the process facilitated within the electrolyzer unit:

$$H_2O + 237.2 \text{ kJ/mole electricity } 0 + 48.6 \text{ kJ/mole heat} \rightarrow H_2 + \frac{1}{2} O_2$$

The heat required in the electrolysis process is generated from reaction within the electrolytic cell. As electric and ionic currentsflow through the electrolytic cell they encounter internal resistance, generating heat. Heat generated in the electrolytic process is the direct a result of input electricity, so in actuality it takes 285.8kJ of input electricity complete electrolysis, rather than, aforementioned 237.2kJ. (Harrison, et al. 2010) The loss of 48.6kJ of electricity to heat in the process of electrolysis is inevitable, constituting the impossibility of 100% efficient electricity to hydrogen conversion. Actual perfect efficiency of electrolysis is 84.5% electricity to hydrogen conversion. (Ivy 2004) This illustrates the fundamental limitation of electrolytic hydrogen production, in the best case scenario 15.5% of input electricity will be lost to heat in conversation to hydrogen.

Under optimal conditions of electrolysis, 39 kWh of electricity and 8.9 liters of water would produce a single kg of H_2 at 25°C and 1 atmosphere of pressure. This represents the ideal 84.5% electricity to hydrogen conversion efficiency, but current commercially available electrolyzers do not have the ability operate at such high efficiency rates. Today's commercially available electrolyzer units operate at 56-73% efficiency equating to a range of 70.1-53.4kWh of input feedstock electricity per kg of hydrogen produced.

(Kroposki, et al. 2006) How efficiently an electrolyzer can convert electricity into hydrogen is a vital determinant of economic viability of a large scale electrolysis project. In the electrolysis process there are several key factors which determine how efficiently electricity is converted to hydrogen, predominantly: cell size, voltage, conductivity, current density and process temperature. (Kruger 2000) Setting an electrolyzer to its highest efficiency rating is not always the best economic decision in an electrolysis project. Efficiency changes with variance in electricity load, (current density). Literature states, that amidst electrolysis as current density drops ". . . the specific capital costs of electrolyzer ($/kg) increases rapidly as capacity decreases." (Ouellette, Rogner and Scott 1997, p.399) This suggests that economic vitality is reliant on large scale electrolysis employing as high a current density as possible. Higher versus lower current density, generates a tradeoff between production level and feedstock costs. High hydrogen gas production levels yield from higher current density,and constitute better return on capital investment. In response, high production levels decrease electrolysis efficiency, increasing electricity costs per unit of hydrogen produced. (Ouellette, Rogner and Scott 1997) In a project such as this thesis, with the high capital costs inherent in large scale electrolysis and low costs of surplus feedstock hydroelectricity, it is the optimal choice to compromise efficiency for a higher hydrogen production rate.

With improvement of technology, a realistic efficiency goal for future electrolyzers is roughly 50kWh/kg, or 78%, but this also includes compression of gas to 6000 psi. However, current electrolyzer technology with the ability to compress to 6000 psi only operates at the 60kWh/kg range, does not have the production capacity of forecourt scale.. (Ivy 2004) Hydrogen gas has a very low density, without compression, hydrogen requires a large volume of storage space. Compressing raw hydrogen gas is considered a finishing stage for retail sale. Some electrolyzers have the capacity to compress gas through the electrolysis process. When this is the case, electrolysis reduces the energy input of hydrogen storage, transportation and delivery. This study only considers costs of producing raw hydrogen gas: storage, transportation and delivery are beyond the scope of research.

Electrolysis of water has secondary advantages over conventional hydrogen production and petroleum products. The process of electrolysis generates very pure gas, which generates superior performance of hydrogen fuel. The simplicity of basic water electrolysis produces H_2 and O_2 to purities up to 99.9995%. (Kroposki, et al. 2006) Additionally, electrolysis produces two other merchantable products besides hydrogen: oxygen (O_2) and heavy water (Deuterium monoxide). Oxygen and heavy water account for up to 45% of the total products generated in the electrolysis process, 30% oxygen and 15% heavy water. (Ouellette, Rogner and Scott 1997) These by-products represent additional incentive for a large scale electrolysis project. But the literature warns, ". . .these [oxygen and heavy water] benefits should not be the determining factor for the project feasibility." (Ouellette, Rogner and Scott 1997, p.399) Although an electrolysis plant at the scale of this study would produce substantial quantities of oxygen and heavy water, the value of these by-products is not considered in this study.

Hydrogen has had a reputation problem as a potentially dangerous substance, largely steaming out of popular culture. Ease of hydrogen's flammability was demonstrated in the 1937 Hindenburg disaster. Hydrogen has endured bad sentiment in its association with the Cold War hydrogen bomb. (Hydrogen Society 2012) In actuality, hydrogen currently plays a large role in manufacturing and industry. The safety concerns of hydrogen ease of flammability, and potential volatility are mitigated by the assertion that successful testing, implementation, and practice of safety procedures are already in place in storage, transportation and consumption of hydrogen. (Tomczyk 2009) Hydrogen should be handled as a potentially hazardous, flammable product, but is considered no more dangerous than the multitude of fossil fuels widely present in everyday life. (Rodgers, et al. 2010)

Electrolytic hydrogen's reputation for its high level of purity, process simplicity and eco-friendliness, (Wang, Wang and Guo 2010) sets it apart from conventional hydrogen production. Although electrolysis is limited by an unobtainable 100% feedstock electricity-to-hydrogen conversion efficiency, technology has maturated to the extent that high production capacity, of greater than 1,000 kg a day, is possible at efficiency rates of 73% . (Ivy 2004) Whether a conversion efficiency of 73% is sufficient enough to make electrolytic hydrogen a competitive viable opportunity for the Pacific Northwest will be developed in Section VI.

Electrolysis Opportunities for Power Utilities:

With high water year conditions yielding large hydroelectricity supplies, Pacific Northwest, utilities most contend with the generation of a surplus energy supply. The power grid does not have the ability to store electricity and as a consequence, utilities need to find consumers for all power generated above regional demand. The necessity to align supply with demand is called 'load balancing,' and has engendered a complex energy exchange system of Independent Service Operators (ISOs) and Regional Transmission Organizations (RTOs), where electricity is traded from one region to another. Even with energy exchanges, on occasion regional and inter-regional demand is so insufficient that hydroelectric dams have had to be spilled without power generation and wind turbines are shut down. (Sickinger 2011) This illustrates a significant problem with the current electric grid: there is no capacity to store power; all electricity needs a consumer, even to the point of economic detriment to the energy supplier. Electrolytic hydrogen presents an opportunity for power utilities to have a consistently available consumer that can store a substantial portion of the input energy for later use.

The current electricity grid is burdened with large amounts of energy transmitting constantly within and outside utility regions. Especially over long distances, transmission congestion and bottlenecking causes substantial losses intransmitted energy. Nationally, problems with transmission and distribution results in the losses of 6-8%of annual total generated electricity.(Fesmire 2007) Regionally, each year several hundreds of megawatts of electricity are lost in long distance transmission and bottlenecking. (Bonneville PowerAdministration 2011.) Further inefficiencies are created by inter-regional transmission services. Congestion and regional price discrepancy generates revenue opportunities for transmission line owner. "When facing unregulated pricing of transmission services, an owner of a transmission network may not have economic incentive to efficiently mitigate transmission congestion." (Kleit and Reitzes 2008, p. 6) Electrolytic hydrogen production presents utilities a chance to reduce transmission congestion. Rather than transmitting all surplus electricity out of region, producing hydrogen from a proportion of surplus can help balance regional electricity supply and demand and reduce electricity loses in transmission bottlenecking and congestion.

The dominance of hydroelectricity in the Pacific Northwest constitutes high power production in spring and summer months because of snow-pack melt and reduced capacity amidst the fall and winter. This presents a local problem as high production and high demand occur during opposite seasons. Fall and winter seasons require the highest energy demand, whereas spring and summer energy demand is reduced. (Abraham 2002) Generating hydrogen with electricity above that demand load during melt months could be stored and used during times of potential energy deficits in the colder months. Utilities could also produce hydrogen at times of off peak demand, periods where power costs are significantly lower. The hydrogen is compressed or liquefied and stored to be used in a fuel cell to provide supplemental electricity during times of high demand. (Flour Daniel, Inc. 1991)

Electrolytic hydrogen represents a resource management opportunity for hydroelectricity producers. The inability to store electricity means supply must always be balanced with consumption demand. Electricity to hydrogen conversion represents an opportunity to have consistently available energy consumer to help utilities balance energy demand with supply. Beyond load balance, converting electricity into hydrogen offers long term storage of a high percentage of the input electricity's energy. Energy stored in hydrogen can be converted back into grid electricity by fuel cell or in combustion turbine, or the raw gas can be sold as commodity. Hydrogen production from Pacific Northwest hydroelectric resources represents opportunity for more efficient and sustainable natural resource conservation.

Section IV: Background Hydroelectricity to Electrolytic Hydrogen Studies

This study is not pioneering research in hydrogen production from non-fossil fuel sources. It is rather a Pacific Northwest regional consideration to the capacity and cost to convert regionally generated surplus hydroelectricity into electrolytic hydrogen.This research builds off major findings of other alternative energy to electrolytic feasibility studies and models and applies research findings as foundational study design. The following subsections review significant background study findings which directed this research's scope.

Renewables to Hydrogen and Hydroelectricity's Advantage:

With the maturation of renewable energy technology, electrolytic hydrogen produced from alternative energy sources has recently received significant research activity. Much of the current research has focused on wind and solar power as feedstock electricity. Studies continually reiterate the key factor of the economic competitiveness of electrolytic hydrogen is the cost of input electricity. Typically 40% of the total cost to produce raw hydrogen through electrolysis is electricity.(Ouellette, Rogner and Scott 1997) The current high price of installed solar and wind energy limits the ability to produce electrolytic hydrogen economically competitive with conventional fossil fuel based hydrogen production in the near term.

Studies have found that intermittency of solar and wind also generates potential impediments to electrolytic hydrogen production. Variable current density changeselectrolyzer efficiency, and production capacity, as optimal power input may not be reached. Intermittency continues to harm efficiency with the possibility of electrolyzers not reaching necessary operation temperature. These conditions generate uneconomical consumption of input electricity and hydrogen production output. Safety is also a concern with solar and wind electrolysis. Operation at low capacity can cause gases to permeate through the electrolyte and come into contact with each other, potentially causing dangerous inflammable consequences inside the electrolyzer unit. (Bartels, Pate and Olson 2010)

Results of solar and wind to hydrogen production studies have found a wide variance in prices of electrolytic hydrogen. Wind power resulted in range of prices from $2.27 – 6.03 per kg of H_2, but the lowest prices reflect long-term production with considerable electricity subsidies. Solar based electrolysis prices ranged from $5.10- 23.27, but prices reflected a wide range in variables and production conditions. (Bartels, Pate and Olson 2010) Studies reflect there are still significant barriers impeding economic competitiveness of wind and solar electrolysis, mainly the large capital investment in wind and solar power generation in addition to electrolyzer capital investment. Hydropower has a significant advantage over solar and wind to hydrogen, as the capital costs of hydroelectricity have largely been mitigated over many decades of production since dam installation. Although hydropower and renewable energy could work in concert, renewable electricity's cost per kWh needs to be reduced before challenging conventional hydrogen and fossil fuel prices.

Hydroelectricity to Hydrogen Studies:

Utilizing hydroelectricity to produce economically viable hydrogen through electrolysis has received significant previous research. Though the majority of recent studies have focused on the alternative energy sources of solar, wind and nuclear, electrolytic hydrogen production plants have been operating near hydroelectric dams since the early 20th Century. Several regional feasibility studies have been conducted since the early 1980s suggesting favorable conditions for producing economically viable electrolytic hydrogen. The studies also acknowledge significant obstacles that could impede economic competitiveness of electrolytic hydrogen produced via hydroelectricity. As noted, feedstock electricity costs are continually acknowledged as the prominent factor in producing low costs hydrogen through electrolysis.

Hydrogen production facilities have been operating at hydroelectric plants for some time. D.S. Tarkay highlights electrolysis plants located at hydropower dams and outlines opportunities for hydroelectric utilities in his 1985 article *Hydrogen Production at Hydro-Power Plants*. Labeling electrolytic hydrogen from hydroelectricity, "technically and economically feasible," Tarkay concludes that, "If the professional and business community will recognize the potential of proposed hydrogen production. . . it can open the door for a new hydrogen era" (Tarkay, 1985 p.583)

Tarkay's research contends that in 1985, hydroelectric utilities were producing economically viable electrolytic hydrogen, bolstering the rationale of this thesis. If out-of-date technology can produce volumes of electrolytic hydrogen competitively, it is an encouraging prospect that hydrogen could be produce economically, considering this study models production from a more advanced electrolyzer unit. Despite being an early and vague feasibility analysis, Takay's study supports the parameters of this thesis.

Regional feasibility studies analyzing the use hydroelectricity to produce electrolytic hydrogen in the Pacific Northwest first appeared in 1984. As a response to the Pacific Northwest Electric Power Planning and Conservation Act's (PL96-501) directive to consider renewable energy opportunities, the Bonneville Power Administration produced *Feasibility Assessment of Electrolytic Hydrogen in the Pacific Northwest*(1984). This study researched the potential of using 'state-of-the-art' technologies to produce electrolytic hydrogen from surplus and purchased hydropower. The preliminary technical and economic feasibility analysis concluded that production of electrolytic hydrogen was, "attractive" with use of surplus and purchased hydropower. The study concluded that because only approximately 3.5 months produced substantial amounts of surplus power, a hydrogen plant would need to purchase additional electricity. Although, surplus power alone could not produce economical electrolytic hydrogen, "Nevertheless, the cost of hydrogen generated by a mix of unused surplus hydropower and purchased power proved to be very attractive." (Pratt, et al. 1984, p. 8-2) Furthermore, the study concluded that, electrolytic hydrogen produced in the Pacific Northwest could be accomplished ". . .at less cost than it can be produced by steam reformation of natural gas in most other parts of the country."(Pratt, et al. 1984, p. 8-2)

BPA's *Feasibility Assessment of Electrolytic Hydrogen in the Pacific Northwest* (1984) supports several components of this thesis' hypothesis and rationale. Pacific Northwest hydroelectricity's low cost gives regional advantage in electrolytic hydrogen production. The study indicates there is opportunity to use surplus hydropower to produce electrolytic hydrogen. Finally, the research supports that electrolytic hydrogen produced in the Pacific Northwest can be competitive with conventional hydrogen produced elsewhere. Although this study suggests electrolytic hydrogen produced with surplus electricity is only feasible amidst peak melt months, the study models electrolyzer technology nearly 30 years old. This thesis models the use of electrolyzer technology with greatly improved efficiency and production capacity, potentially supporting electrolytic hydrogen production from surplus hydropower for additional months.

In 1991 Bonneville Power Administration continued to assess feasibility of hydroelectricity to electrolytic hydrogen production in: *Pacific Northwest Hydrogen Feasibility Study* (1991), produced by Flour Daniels Inc. This study modeled 100 MW of electrolytic hydrogen production to be used astransportation fuel for consumption in hydrogen internal combustion engine (ICE). The study modeled feedstock electricity at the lowest BPA guaranteed costs of 1.5 cents (1991 dollars) a kWh. (Flour Daniel, Inc. 1991) Using 1991 technology and a feedstock electricity cost of 1.5cents a kWh, the study concludedthat Pacific Northwest produced electrolytic hydrogen fuel would cost motorists 3.5 cents (1991 dollars) per mile. Even accounting for a 10 – 30% hydrogen engine efficiency advantage for hydrogen fuel, the study concluded that producing hydrogen for transportation could not be competitive with gasoline, which reported a cost of only 1.5 cents a mile. (Flour Daniel, Inc. 1991) At the time of this study BPA references wholesale gasoline prices as $0.60.gallon (1991 dollars) and concludes that unless gasoline surpassed the wholesale cost of $1.41 (1991 dollars), gasoline would continue to economically outcompete hydrogen based fuel. (Flour Daniel, Inc. 1991)

Now more than twenty years later, the *Pacific Northwest Hydrogen Feasibility Study* (1991) offers support for electrolytic hydrogen based fuel to be cost competitive with gasoline. BPA's proposed benchmark of $1.41 (1991) a gallon wholesale represents the potential tipping point for hydrogen fuel to be cost competitive with gasoline. This point appears to have been reached. Updated for inflation $1.41 in 1991 amounts to $2.38 in 2012 dollars. (United States Bureau Of Labor and Statistics 2012) Over the past year (May 2011 – May 2012), wholesale gasoline prices have had monthly averages ranging from $2.61 - $3.17 (United States Energy Information Administration 2012) Wholesale gasoline has seen large price volatility over the preceding twelve months, but remains above BPA's 1991 assessment for hydrogen fuel to reach cost competitiveness. The cost of feedstock electricity in the 1991 study was $0.15/kWh (1991 dollars), and adjusted for inflation equates to roughly $0.03/kWh (2012 dollars) which is very close to BPA's current guaranteed lowest payer rate. Electrolyzer technology improvement witnessed in the two decades since this study promises better efficiency and production rates than electrolysis employed in 1991 study. Preliminary assessment of the *Pacific Northwest Hydrogen Feasibility Study* (1991),indicates producing electrolytic hydrogen fuel in the Pacific Northwest can be cost competitive with conventional gasoline.

The 1997, Ouellette, Rogner and Scott, study: *Hydrogen-Based Industry from Remote*

Excess Hydroelectricity, investigates the economics of producing electrolytic hydrogen from surplus hydroelectricity in the remote Northwest Territories, Canada (NWT). The Taltson Dam, NWT produced a year-round minimum surplus of 8.5 MW at High Load Hours of operation and 15 MW at Light Load Hours of operation. The study assumed a 1 cent/kWh (1993 Canadian Dollars) rate for feedstock electricity. Ouellette, Rogner and Scott saw opportunity to produce electrolytic hydrogen because of such low demand and an inability to transmit hydropower outside of the dam region. The study concluded that compressed and liquefied electrolytic, which is considered hydrogen's retail product state, could be produced via excess hydroelectricity more economically than hydrogen produced through steam reformation. (Ouellette, Rogner and Scott 1997) Although local conditions allow for a more easily predictable surplus loads, the Ouellette, Rogner and Scott study validates that under the circumstances of low-cost input electricity, electrolytic hydrogen derived from surplus hydroelectricity can outcompete conventional hydrogen production methods.

Contreras, Posso and Nejat Veziroglu's 2007 study: *Modeling and Simulation of the Production of Hydrogen Using Hydroelectricity in Venezuela,* models production costs of using hydroelectric resources to produce substantial quantities electrolytic hydrogen in Venezuela. This research emphasizes the advantage of Venezuela's low cost of electricty enabled generation of electrolytic hydrogen at a fraction of the cost of electrolysis cost studies with higher electricty tarrifs. (Contreras, Posso and Nejat Veziroglu 2007) The low cost feedstock electricity allowed Venezulean production cost models to outcompete studies that produed more favoriable ecnomies of scale. The study concluded that using

Venezuela's hydropower resources for producing electrolytic hydrogen would be "highly advantageous." (Contreras, Posso and Nejat Veziroglu 2007)

Contreras, Posso and Nejat Veziroglu provides this thesis with the foundational cost equation for total electrolytic hydrogen production costs.

$$\frac{\text{Cost of energy consumption (annual)} + \mathit{Cost\ of\ Investment\ (annual)} + \mathit{Cost\ of\ O\ \&M\ (annual)}}{\mathit{Total\ hydrogen\ kg\ produced\ (annaul)}}$$ [1]

Calculation of the total cost of electrolytic hydrogenproduction is a simple equation entailing the summation of the three numerator variables: total cost of feedstock electricity consumption, total cost of capital, and total cost of operation and maintenance; divided by denominator variable: total kilograms of electrolytic hydrogen produced. The resulting metric represents the overall cost of per kilogram of electrolytic hydrogen. This cost equation will be employed in Section VI to calculate total production costs of electrolytic hydrogen produced with Pacific Northwest surplus hydropower.

The review of background electrolytic hydrogen production studies provides this thesis foundational support in the feasibility of cost competitive electrolytic hydrogen production. Background studies establish potential economic viability of regional electrolytic hydrogen production and the potential to produce electrolytic hydrogen at costs competitive with conventional hydrogen and gasoline. Previous studies address the vitality of low cost feedstock electricity and suggest management strategies in balancing efficiency with production. Finally, background research furnishes this thesis with a

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[1] Contreras, Posso and Nejat Veziroglu. 2007. p.1222

validated equation for producing an overall hydrogen cost per kilogram metric. Having addressed the foundational studies guiding this thesis, this study now progresses to quantify surplus electricity capacity and production costs.

Section V: Quantification of Surplus Hydroelectricity Capacity, and Fixed and Variable Electrolysis Production Costs

In order to draw conclusions on the viability of utilizing Pacific Northwest surplus hydroelectric resources to produce electrolytic hydrogen, it is necessary to quantify surplus hydropower capacity, and associated production costs of a large scale electrolysis project. Surplus hydropower capacity will be quantified from Bonneville Power Administration's *Pacific Northwest Loads and Resources Study 2011*, also known as the*2011 White Book.* This annually produced document, forecasts energy loads and resources based upon historic water year conditions. Fixed production costs will be established through National Renewable Energy Labs literature that reviewed commercially available electrolyzers and associated costs. Variable electrolysis costs will be quantified from Bonneville Power Administration's *2012 Power Rate Schedule and General Rate Schedule Provisions*. With the quantification all production variables, an analysis of capacity and productions costs of electrolytic hydrogen will be made in Section VI.

Hydroelectricity Availability:

The availability of a substantial supply of low cost electricity is vital in producing electrolytic hydrogen at competitive costs. In order to offset the high capital costs of large electrolyzers, electrolysis should be performed nearly around the clock at optimal production capacity, to deliver lowest capital costs. Power intermittency needs to be marginalized, as aforementioned, changes in current density resulting from intermittency generates reductions in electrolysis efficiency and increases thecosts of capital per unit.

Therefore, economic competitiveness hinges on availability of a constant flow of electricity at the electrolyzers maximum capacity rating. The aforementioned Norsk Hydro Atmosphere 5040 (5150 Amp DC)'s optimal production capacity requires2.328 MW of feedstock electricityand without a consistent delivery of 2.328 MW, producing hydrogen at costs competitive with conventional hydrogen production and gasoline may not attainable.

BPA is the marketing authority of all federal hydroelectric power generation projects in the Pacific Northwest. One the largest energy marketing agencies in the Department of Energy, BPA oversees the United States' largest hydroelectric resource. BPA alsohas partial marketing governance over additional regional electricity resources, including nuclear and renewables. BPA produces power from a wide variety of sources, yet even under the worst of water year conditions, hydropower accounts for the highest proportion of power generation, providing about half of the total regional energy resources. BPA has a maximum hydroelectric capacity of 20,594 MW, (enough to power more than 16.4 million homes) and an annual average generation of 6,845 MW. (Bonneville PowerAdministration 2011.) Only in times of critical water conditions, and during winter months, BPA risks producing no monthly surplus.Critical water levels account for only 10% of all water years, so for inthe vast majority of water years there is no risk of monthly power deficit.

Because water year conditions are directly responsible for a very large range inelectricity generation capacity, it is essential for BPA to forecast its potential energy production.

Annually, BPA produces energy capacity reports displaying estimated retail loads, load capacity, surplus, and deficit. The reports projects 10 years in advance, estimating generation capacity under each of the 70 water year conditions. The report compares estimated capacity under each water year to projected retail load, the anticipated electricity consumption. BPA then produces anticipated surplus/deficits under each of the corresponding 70 year water conditions. All surplus power is a direct result of hydropower resources. BPA's other electricity resources, nuclear, coal, combustion turbines, cogeneration units, etc., provide base-load power to the region with fixed annual generation capacity. These sources are contractually guaranteed to connect to the grid and always provide the same constant electricity input, but are insufficient to cover the entire retail load. Additional power generated above these fixed amounts must be derived from hydropower. Table 3, displays Bonneville Power Administration's anticipated average annual regional surplus power, in average megawatts (aMW), for the next ten years under variable water year conditions:

Table 3: Forecasted Surplus Electricity Generation in Average Megawatts Under Variable Water Year Conditions

Operating Year	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021*
Critical Water Level	3,972	3,761	3,419	3,008	2,748	2,274	2,257	1,758	1,594	663
Bottom 10% Water Years	3,945	3,728	3,383	2,973	2,714	2,241	2,222	1,725	1, 560	630
Middle 80% Water Years	7,296	6,997	,614	6,192	5,936	5,466	5,439	4,950	4,780	3,855
Top 10% Water Years	10,632	10,283	9,856	9,415	9,165	8,656	8,659	8,140	8,009	7,045

Table 3 displays average megawatts of forecasted surplus hydropower generation in the Pacific Northwest for the years 2012-2021 under Critical, Bottom 10%, Middle 80% and Top 10% water conditions
Source: Bonneville Power Authority: *2011 Pacific Northwest Loads and Resources Study.* May 2011 p 71.
*2021 surplus decline attributed to scheduled Centralia coal plant retirement.

The data displayed in Table 3, shows the large range in surplus availability associated with variable water year conditions, with a minimum surplus of 630 aMW to a maximum surplus of 10,638 aMW. This report depicts very favorable conditions for electrolytic hydrogen production for surplus hydropower resources. Furthermore, this surplus data does not include all regional hydroelectricity production. It reflects only electricity generated by BPA and delivery of electricity from Independent Power Producers, who historically contribute to BPA base-load power supply. Significant amounts of hydroelectricity is generated by non-federal firms including, but not limited to: Seattle City Light, Tacoma Power, and Puget Sound Energy, all of which have the capacity to generate surplus power, depending on the water year. Since data in Table 3 does not represent all potential surplus hydroelectric capacity in the Pacific Northwest, it represents conservative surplus estimates of surplus capacity. As seen in Table 3, indicates strong support for sufficient availability of surplus of hydroelectricity to employ at least one Norsk Hydro Atmosphere Type 5040 (5150 Amp DC.). On an annual scale, even under critical water conditions, the average MW surplus far exceeds the 2.33 MW necessary minimum to consistently run the selected electrolyzer. Annual data indicates a large capacity of surplus power for the proceeding ten years, producing ample supply to operate at least one electrolyzer unit full time.

Annual surplus numbers suggest ample capacity for electrolytic hydrogen production from surplus power, but hydroelectric outputs vary drastically depending on the month. This makes it is important to consider projected monthly surplus conditions. Appendix A displays a table for the years 2012-2021 projected monthly electricity surplus in average megawatts under critical, bottom 10%, middle 80% and top 10%water year conditions. Under cortical water conditions, over the next 120 months, only four months are projected operation in a deficit. All four months of deficit occur in 2021 when the Centralia Coal Plants are scheduled for retirement. The remaining 116 months all provide ample surplus to operate at least one forecourt electrolyzer. Even if the roughly 1,000 aMW of the Centralia Coal Plant are not replaced, data suggests there is ample surplus electricity capacity for electrolytic hydrogen to be produced in the eight remaining months, even under critical water conditions. Critical water conditions represent only roughly 10% of all water years, giving deficit months only a marginal percentage of occurrences. Consequently, electrolytic hydrogen represents an opportunity to mitigate times of deficit, as hydrogen could be used to generate grid power, potentially alleviating rare occurrences of energy deficit.

Analysis of regional surplus hydroelectricity data suggests the Pacific Northwest has the capacity to utilize its surplus electricity resources to realistically produce constant electrolytic hydrogen. The vast majority of months for the next ten years are projected to produce far more surplus than the minimum 2.33 MW required to operate the Norsk Hydro Atmospheric's optimal production state. With surplus electricity capacity data suggesting favorable resources for electrolysis, the study can proceed to quantify production cost variables.

Feedstock Electricity Costs:

As mentioned earlier, a single forecourt electrolyzer unit'sconstant consumption of 2.33 MW of electricity is enough to power approximately 1850 homes. This large of an energy demand means fractions of cents per kWh can make the difference between project economic feasibility orfailure. This high consumption demand facilitates the need to acquire the least expensive feedstock electricity as possible. The Pacific Northwest's substantial hydroelectric capacity helps deliver electricity at the lowest rates in the entire United States. The high capacity and low electricity tariffs make the Pacific Northwest a very attractive location for this pilot electrolytic hydrogen production study. Feedstock electricity is the only variable cost in total electrolytic hydrogen production costs. In the Pacific Northwest electricity prices per kilowatt hour can vary annually dependent on operating water year conditions; monthly, dependent on seasonal river conditions; and daily, dependent on Heavy Load Hours versus Low Load Hours. With forecourt electrolysis' high energy demand, these feedstock price variations have drastic impact on costs per kg produced.

It is difficult to forecast prices for surplus electricity. Surplus availability is dependent onwater year conditions, and availability dictates surplus price. Water year conditions remain unknown until operation within said calendar year. High water years produce a greater surplus and a low price for surplus electricity, whereas lower water years engender a reduced surplus, which subsequently demands a higher price per kilowatt hour. Water year conditions have less influence over contractual payer rates, as they are set prior to the beginning of the water year calendar. Regardless of water year, this study assumes that price of surplus electricity would be at least as low as the lowest contractually guaranteed rate paid by energy consumers. Bonneville Power's lowest rate is paid by Priority Firms and defines the energy as,". . .electric power . . .continuously available for direct consumption or resale by public bodies, cooperatives, and Federal agencies." (Bonneville Power Administration 2007, p.95) Priority Firms rates vary with seasons and load operating hours, and have a publicly listed 2012 average rate of $30.17 per MW consumed. (Bonneville Power Administration 2012) Table 4 displays monthly rates for Priority Firms during High Load Hours (HLH) and Low Load Hours (LLH), which for this study will employ to represent surplus electricity rates.

Table 4 BPA Priority Firm Rates

Month	Heavy Load Hour Rate*	Light Load Hour Rate*
October	31.04	24.38
November	31.55	24.58
December	34.28	26.57
January	33.21	24.88
February	34.11	26.35
March	32.75	25.51
April	30.71	23.59
May	28.24	17.58
June	29.15	16.2
July	35.25	23.09
August	37.53	25.33
September	36.63	26.77
Average	32.871	23.736

*Rate in mills/kWh

Table 4 displays BPA monthly Priority Firm Rates for electricity consumption during High Load Hours and Low Load Hours of operation

Source: Bonneville Power Administration: *2012 Power Rate Schedule and General Rate Schedule Provisions*

www.bpa.gov/corporate/ratecase/2012/docs/FinalPowerRateSchedulesGRSPs_Upload_01-17-2012.pdf

Table 4 displays BPA's lowest contractually guaranteed rates. The payer rates vary month to monthdue to river conditions and daily operating load hours. For this study, these Priority Firm Rates will represent the highest surplus electricity prices and will reflect the feedstock electricitycosts per kWh for the electrolytic hydrogen production from surplus hydroelectricity. Heavy Load Hours (HLH) reflect energy consumption Monday through Saturday 06:00 -21:00, and Light Load Hours (LLH) constitute energy consumption Monday through Saturday 21:00 – 06:00, all day Sunday, and six additional federal holidays. LLH amass to 3,576 hours annually or nearly 41% of total load hours. HLH make up the remaining 5,184 hours, roughly 59% of the time annually. Priority firms pay an average rate of 32.871 mills/kWh (~3.3¢/kWh) during HLH, and 23.736 mills/kWh (~2.4¢/kWh) during LLH.

Priority Firm Rates seen in Table 4 are selected as study parameters for electricity feedstock prices because of their annual predictability regardless of operating water year.Setting Priority Firm Rates as feedstock electricity price represents a high surplus price estimate, enabling their projected hydrogen production rates to be more conservative than assigning arbitrary surplus electricity prices, which would be hard to substantiate because of inability to project water year conditions.

Capital Costs of Electrolysis:

Operating an electrolysis plant entails two categorical fixed investment costs: Capital costs and operation and maintenance (O&M) Costs. Each of these input expenses make up a substantial proportion of the price per kilogram of hydrogen produced. Fixed costs are static, and remain constant through the entire life of an electrolysis project, assuming electrolysis is continually operating at the current density for optimal production.

Capital costs represent the most burdensome of electrolysis’ two fixed production costs.

Although electrolysis is fundamentally a simple process, it requires largest startup capital expenses, including but not limited to: procurement of the electrolyzer unit, physical plant of a production facility, construction, engineering costs, and substantial contingency capital. (Ivy 2004) Even with capital costs spread out over the expected 40 year electrolysis plant life, capital costs represent the most substantial proportion of electrolytic hydrogen's production costs.

Capital costs' impact on and electrolysis projectcan be reduced with economies of scale. Compared to smaller levels of electrolytic hydrogen production, forecourt electrolysis' high capacitygenerates greatly reduced capital investment per kg of H_2 produced. Electrolysis systems that produce around 100 kg daily accrue capital costs amounting to roughly 55% of the total cost of production. Scaling down to about 20 kg a day capital costs rise to more than 70% of all production costs. The substantial capital costs currently rule out economically competitive small scale electrolytic hydrogen production, as it generates hydrogen at the $8-19 a kg price level. (Ivy 2004) Literature determined the large production volume of forecourt electrolysis can reduce capital costs to below one-thirdof total hydrogen production costs, which is the only production scale able to mitigate capital costs to that low of a proportion of total costs. (Ivy 2004)

According to literature, the Norsk Hydro Atmosphere type 5040 (5150 Amp DC) produces raw gas with capital costs of $1.32 (2000 dollars) per kg. This cost expects a 40 year plant life with electrolyzer stack replacement at the 10th, 20th and 30th year of operation. Unlike feedstock costs which fluctuate with season and time of day, capital costs remain constant, as long as electrolysis is produced at optimal production capacity. The burden of capital costs of electrolysis practically mandates forecourt scale production to attain economically competitive electrolytic hydrogen production.

Electrolysis Operation and Maintenance Costs:

Like capital costs, operation and maintenance (O&M) costs are fixed. Literature defines primary O&M expenditures of electrolysis plant as labor and overhead expenses as well as operation expenditures of insurance and taxation. O&M contribute to roughly 10% of the cost to produce electrolytic hydrogen, amounting to $0.37 (2000 dollars) per kg produced. (Ivy 2004) O&M costs remain proportional to scale in electrolysis, amounting to about 10% of production costs whether producing 20 or 1000 kg daily.

Literature contends there are secondary O&M costs. Other raw materials and miscellaneous O&M are less scheduled expenses throughout the life of an electrolysis project. Other raw materials and miscellaneous O&M primarily are used for electrolyzer calibration and efficiency optimization and include:replacement KOH electrolyte, de-mineralized water, cooling water, and inert gas. (Ivy 2004) Combined secondary O&M costs account for about $0.05 (2000 dollars) per kg of H_2.

Capital and O&M fixed costs reflect the unavoidable costs of electrolytic hydrogen production. At forecourt scale the combined capital and O&M costs amount to $1.74 (2000 dollars) per kg. Adjusting for inflation, capital and O&M expenses at $1.74 in 2000 dollars amasses $2.32 in 2012 dollars. (United States Bureau Of Labor and

Statistics 2012) This represents the bare minimum cost of electrolytic hydrogen production for the Norsk Hydro Atmosphere 5040 (5150 Amp DC). If the third variable of production costs, feedstock electricity, was free of charge, raw hydrogen gas could be produced at the $2.32 per kg, a highly competitive price for fuel. Although free electricity is not expected, years of high surplus hydroelectricity can engender very inexpensive feedstock energy.

With the establishment and validation for all the input costs variables of electrolytic hydrogen production, analysis of total costs of electrolytic hydrogen from surplus hydroelectricity can now be made. The following section will combine all independent cost variables and assess the potential price per kilogram of electrolytic hydrogen produced from surplus hydroelectricity in the Pacific Northwest.

Section VI: Cost Calculation of Electrolytic Hydrogen form Surplus Hydroelectricity

With the validation of sufficient surplus hydroelectric capacity to support at least one forecourt electrolyzer and the quantification of feedstock electricity, capital and operation and management costs, the total production costs of raw electrolytic hydrogen gas can be determined. As mentioned earlier on page 37, this study utilizes the Total Production Costs equation as employed by Contreras, Posso and Nejat Veziroglu (2007).

The following table, Table 5, Costs per Kilogram of Electrolytic Hydrogen with Variant Feedstock Electricity Rates, displays a multiple feedstock electricity rates:feedstock [1], a rate of $0.048 kWh, represents the national average of industrial electricity rates. [2], [3], and [4] represent round benchmark feedstock electricity rates, reflecting potential low electricity prices under high surplus conditions.[5] displays BPA's mean Industrial Firm Rate under High Load Hours (HLH) operation. [6] displays BPA's mean Industrial Firm Rate under Low Load Hours (LLH) operation. [7] demonstrates BPA's mean Priority Firm Rate under HLH conditions. Finally, [8] demonstrates BPA's mean Priority Firm Rate under LLH conditions.

Table 5: Costs Per Kilogram of Electrolytic Hydrogen with Variant Feedstok Electricty Rates

	$/kWh	Electrcity Costs Hourly (kWh X 2328)	Electricty $/kg ($/43.6kg/hr)	Capital & OM ($/kg)	Capital & OM $/hr	Total $/kg
[1]	$0.048	$111.744	$2.563	$2.32	$101.152	4.883
[2]	$0.03	$69.84	$1.602	$2.32	$101.152	3.922
[3]	$0.02	$46.56	$1.068	$2.32	$101.152	3.388
[4]	$0.01	$23.28	$0.534	$2.32	$101.152	2.854
[5]	$0.040381*	$94.006968	2.156	$2.32	$101.152	4.476
[6]	$0.031206**	72.647568	1.666	$2.32	$101.152	3.986
[7]	$.03287083***	76.52329224	1.7551	$2.32	$101.152	4.075
[8]	$.02373583****	55.25701224	1.2674	$2.32	$101.152	3.587

Table 5 displays the effect of varaible feedstock electricty prices on in the cost per kilogram of electrolytic hydrogen production.

Table Notes: *BPA average HLH Industrial Rate **BPA average LLH Industrial Rate[2]
*** BPA average HLH PF ****BPA average LLH PF rate

Table 5 demonstrates electrolysis' total production costs dependence on the price of feedstock and reiterates literatures' assessment of feedstock electricity's importance to competitive electrolytic hydrogen costs. Results of Table 5 calculations and all feedstock electricity rates from $0.00-$0.58 kWh, are represented in Figure 3 by the linear expression: y($/kg)=53.3936x ($/kWh)+2.31997.

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[2] Payer rate information courtesy of BPA.*2012 Power Rate Schedules and General Rate Schedule Provisions*p.21
http://www.bpa.gov/corporate/ratecase/2012/docs/FinalPowerRateSchedulesGRSPs_Upload_01-17-2012.pdf

Figure 3: Total Cost Forecast For Forecourt Electrolytic Hydrogen Production with Variable Feedstock Electricity Costs

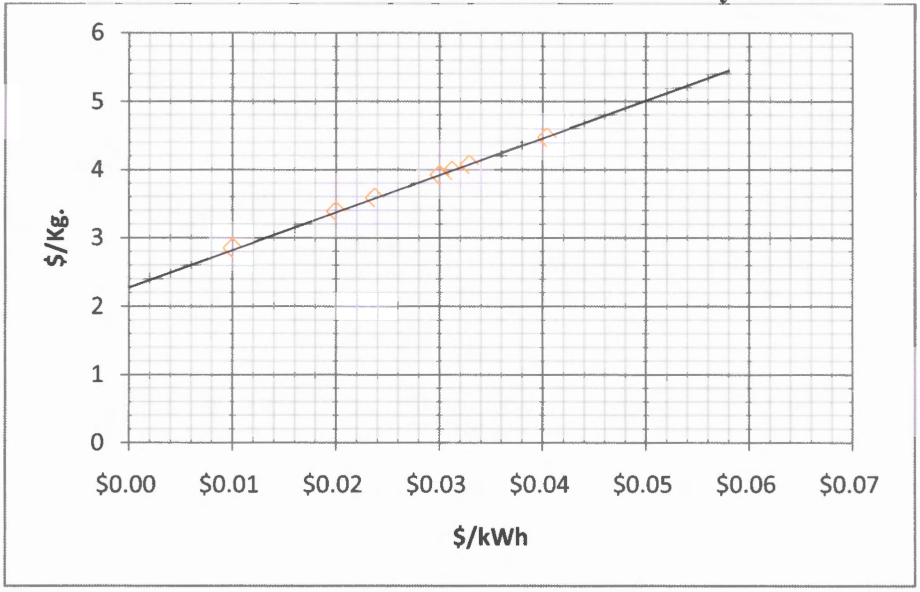

Figure 3 displays projected total production costs of electrolytic hydrogen per kilogram produced with the Norsk Hydro Atmosphere 5040 (5150 DC) electrolyzer under variable feedstock electricity costs.
Linear Equation: $y=53.3936x+2.31997$

Figure 3 also displays the potential economic viability of forecourt electrolysis. Under conditions of feedstock electricity rates averaging at or below $0.0315 electrolytic hydrogen can be produced at $4 per kilogram. To reach the National Renewable Energy Labs goal of $3 per kilogram hydrogen feedstock electricity would have to have an average cost just over $0.0127 per kilowatt hour. These prices only reflect hourly production under variable circumstances. Table 6 displays anticipated annual production rates and costs comparing annual electrolytic production costs of Industrial payer electricity rates and Priority Firm Rates, which represent a conservative surplus electricity pricing. Production capacity and costs are calculated for each payer's mean HLH and LLH operation. Each payer's HLH and LLH costs and production outputs are combined to display the mean costs per kilogram of electrolytic hydrogen over an entire year of production.

Table 6: Annual Electrolytic Costs and Production Capacity at Industirial Firm and Prirority Firm Electricity Rates

Feedstock Rate	Equivilent Production Costs ($/kg)	Annual Operating Time (hr.)	Annual Production Capacity (kg.)	Annual Electrcity Consumption ($)	Annual Capital Costs ($)	Annual O&M Costs ($)	Annual Total Costs ($/yr.)	HLH and LLH Combined $/kg
IR HLH	4.476	5184	226022.4	487332.122	397799.424	126572.544	1011676.26	~4.276
IR LLH	3.986	3576	155913.6	259787.703	274407.936	87311.616	621471.61	
PF HLH	4.075	5184	226022.4	396696.747	397799.424	126572.544	921041.28	~3.876
PF LHL	3.587	3576	155913.6	197599.076	274407.936	87311.616	559261.01	

Table 6 displays electrolytic hydrogen production capacity and production costs on an annual scale at BPA's Industrial Rates (IR) and Priority Firm Rates (PF). Production capacity and costs are presented under High Load Hours (HLH) and Low Load Hours (LLH) and load operating hours costs and production are combined to demonstrate an overall mean cost per kg of electrolytic hydrogen. PF Rates represent conservative surplus electricity rates.

The cost of production electrolytic hydrogen under Priority Firm and Industrial Firm rates as presented in Table 6 is calculated by employing Contreras, Posso and Nejat Veziroglu 2007 Total Production Costs of Electrolysis equation. Displayed below is the Priority Firm data presented in Contreras, Passo, and Nejat Veziroglu total cost equation:

$$\$/\text{kg} = \frac{\text{Cost of energy consumption (annual)} + \text{Cost of investment (annual)} + \text{Cost of O\&M (annual)}}{\text{Total hydrogen kg produced (annual)}}$$[3]

$$\$/\text{kg} = \frac{(\$594295.823) + (\$672207.36) + (\$213884.16)}{381936 \text{ kg.}}$$

$$\$/\text{kg} = \$3.876$$

Table 6bestarticulates the opportunity for electrolytic hydrogen production in the Pacific Northwest region, as long as there is a consistent delivery of 2.33MW of electricity, a single forecourt electrolyzer can produce a maximum of 381,936 kg. of electrolytic hydrogen annually. Regardless of input electricity costs, there are unavoidable fixed costs

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[3] Contreras, Posso and Nejat Veziroglu. 2007. p.1222

totaling $886,091.52 to operate a forecourt electrolyzer annually. The high fixed costs of a forecourt electrolysis project preventthe ability to produce electrolytic hydrogen below $2.32 per kg, and this requires zero cost feedstock electricity. Table 6 demonstrates production costs of both Industrial Firms and Priority Firms for two reasons: Primarily, Priority Firms is used to represent a potential conservative surplus electricity price rate and providing Industrial Firm production costs allows for comparison of surplus feedstock electricity to a contractually guaranteed payer rate. Secondly, using both IR and PF displays the electrolytic production at the two lowest contractually guaranteed electricity rates by Bonneville Power Administration, and demonstrates the opportunity to contract feedstock electricity rates and perform electrolysis, which would eliminate the potential risk of relying on higher water year condition to generate ample power surplus.

Results of the cost analysis of producing electrolytic hydrogen utilizing projected surplus Pacific Northwest hydroelectricity indicate quite attractive hydrogen production opportunities. Analysis of availability of surplus hydroelectricity appears sound regardless of water year conditions until 2021. The anticipated 2021 closure of the Centralia Coal Plant, reduces regional base-load electricity capacity by approximately 1,000aMW, requiring a substantial quantity of surplus hydropower to replace the diminished base-load capacity. This presents a long-term potential obstacle for surplus power electrolytic hydrogen production, but only in critical water year conditions and only in the four low river flow months. Perceivably, the lost capacity from Centralia Coal Plant closures could be mitigated by increased renewable projects planning to connect to the grid in the near future.

Overall, results suggest there is capacity to generate electrolytic hydrogen through surplus hydroelectricity in the Pacific Northwest at competitive costs. The projected production cost of approximately $3.88 per kilogram, puts electrolytic hydrogen produced from surplus hydropower in the $1-$5 per kilogram price range of conventional hydrogen production as reported by literature. Preliminary comparison of electrolytic hydrogen to gasoline suggests gasoline still has an economic advantage. Raw electrolytic hydrogen produced at a cost of $3.88 per kg. is above the $2.61 - $3.17 per gallon wholesale price range of gasoline witnessed over the past twelve months. Hydrogen outperforms gasoline significantly in efficiency, and prior to sale to direct consumers both raw hydrogen and wholesale gasoline entail additional costs including: transportation, delivery and taxation, so further study needs to be conducted in final hydrogen and gasoline cost comparisons. Nevertheless, results suggest electrolytic hydrogen production utilizing surplus hydroelectricity is a feasible project for the Pacific Northwest and generates hydrogen gas at a cost within the range of competitiveness to conventional hydrogen production.

Section VII: Conclusions

Electrolytic hydrogen represents an opportunity to fundamentally change the landscape of energy resources. Clean, efficient and simple to produce, electrolytic hydrogen can be produced from renewable, domestic power resources. Electrolytic hydrogen retains a substantial portion of the input electricity, presenting an energy storage opportunity that our electrical gird currently lacks. Hydrogen has the versatility to generate grid electricity or can be consumed as transportation fuel. Hydrogen can perform all the duties of fossil fuels without many of the undesirable environmental and social consequences. When consumed hydrogen only emits pure water and a minute amount of NO_3. When produced from renewable energy sources,electrolytic hydrogen has marginal life-cycle greenhouse gas emissions. Transitioning to a hydrogen based transportation system would alleviate substantial greenhouse gas emissions and decline the necessity to conduct business in socially turbulent petroleum producing nations. What suppresses transition to the hydrogen economy is an inability to produce large volumes of electrolytic hydrogen at prices competitive with fossil fuels.

This study considered economic competiveness of electrolytic hydrogen produced with surplus hydroelectric resources forcomparison to gasoline and conventional hydrogen production. The study analyzed the Bonneville Power Administrations projected surplus electricity availability for the next 10 years, established a maximum price for surplus electricity and establishedcosts of capital and operation and maintenance of the largest commercially available electrolyzer.Analysis of projected surplus hydroelectricity suggests there is ample capacity for electrolytic hydrogen production to constantlyoperate at least one forecourt electrolyzer even at critical water year conditions, meaning under the worst of water year conditions, there is the capacity to produce more than 300,000 kg. of electrolytic hydrogen annually. This study considered electrolytic hydrogen production under very conservative parameters of critical water year conditions and surplus feedstock electricity at conservative rates. More favorable water year conditions would allow for a great deal more electrolytic opportunities at lower costs. Literature supplied the equation for calculation of total production costs: the summation of the cost of total electricity consumption, total capital cost and total O&M costs all divided by total hydrogen production. The resulting metric represents the overall cost per kilogram of the electrolysis project. Literature supplied electrolysis fixed cost data and production capacityfor the Norsk Hydro Atmospheric electrolyzer. The variable costs of feedstock electricity were supplied from BPA's Priority Firm Rates. The study resulted in electrolytic hydrogen produced at an average cost of about $3.88 per kilogram. Priority Firm Rates and the associated costs of $3.88 per kilogram represents a conservative total production costs for electrolytic hydrogen utilizing surplus hydropower in the Pacific Northwest.

Although above the targeted $3/kg goal for electrolytic hydrogen set by National Renewable Energy Labs, electrolytic hydrogen at $3.88 per kg. is in the range of $1-5 per kg of conventional hydrogen costs cited by literature. This suggests that electrolytic hydrogen produced with Pacific Northwest hydroelectricity can be competitive with conventional hydrogen production. Moreover, results suggest electrolytic hydrogen can be produced in the $1-5 per kg range with feedstock electricity rates up to $0.05 per kWh.

BPA has several contractually guaranteed payer rates at costs below $0.05 per kWh, suggesting because of the low cost of feedstock electricity in the Pacific Northwest region, electrolytic hydrogen can be produce at costs competitive with conventional hydrogen without utilizing surplus electricity.

Producing raw hydrogen at costs of $3.88 per kilogram is above the twelve month price range of wholesale gasoline of $2.61 - $3.17 per gallon. This only reflects a cursory comparison of electrolytic hydrogen and gasoline. Both fuels entail further finishing costs before retail sale, and although gasoline per gallon and hydrogen per kg contain the same energy capacity, hydrogen gains up a 2.5 times greater energy efficiency. These factors require significant additional research before a complete comparison of electrolytic hydrogen to gasoline may be concluded on.

Transition to the hydrogen economy on the national scale is stymied by lack of feedstock electricity. Utilizing the largest electrolyzer only produces approximately 1000 kg a day and consumes 2.33aMW. Converting our entire transportation fleet to hydrogen would require nearly double the entire United States electricity capacity. Total electricity capacity could be increased by continual generation at maximum sustainable yield, enabling generation to remain at its most efficient output all the time, but increased capacity is still necessary. Outside of the Pacific Northwest the substantial proportion of electricity is produced with less environmentally friendly energy sources. There is little value in producing electrolytic hydrogen from fossil fuel-based electricity sources.

Nevertheless, results of this study indicate there is significant opportunity to the produce electrolytic hydrogen through the Pacific Northwest's surplus hydroelectricity capacity. The Norsk Hydro Atmosphere has a large energy demand at 2.33aMW, but for the majority of the water year conditions this is a marginal proportion of anticipated surplus electricity. For the next nine years thereis sufficient surplus hydroelectricity capacity to utilize additional electrolyzer units even under critical water year conditions. This suggests there is great opportunity for the Pacific Northwest utilities to invest in multiple forecourt electrolyzers and produce large quantities of electrolytic hydrogen for surplus hydropower. There would be limited risk in such a venture considering 90% of water year conditions produce a minimum of 600 aMW surplus, which is enough surplus energy to run more than 250 of the largest electrolyzer, producing more than 75 million kg of hydrogen annually. This level of electrolytic production would be a significant step in the transition towards hydrogen energy. After the scheduled 2021 closure of the Centralia Coal Plant, the lowered electricity capacity in the Pacific Northwest creates increased risk in utilizing surplus energy for hydrogen production, but years with water years above critical conditions should have ample capacity to run far more electrolyzers than just single unit modeled in this pilot study.

This study finds evidence that highly suggests that the Pacific Northwest has the capacity to generate electrolytic hydrogen that can compete with conventional hydrogen and potentially competitive with gasoline. Results support that there is hydroelectric capacity to generate a forecourt scale electrolysis project, presenting the region with an opportunity to produce hydrogen to help balance electricity load, store a backup energy supply, alleviate transmission congestion, and generate merchantable gases. Electrolytic hydrogen from surplus hydroelectricity represents aviableopportunity for the sustainability of the Pacific Northwest energy resources and the movement towards a clean energy future.

Section VII: Suggestions for Further Research:

Researching the opportunity to produce electrolytic hydrogen from surplus hydroelectricity generated additional avenues for further research that fell beyond the scope of this thesis. This study was able to conclude that there is capacity to produce electrolytic hydrogen utilizing surplus hydropower at economically competitive costs to conventional hydrogen production, but there is room for further assessment of overall capacity and evaluation of conditions and opportunities which could alter production costs.

Climate Change poses major concerns for hydroelectricity producers. Forecasted surplus electricity data did not reflect Climate Change's impending impact on precipitation rates, stream length, peak flow, and power generation timing. There is substantial opportunity to assess Climate Change's influence on electricity capacity in the Pacific Northwest region. A change in electricity capacity could mean substantial change in feedstock electricity prices, which is the only variable costs in the electrolysis process.

Water year conditions play the dominant role in determining surplus electricity capacity. A thorough risk assessment of potential months, conditions and times of electricity deficit could give a clearer image of long term viability of continual electrolytic hydrogen production. Although review of monthly data suggested only 4 months out 120 operating at deficit under critical water year conditions, additional review of low flow months should be studied.

This study did not consider costs and methods of hydrogen compression, transport and delivery. If a study determines these additional costs, a more accurate assessment of retail hydrogen gas could be made. There are many methods of compression, transportation and delivery, so it is vital to study which is the most cost effective and efficient. These conditions play key roles in transition to the hydrogen economy.

There are emerging technologies which support more efficient hydrogen production. High gravity, high temperature and new polymer electrodes have great potential in lowering production costs of electrolysis. An assessment of how these emerging technologies could reduce feedstock cost and produce cheaper hydrogen gas could improve electrolysis cost effectiveness.

Electrolysis produces two additional merchantable commodities: oxygen and heavy water. This study did not assess the potential value of these byproducts. An assessment of how oxygen and heavy water production could reduce capital costs of electrolysis could offer more incentive for electrolytic hydrogen production.

This study analyzes only a single electrolyzer unit. A maximum electrolysis capacity study would give a clearer image of a realistic target for high volume hydrogen production utilizing multiple electrolyzer plant. There are additional areas of study as new technology continually emerges. This study by no means covers the gamut of electrolytic hydrogen production, but hopefully provides jumping off points for additional research.

Appendix A: Pacific Northwest Monthly Surplus Electricty Data

Projected Monthly Surplus at Top 10%, Middle 80% and Bottom 10% water Year Conditions in Averagre Megawatts

Year	WY	Aug1	Aug16	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr1	Ap16	May	Jun	July	Aug
2011-2012	Top	7356	4803	4319	6475	8709	10921	13732	13517	13164	15012	14584	11831	13395	10711	10621
	Mid	5730	3645	4016	5096	5623	5573	7547	7122	7130	10963	10790	10159	11942	7778	7285
	Bot	3853	2112	2896	3992	4131	3092	2868	2718	2590	4890	4902	6020	6396	4662	3934
2012-2013	Top	7540	5629	4623	6382	8621	10684	13582	13282	13157	13398	13336	11025	12206	10014	10273
	Mid	5672	4218	4571	5002	5541	5359	7462	6934	7112	9425	9621	9421	10922	7151	6986
	Bot	4077	2627	3760	3899	4049	2879	2768	2529	2621	3370	3751	5349	5731	4093	3718
2013-2014	Top	7056	5161	4331	6034	8198	10174	12850	12592	12244	13752	12846	10799	12411	9373	9846
	Mid	5196	3748	4271	4653	5123	4882	6771	6276	6287	9795	9187	9353	11118	6655	6603
	Bot	3608	2153	3466	3551	3632	2403	2075	1878	1810	3748	3342	5557	5965	3685	3372
2014-2015	Top	6563	4819	3930	5641	7843	9732	12603	12342	11753	13696	13175	10639	10430	9067	9404
	Mid	4705	3403	3873	4253	4774	4452	6468	6015	6041	9858	9610	9107	9274	6231	6181
	Bot	3126	1816	3061	3147	3270	1970	1775	1611	1587	3865	3789	5119	4518	3173	2962
2015-2016	Top	6264	4506	3585	5384	7488	9383	12118	12027	11656	11882	11181	11083	11479	8864	9154
	Mid	4395	3089	3526	3997	4418	4103	5988	5728	5911	8057	7629	9518	10331	6082	5925
	Bot	2809	1500	2716	2890	2914	1621	1269	1328	1489	2061	1804	5508	5563	3056	2703
2016-2017	Top	5986	4094	3334	5148	7154	9043	11703	11460	10879	12227	11547	9674	10309	8357	8645
	Mid	4124	2672	3272	3759	4094	3785	5626	5215	5177	8382	7985	8340	9137	5574	5456
	Bot	2549	1091	2465	2655	2591	1303	915	822	759	2385	2166	4515	4098	2513	2231
2017-2018	Top	5637	3767	3059	4902	6933	8759	11482	11244	11041	13054	12112	10525	10594	8198	8648
	Mid	3787	2348	2993	3515	3864	3478	5353	4944	5296	9229	8559	8960	9446	5417	5428
	Bot	2226	768	2190	2409	2360	997	633	545	874	3233	2735	4950	4678	2391	2211
2018-2019	Top	5325	3433	2732	4634	6634	8423	11122	10889	10641	11714	11224	9165	9893	7813	8129
	Mid	3464	2012	2670	3245	3574	3165	5045	4644	4939	7869	7662	7832	8721	5030	4940
	Bot	1888	430	1863	2140	2071	683	334	251	521	1871	1843	4006	3682	1969	1715
2019-2020	Top	4971	3112	2490	4372	6340	8151	10886	10856	10461	11837	10823	9718	9973	7518	7998
	Mid	3120	1693	2424	2985	3270	2871	4756	4557	4716	8012	7271	8153	8825	4737	4769
	Bot	1560	112	1621	1878	1766	389	37	157	295	2016	1447	4144	4057	1711	1550
2020-2021	Top	4596	2873	2216	4123	6104	7240	9523	9328	8994	11231	10277	8517	8047	6050	7034
	Mid	2734	1451	2154	2734	3044	1982	3446	3083	3292	7386	6714	7184	6875	3268	3845
	Bot	1159	-130	1347	1629	-1541	-500	-1265	-1310	-1125	1389	896	3358	1836	206	619

Appendix A displays month hydropower surplus averages for the years 2012-2021 under variable water year conditions. Top represents top 10% of Wate Years,Mid repreents middle 80% of water years, and Bot represents botoom 10% of Wate Years.

Source: http://www.bpa.gov/power/pgp/whitebook/2011/WhiteBook2011_TechnicalAppendix_Vol%201_Final.pdf
*Data is in average megawatts

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