



**Economic Modeling of Cost Effective
Hydrogen Production From Water Electrolysis
by Utilizing Iceland's Regulating Power Market**

Jeffrey Jacobs

Thesis of 60 ECTS
**Master of Science (M.Sc.)
in Sustainable Energy Science**

January 2016



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Thesis of 60 ECTS credits submitted to the School of Science and
Engineering at Reykjavík University in partial fulfillment of the
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Science**

January 2016

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Abstract

Water electrolysis technologies have demonstrated their ability to perform sufficiently enough for electrical grid balancing services while also producing gaseous hydrogen, which is a useful product in today's society. As installed renewable energy capacity increases, and hydrogen demand increases as well, electrolytic technologies will be needed to serve as flexible demand side management (DSM) techniques for a transmission grid operator to use in times of grid instability. A financial analysis was performed on hypothetical alkaline electrolysis plants attempting to lower manufacturing costs by participating in Iceland's regulatory power market as a DSM tool. The market is based on bidding to provide up or down regulation power, and this analysis focused more so on up-regulation bidding because of higher profits available (>4000 ISK per bid). Production prices not including bids ranged from 2,7 – 3,1 €/kg amongst the cases, which were characterized by a different number of electrolyzers. Production prices including bids reached lower than 2€/kg. Wholesale electricity costs positively correlate with production price when not including revenue from bids. Revenue from bids both positively and inversely correlated with production prices depending on the frequency of bids at a specific target price. The 11,5 MW (5 unit) case study in particular showed the most promise due to its favorable capital costs and mid-sized capacity. Results from the financial model do indicate that it is possible to lower production prices by participating in the regulatory power market. However, more structured secondary markets, and more competition in these markets in the future could be even more beneficial to the success of these energy-balancing technologies.

Key Words: Hydrogen, Electrolysis, Demand Side Management (DSM), Alkaline, Iceland

Fjárhagslíkan af arðbærri framleiðslu vetnis með rafgreiningu á vatni sem notast við íslenska reglunaraflsmarkaðinn

Jeffrey Jacobs

January 2016

Sýnt hefur verið fram á að rafgreining á vatni getur verið nýtt til að regla raforkudreifikerfi, ásamt því að framleiða vetni sem er mikilvæg afurð í dag. Með aukinni hlutdeild endurnýtanlegra orkugjafa í kerfinu og aukinni eftirspurn eftir vetni, þá eykst þörfin fyrir tækni sem getur aðstoðað við að ráða við breytilega eftirspurn (DSM) sem stjórnandi dreifikerfisins getur nýtt til að glíma við óstöðugleika. Kostnaðargreining var framkvæmd á alkalískri rafgreiningarstöð þar sem reynt var að lækka framleiðslukostnað á vetni með því að nýta stöðina einnig til reglunar á dreifikerfi landsins. Markaðurinn byggir á uppboðum til að tryggja upp eða niðurreglunar afl, en þessi rannsókn skoðaði meira uppreglun vegna þess að meiri tekjur voru í boði (>4000 ÍSK í hverju boði). Framleiðslukostnaður á vetni án uppboða var frá 2,7 – 3,1 €/kg eftir tilvikum, þar sem reiknað var með mismunandi fjölda rafgreiningareininga. Framleiðslukostnaður á vetni með uppboðum lækkaði niður í 2 €/kg. Það var jákvæð fylgni milli raforkuverðs og framleiðslukostnaðar þegar ekki var gert ráð fyrir tekjum frá uppboðsmarkaði. Tekjur frá uppboðsmarkaði sýndi bæði jákvæða og neikvæða fylgni við framleiðslukostnað en það stýrðist af tíðni boða á gefnu verði. Í tilfelli 11,5 MW framleiðslustöðvar (5 rafgreiningareiningar) var fjármagnskostnaður hagstæður og afkost í góðu samræmi við íslenska raforkuverfið. Niðurstöður kostnaðarlíkans benda til að hægt sé að lækka framleiðslukostnað á vetni með því að taka þá í uppboðsmarkaði reglunarafls á raforkumarkaðnum. Hins vegar, mun aukin samkeppni og þróun undirmarkaða í framtíðinni geta stutt enn frekar við tækni sem hægt er að nýta á reglunarorkumarkaði.

TABLE OF CONTENTS

1. Introduction	- 1
1.2 Water Electrolysis Origins and Theory	- 2
1.3 Alkaline Electrolysis	- 3
1.3.1 Alkaline Electrolysis: Real World Applications	- 5
1.3.2 Alkaline Electrolysis: Limitations and Further Development	- 6
1.4 Polymer Electrolyte Membrane (PEM) Electrolysis	- 6
1.4.1 PEM Electrolysis: Real World Applications	- 8
1.4.2 PEM Electrolysis: Limitations and Further Development	- 8
1.5 High Temperature Electrolysis – Future Electrolysis	- 9
1.5.1 HTE Electrolysis: Real World Applications	- 10
1.5.2 HTE & Co-Electrolysis	- 10
1.5.3 HTE: Limitations and Further Development	- 10
1.6 Electrolysis Conclusion and Future Perspectives	- 11
2.1 Introduction	- 14
2.2 Hydrogen in today's society	- 14
2.3 Electrical Network Balancing	- 15
2.3.1 Instantaneous Reserves	- 15
2.3.2 Primary Reserves	- 15
2.3.3 Secondary Reserves	- 16
2.3.4 Tertiary Reserves	- 16
2.4 Iceland's Electricity Market	- 17
2.5 Renewable Energy Installed Capacity	- 20
2.6 Electrolysis	- 20
2.7 Demand Side Management	- 21
METHODS	
2.8 Electrical Grid System Boundaries	- 23
2.8.1 Electrolysis Review	- 23
2.8.2 Case Study	- 24
2.8.3 Electrolysis Methods	- 24
2.8.4 Capital Cost	- 26
2.8.5 Total Manufacturing Costs	- 26
2.8.6 Electricity Costs	- 27
2.8.7 Fixed Costs	- 27
2.8.8 Model Limitations	- 28
RESULTS	
2.9 Capex	- 28
2.9.1 Electricity Charges	- 29
2.9.2 Hydrogen Production Prices	- 31
2.9.3 75%, 50%, 25% Scenarios	- 32
2.9.4 Wholesale Electricity Price	- 33
2.9.5 Historical Regulating Power Market Prices and Trends	- 33
2.10 Discussion/Conclusion	- 34

LIST OF TABLES/FIGURES

Figure 1: Worldwide hydrogen production - 1
Figure 2: Schematic of an alkaline electrolysis cell - 4
Figure 3: A typical solid electrolyte cell - 7
Figure 4: Thermal and electrical energy requirements for HTE - 9
Figure 5: Evolution of power reserves over time - 17
Figure 6: 5 year data on regulating power from Landsnet - 19
Figure 7: Graphical representations of DSM techniques - 21
Figure 8: NEL electrolyzer approximate energy consumption - 25
Figure 9: Electrolyzer CAPEX (€/kW) compared to plant capacity (MW) - 26
Figure 10: Manufacturing cost of hydrogen for each case including revenue from bids - 32
Figure 11: Production price as a function of electricity price per MWh for the 11,5 MW (5 unit) case - 32
Figure 12: Reality scenarios at 75%, 50% and 25% including revenue from 6000 ISK bids - 33
Figure 13: Manufacturing price at different wholesale electricity prices including revenue from bids - 33
Table 1: Research and development necessary for future alkaline electrolysis advancement - 6
Table 2: Operating and performance parameters for Alkaline and PEM electrolysis technologies - 7
Table 3: Research and development goals for PEM electrolysis - 8
Table 4: Characteristics of NEL atmospheric pressure alkaline electrolyzer - 24
Table 5: Cases studied for analysis - 25
Table 6: Cost assumptions used for each case including auxiliary equipment - 26
Table 7: Electricity costs and tariffs assumed in financial model - 27
Table 8: CAPEX associated with different sized electrolysis plants - 28
Table 9: Wholesale electricity costs for each case assuming operation at 100% capacity and 8760 hours per year and electricity price of 40€/year - 29
Table 10: Additional electricity charges expected for each case assuming operation at 100% capacity and 8760 hours per year - 29
Table 11: Ancillary Service and Transmission losses charges for each case assuming operation at 100% capacity and 8760 hours per year - 29
Table 12: Excel spreadsheet including all parameters and displaying manufacturing costs without revenue (highlighted in yellow) - 30

Part 1:
A Review of
Water Electrolysis Technologies

1. Introduction

In today's society as global energy demands are addressed, it is expected that hydrogen will play a crucial role in future energy infrastructure. Hydrogen is being turned too as an energy carrier in hopes to wean our current society away from carbon emitting fossil fuels and to mitigate their effects on the atmosphere. Hydrogen has a gross energy or higher heating value of 142 MJ/kg compared to natural gas or crude oil that register at 52 and 45 MJ/kg respectively¹. Hydrogen also has demonstrated its ability as fuel for vehicles, electricity storage via fuel cells and a number of other useful attributes in the chemical and metallurgical industries.

Hydrogen (H_2) is the single most abundant element on earth however, it does not exist by it self in nature, and typically is bonded with oxygen to form water. Methods do exist to split hydrogen's bonds with other molecules and these are shown

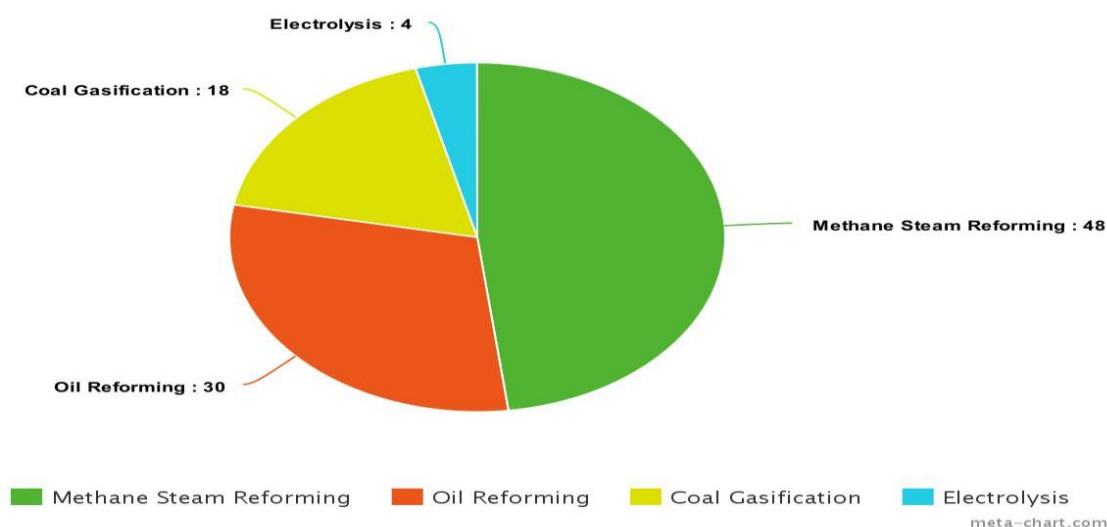


Figure 1: Worldwide hydrogen production methods ².

in Figure 1 along with their respective production percentage share in the hydrogen industry ². The most popular method of hydrogen production is methane reforming where a high temperature process cleaves hydrogen off of a carbon molecule. An example of a lesser-utilized hydrogen production method is water electrolysis where an electrical current splits water molecules into separate entities of hydrogen and oxygen. Electrolysis is more ecofriendly from an emissions point of view, however the process is energy intensive and non sustainable in this regard.

Sustainable hydrogen production via electrolysis can be achieved if the energy consumed comes from a renewable source such as wind, solar or geothermal instead of fossil fuels or nuclear uranium. With renewable energy installed capacity on the rise, electrolysis is poised to become a much more important future hydrogen production strategy. Also, as research and development drive costs down, production prices can be expected to decrease and eventually become competitive with the likes of methane reformation. Electrolysis also offers the potential of electrical grid balancing where a transmission operator (TSO) may increase or curtail electrical loads on an electrolysis plant depending on the overall supply and demand of energy in a given network. Known as a Demand Side Management (DSM) technique, an electrolysis plant can participate in up or down regulation for grid balancing and possibly generate revenue while doing so. This presents another option for lowering hydrogen production costs and eliminates the need to build additional electricity grid infrastructure.

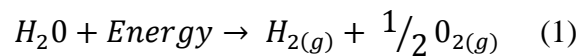
With renewable energy penetration on the rise as well as global hydrogen demand increasing, electrolytic technologies present a uniquely sustainable alternative to conventional hydrogen production strategies. By utilizing renewable energy sources and allowing electrical load flexibility at the transmission operator's control, it can be possible to significantly lower hydrogen manufacturing costs from today's market price.

The aim of this thesis is to a) Identify electrolysis technologies via a literature review taking into account performance and real world applicability b) Perform an economic analysis on a selected electrolysis technology for different capacity electrolysis plants in an attempt to reduce production costs as much as possible by acting as a DSM technique.

1.2 Water Electrolysis Origins and Theory

Water electrolysis is a centuries old technique first demonstrated by the German chemist J. W. Ritter in the 1800s. English scholars then followed suit when they noticed water decomposing when a current was applied during one of their experiments. The French military then began utilizing this technique for their airship fleets, and by the 1900s many industrial processes were producing hydrogen such as the fertilizer industry. Since then, many more electrolysis units have been put on line including the first large-scale unit capable of producing 10,000 Nm³ H₂/h which was introduced in 1939³.

The equation for water electrolysis can be seen below and involves adding electrical energy to water molecules and yielding hydrogen and oxygen gas.



This liquid to gas reaction takes place in a device known as an electrolyzer. The electrolyzer uses electricity as an energy input from an external supply to split the water into its separate entities of hydrogen and oxygen. The electrolyzer is comprised of an electrochemical cell that is made up of two electrodes, an electrolyte reservoir and a connection to an external power supply.

In the first electrolysis applications, an acidic water solution was used in the electrolyte reservoir because pure water was known to be an ineffective electrical conductor. Nowadays, both acidic and basic solutions are used and the reactions differ slightly in overall reaction kinetics. However, regardless of what conductive electrolyte is used, these all have been researched and designed so that no side reactions are observed leading to undesirable byproducts.⁴

Electrolysis is an endothermic ($\Delta H > 0$) and non-spontaneous ($\Delta G > 0$) chemical reaction. During operation inside the cell, when a specific voltage, or the 'critical voltage' between electrodes is applied, H₂O begins to decompose and H₂ forms at the negatively charged cathode while O₂ forms at the positively charged anode. Hydrogen quantities produced per unit time is directly related to the current applied in the system. Under standard temperature and pressure the required energy for the reaction is determined by enthalpy change (ΔH). The following expression shows the thermodynamic relationships inside the electrolysis cell.

$$\Delta G = \Delta H - Q = \Delta H - T \times \Delta S \quad (2)$$

In this equation, ΔG is the Gibbs Free energy change in the form of electricity. Q represents the thermal energy needed and this equals the product of the reaction temperature, T , and entropy change, ΔS .

The necessary cell voltage required for electrolysis is called the reversible cell voltage V_{rev} and is explained by the following equation.

$$V_{rev} = \frac{\Delta G}{z \cdot F} \quad (3)$$

The voltage can be found by dividing the Gibbs Free energy by the number of electron moles transferred (z) multiplied by the Faraday constant, or the charge of one mole of electrons (96.485 C/mol).

The electrical efficiency of an electrolysis system can be calculated by the following equation:

$$\text{Electrical efficiency (HHV)} = \frac{\text{HHV of } H_2 \text{ produced}}{\text{Electricity used}} \quad (4)$$

The HHV is defined as the amount of heat released after combusting a fuel and allowing the products to return back to a standard temperature (25 C). Electrolysis cells can be either singular or designed in stacks with multiple cells thus multiplying capacity. Once the critical voltage in the cell is reached, the efficiency of the voltage can be defined for an individual or a stack of electrolytic cells. This equation is as follows:

$$\text{Voltage efficiency} = \frac{\text{Thermal neutral voltage (E)}}{\text{Cell operating voltage (V)}} \quad (5)$$

Now that a brief introduction into the theory of electrolysis has been presented, different electrolysis technologies will be explained. Each technology will be described by providing a brief history, comments on design and performance, as well as the demonstrated real world applicability and potential to be in tandem with renewable energy.

1.3 Alkaline Electrolysis

Alkaline electrolysis is the most mature of the electrolysis methods, and is considered the easiest as well. Applications include a variety of uses in the chemical and metallurgical industries. A typical electrochemical alkaline cell is shown in Figure 2. The cell consists of an electrolyte reservoir, two electrodes and a diaphragm in between the electrodes.

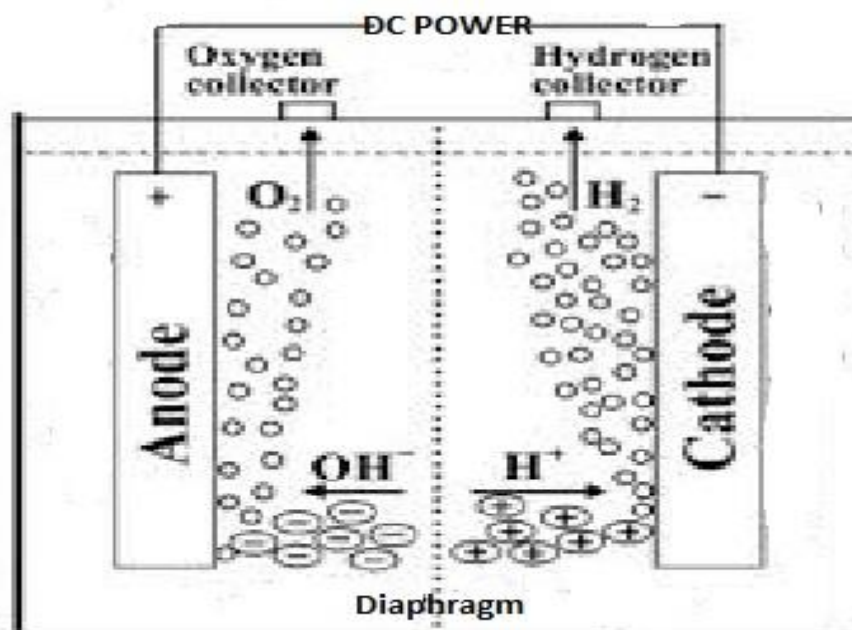


Figure 2: Schematic of an alkaline electrolysis cell with a liquid electrolyte ⁵.

The diaphragm is typically made from composite materials based on ceramic, microporous or a combination of both materials. The electrodes are made from metals like Ni or Ni alloys, however different metals can also be used. Other metals are characterized by the potential difference (voltage) between a half-cell reaction's thermodynamically determined reduction potential and the potential at which the reduction event is observed. This is commonly referred to as over-potential and can be directly related to a cell's voltage efficiency ⁵. Electrolytes used in an alkaline electrochemical cell are typically corrosive agents like KOH or NaOH, and are often found in tandem with neutralizers to help preserve the cell's lifetime. The electrolyte's primary task is to facilitate ionic movement by carrying electrical charge through the cell. An electrochemical catalyst can also be added and aids by diverting both the anode and cathode reaction pathways to a lower activation energy state, thus starting the reaction more easily.

Alkaline electrolyzers are capable of producing high quality hydrogen and other methods do exist for additional purification. Commercial systems range in size and production capacities. Average costs range from 1,000-1,200 €/kW.⁶

There are many examples of successful industrial hydrogen production through alkaline electrolysis throughout the world. Systems sizes and design vary widely from small laboratory set-ups to large-scale electrolysis plants. Despite widespread application, energy requirements are high, energy costs can be volatile, and this energy may be produced from CO₂ emitting feedstock. These three factors suggest the importance of electrolysis facilities to be coupled with renewable energy in order to sustainably produce hydrogen.

In the next sections, various case studies, new research developments and technology limitations will be discussed regarding alkaline electrolysis. Polymer exchange membrane (PEM) and high temperature electrolysis (HTE) will then be discussed in the same context.

1.3.1 Alkaline Electrolysis: Real World Applications

Canada has developed wind power to hydrogen projects in order to bolster the nation's wind energy profile. Ramea Island, south of Newfoundland and Labrador is the site of one such project where hydrogen production and storage was integrated into the already existing wind power to diesel system in operation. Electrolysis was performed with a 90 m³/h alkaline electrolyzer in tandem with a 2000 m³ hydrogen storage unit kept at 10-bar pressure. With this design, system operators demonstrated ability to convert stored hydrogen back into electricity to power four 62.5 kW hydrogen internal combustion engine generators for this remote island ⁷.

The United Kingdom established wind power to hydrogen technologies to investigate its potential, and bolster its renewable energy profile. From 2001-2006 the Hydrogen and Renewables Integration (HARI) project served as a research project to demonstrate and gain experience from this power to gas system. The HARI project consisted of wind, solar and micro hydro turbines totaling 79 kW capacity. For the project, a 36 kW alkaline electrolyzer was installed, capable of 25-bar pressure output. This was accompanied by a 2,856 Nm³ hydrogen storage capacity capable of 137-bar pressure, and connected to two fuel cells at 2 kW and 5 kW, respectively. The system was also mentioned to show potential for electrical grid support and act as a DSM technique.

Along with demonstration projects coupled with renewable energy sources, research and development has been an ongoing effort in the water electrolysis industry. It can be expected that costs will be driven down as processes become more optimized and parts become inexpensive. An example of further optimization and design research has shown that high temperature and pressure alkaline electrolysis is a viable option. New alkaline cells have been built and water electrolysis has been successfully demonstrated at temperatures up to 250 C and 40 bar pressure. This same cell demonstrated electrical efficiencies of 99% at 1.1 A cm⁻² and 85% at 2.3 A cm⁻² ⁸.

Other optimization studies performed observed that creating an ultrasonic field around the electrolyzer assisted in mass transfer and reduced energy requirements on the cell. Experiments showed that performing electrolysis when using an ultrasound increased production efficiency 4.5% and increased energy efficiency 1.3% allowing for a total average production efficiency of 78% ⁹.

Several models have also been created look at electrolytic alkaline hydrogen production coupled with renewable energy. For example, successful simulations have been observed of an alkaline electrolysis cell powered by a photovoltaic module, and gas profiles generated showing production rates compared to solar intensities throughout the day ¹⁰.

1.3.2 Alkaline Electrolysis: Limitations and Further Development

Alkaline electrolysis is the oldest and simplest electrolysis method available today, and is used in a wide variety of chemical and metallurgical processes. Perhaps the single biggest problem associated with alkaline electrolysis is high-energy requirements, however this can be addressed when coupled with renewable energy resources. General limitations and problems that need to be addressed for future improvements in alkaline electrolysis are presented in Table 1.

The improvements needed mainly involve development of cheap and better performing materials capable of performing efficiently inside the cell's harsh environment created during electrolysis. It is also noted that the obstacles to higher efficiency are resistances in the cell, including resistances generated by gas bubbles,

Table 1: Research and development necessary for future alkaline electrolysis advancement^{11,36}

Reducing dissolved gas bubble's time on electrode surface and the associated resistances

Development of cheaper and better performing liquid electrolyte solutions

Development of electrocatalysts to reduce overall reaction resistances (i.e. activation energy)

Development of new cell additives to assist ionic movement and chemical reaction stability

Development of safer and more durable materials

activation energies of electrochemical reactions, mass transfer and electrical resistances in the circuit¹¹. Also it is expected that compatibility issues between electrolyzer, renewable energy and current grid infrastructure could arise in some parts of the world, and these will need to be addressed in future energy infrastructure developments.

1.4 Polymer Electrolyte Membrane (PEM) Electrolysis

Polymer exchange membrane (PEM) electrolysis, also known as 'proton exchange membrane' is the next technique that will be discussed, and it is arguably the better performing electrolysis technology available on the market today. General Electric is credited with the first designed PEM electrolyzer spawning further developments through the 80s and 90s. To date, PEM electrolysis has applications in the chemical and metallurgical industries, as well as with NASA and the U.S. Navy.

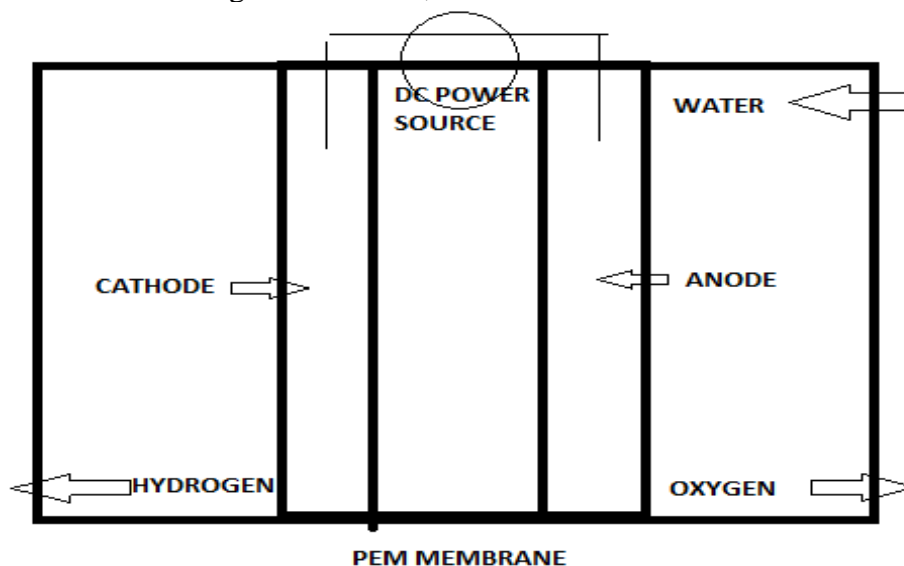


Figure 3: A typical PEM solid electrolyte cell used for water electrolysis

PEM electrolysis is based off using a solid-state electrolyte versus a liquid electrolyte. Figure 3 shows the layout of a typical solid electrolyte cell. Instead of a

porous diaphragm, a solid membrane separates the electrodes. An electro catalyst is also present, and the whole unit is commonly referred to as the Membrane Electrode Assembly (MEA). A gas diffuser and steel bi-polar plates are also necessary to promote ionic movement across the membrane, and the whole system requires a purified H₂O stream.

The MEA is the backbone of the operation and therefore constitutes a majority of cost. The membrane itself is made from a perfluorosulfonic acid polymer and is capable of providing high proton conductivity and withstanding higher pressures. Low membrane thickness (20-300 μm) also allows for compact design, low ohmic drop and high gas permeability¹². Electrodes are typically coated in noble metals plus their oxides, which serve as the electro catalyst. For example, an electrode may be coated in platinum or iridium in tandem with platinum or iridium oxide as the catalyst.

PEM electrolyzer can provide ultra high purity hydrogen, and also range in size and production capacity, however both are higher than in alkaline. Average costs for these systems range from 1,900 – 2,300 €/kW⁶. Table 2 shows the operating and performance parameters of commercially available Alkaline and PEM technologies.

Table 2: Operating and performance parameters for Alkaline and PEM electrolysis technologies⁶

		Alkaline	PEM
Production Capacity	Nm³_{H₂}/h	0.25 – 760	0.01 – 240
Electrical Input	kW	1.8 – 5,300	0.2 – 1,150
Operating Temperature	C	40 – 90	20 – 100
Operating Pressure	Bar	<30	<200
Hydrogen Purity	%	99.5 – 99.9998	99.9 – 99.9999
System Cost	€/kW	1,000 – 1,200	1,900 – 2,300

***HTE not included because it is not commercially available.**

1.4.1 PEM Electrolysis: Real World Applications

In 1987, a Swiss metallurgical specialty company placed the first commercial scale PEM electrolyzer unit on line. The plant consisted of 120 cells, each with 20 x 20 cm² active area, grouped into four separate modules. The unit was designed to produce up to 20 Nm³/h hydrogen at 1-2 bar pressure³.

Single cell PEM electrolyzers have been documented performed with 87% efficiency. Multiple cell stacks (5 to 10) showed efficiencies around 80% and the capability to produce hydrogen at 5 l/min while consuming 1280 kw¹³. The GenHyPEM project in Germany also demonstrated stack efficiencies close to 80% while operating at high current densities $\sim 1 \text{ A cm}^{-2}$. The project also demonstrated experimental storing hydrogen in pressurized vessels (1-130 bar)¹⁴. In 2010, Oreion Alpha designed a self-pressurizing transportable PEM electrolyzer and demonstrated operation while coupled with a 2.4 kW photovoltaic solar array¹⁵. PEM has been noted to be especially well suited be powered by photovoltaic cells for both grid connected and grid independent applications by matching both the panel and the electrolyzer's *i-V* polarization curves¹⁶.

German researchers have demonstrated solar-hydrogen production from a dual-unit 100 kW commercial scale system. This power to gas research project aimed to study the electrolysis cell's lifetime and then adjust accordingly in a second demonstration plant³. Hydrogen production from a geothermal source has also been demonstrated with a binary geothermal power plant, heat exchanger and PEM electrolyzer. At 160 C resource temperature, model outputs showed 3810 kW

electrical output and 0.0340 kg/s H₂ production. The model also calculated overall energy and exergy efficiencies of 6.7% and 23.8% respectively. The researchers concluded that higher efficiencies were observed if water enters the PEM electrolyzer preheated and that hydrogen production was proportional to geothermal resource temperature¹⁷.

1.4.2 PEM Electrolysis: Limitations and Further Development

PEM has been around for a much shorter time than alkaline electrolysis, and faces some of the same main challenges like high-energy and capital cost requirements. Table 3 shows some of these limitations regarding the system itself and problems when coupling with renewable energy. Nonetheless, research and development projects are ongoing and are expected to bring future costs down low enough to be competitive with alkaline electrolysis.

Table 3: Research and development goals for PEM electrolysis^{12,14-16}

Develop low cost substitutes for noble metal catalysts able to handle the acidic conditions in the MEA

Maintain efficiency and low ohmic resistances in up scaled systems

Increase production capacity while maintaining overall system efficiencies

Achieve higher operating current densities and pressures to reduce capital cost

Renewable energy is intermittent and small drops in efficiency have been observed due to coupling

Technology necessary to monitor electrolysis processes and act as fail safes

Develop low cost and corrosion resistant diffusers and bi-polar plates

Stack development into the MW range

1.5 High Temperature Electrolysis – Future Electrolysis

HTE is most recent electrolysis technology to be in the electrochemical spotlight, and there is lots of intrigue and research currently surrounding this idea. HTE is mostly attractive because it becomes thermodynamically favorable at higher operating temperatures (800-1000 C). This allows for significantly less electricity to

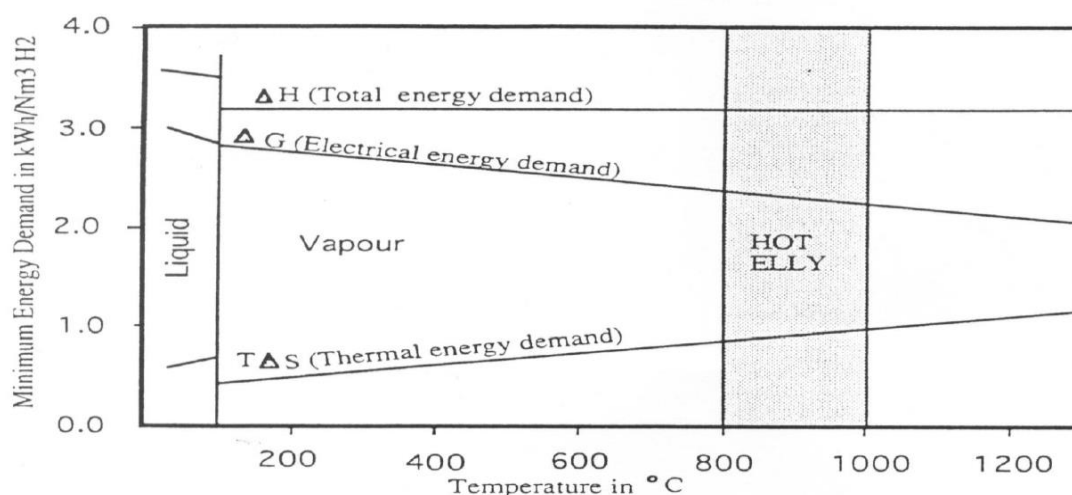


Figure 4: Thermal and electrical energy requirements for HTE³⁷.

be consumed by the reaction because a portion of the energy comes in the form of heat. Heat is also generally cheaper than electricity making the economic benefits associated with this technology to be rather appealing. High heat requirements are usually achieved by exchanging heat from nuclear reactors, however geothermal heat is also being explored as a possibility and research has demonstrated HTE viability through a network of heat exchangers and 230 C resource temperature¹⁸. The Idaho National Laboratory performed an economic analysis of HTE coupled with a high temperature helium cooled nuclear power plant, and estimated hydrogen production costs at \$3.23 per kg hydrogen¹⁹.

HTE is performed in a solid oxide cell (SOC) and principally operates the same as alkaline or PEM systems by using electrical current to split water molecules, which in this case are in the form of pure steam or a steam liquid aqueous mixture. HTE operates under the so called 'thermoneutral voltage,' where the electricity input matches the total energy demand for the reaction. This occurs because electrical energy required decreases as temperature increases and heat energy takes over to split the molecule. It has been noted that in theory, this means that conversion can be achieved at 100%²⁰. Figure 4 illustrates the principle behind which these high temperature systems operate. In the vapor phase, both electrical and thermal energy demands decrease dramatically, and this can be achieved while simultaneously maintaining high efficiency levels. SOC's have been designed to act as both a fuel cell and an electrolysis cell, and they are sometimes referred to as reversible solid oxide fuel cells (RSOFC).

1.5.1 HTE Electrolysis: Real World Applications

The first prototype to demonstrate this was the HOT ELLY system designed by German engineers in the 1980s. This system utilized the thermodynamic advantages of high temperature and phase changes mentioned above to achieve much higher efficiencies than PEM or alkaline methods. At the moment, only a few materials have been considered applicable as HTE electrolytes. These include ZrO_2 , CeO_2 , LaGaO_3 and Bi_2O_3 . These electrolytes are used because they have demonstrated sufficient oxide ion conductivity over a wide range of operating pressures. Electrodes for HTE are typically made from lanthanum strontium manganite (LSM) mixed with an ionic conductor matching the solid electrolyte's composition²¹.

In some of the first demonstration trials, single SOC's were operated for long-term periods at -0.3 A cm^{-2} current density. At low voltage around 1.07 V, the cells reached 100% Faraday efficiency, which is possible in theory to do by utilizing the favorable thermodynamics of the HTE system²². A HTE process coupled with geothermal energy was investigated from an overall energetic and exergetic standpoint before as well. Overall energy and exergy efficiencies were calculated 87% and 88%, respectively. The research also concluded that without including auxiliary equipment, HTE consumed 3.34 kWh_e at 230 C while generating 573 mol/s H_2 ².

Despite demonstrated success with geothermal heat as an energy input, HTE is more compatible with much higher temperature waste heat from nuclear reactors. However, as geothermal drilling technology advances, higher temperatures may become accessible in the near future.

1.5.2 HTE & Co-Electrolysis

When operating in electrolysis mode, the RSOFC device will electrolyze water vapor or steam to produce hydrogen. The device also has demonstrated that it can electrolyze a mixture of H_2O and CO_2 , resulting in hydrogen and carbon monoxide (CO). This process is known as co-electrolysis, and leads to the formation of syngas ($\text{H}_2 + \text{CO}$). Syngas, is a pre-cursor to alternative fuels, and there is a lot of demand for this product in today's green energy revolution. Syngas can be further processed into higher carbon fuels by utilizing the Fischer-Tropsch chemical reaction process. Co-electrolysis is therefore a highly anticipated technology and lots of research is being conducted to make it commercially available.

1.5.3 HTE: Limitations and Further Development

HTE is still a very young and immature technology, however the potential seems to be enormous. Performing electrolysis at high temperatures allows for a highly favorable shift in reaction thermodynamics by introducing heat into the system and effectively lowering overall energy requirements. Geothermal energy has shown to be a viable heat source but requires a series of heat exchangers. Future technology developments in concentrated solar power and geothermal drilling will determine the role of HTE in future electrolytic industries and markets.

1.6 Electrolysis Conclusion and Future Perspectives

Hydrogen production methods from three water electrolysis techniques have been presented above. The traditional alkaline and PEM electrolysis today are the only commercially available technologies with HTE still in laboratory and pilot scale. Despite being commercially available, alkaline and PEM are plagued by high-energy requirements, consequently hindering these technologies from being economically competitive with current and non-sustainable hydrogen production methods like methane reformation. HTE is still under development, and this technology will continue to attract much attention because of its thermodynamic advantages. Lowering energy requirements is the main issue with electrolysis, and replacing electrical energy with heat energy as HTE does is both novel and cost effective. Alkaline electrolysis, despite its maturity and market saturation has comparatively low efficiency operating parameters compared to other electrolysis technologies. PEM and HTE clearly have higher performance capabilities however these are then associated with high capital costs for PEM, while HTE is not yet commercially available.

The future of electrolysis will continue to heavily depend on the demand for hydrogen and the research and development progress made within these industries. Demand will be influenced by a number of factors including progress in fuel cells, hydrogen vehicles, syngas and renewable energy penetration. As progress is made, it is expected that capital costs will decrease in the future.

In 2014, the United States Department of Energy stated that hydrogen production costs will be under \$4.90 by 2025. The European Union predicts between \$4-5 average across multiple countries by 2030²³. Both of these estimates though were calculated using mainstream grid electricity prices assumed to be generated by nuclear or another non-sustainable feedstock. In reality, these prices can be lowered by coupling electrolysis with renewable energy sources or by competing in electricity spot markets as a flexible industrial entity that can help regulate electrical grids. In

order to do the latter, some more technical requirements are required for electrolyzers, and reliable performance is necessary.

When a power disruption occurs, systems must respond quickly to reconcile the imbalance. Thanks to smart grid equipment, signals can be sent very quickly, but then it is up to the end receiver to read and perform the function. Therefore, machines must be capable of reading these signals and responding immediately. The National Renewable Energy Laboratory conducted a study to assess electrolyzer's variable operation performance, including tests on: response time and ramp rate after a load change, frequency disturbance corrections and startup/shutdown times. Both PEM and alkaline responded to load changes within milliseconds, demonstrated wide operating range (10-90% capacity) and also showed capability of grid frequency restoration during simulations on a mini-grid ²⁴.

These results indicate that electrolyzers have potential beyond just creating hydrogen. Whether or not electrolyzers will be successful in grid stabilization will heavily depend on the electricity markets, rate structures and guidelines put in place by individual countries or governing regions. However, with the emergence of intermittent renewable energy underway, it is clear that more options will be required to balance energy supply with demand. The evidence suggests that electrolyzers can be a solution to the growing energy infrastructure and can assist electrical grids in maintaining balance and therefore a secure supply of electricity to all end users.

The next section of this paper will discuss the potential of electrolysis as an electrical grid-balancing tool in the Icelandic electricity network. After conducting research on the electrolysis technologies available for this, the next step forward is to investigate whether or not an electrolysis plant competing in Iceland's regulating power markets can significantly lower hydrogen production costs.

Part 2:

Case Study

2.1 Introduction

A global initiative to combat climate change and reduce greenhouse gas emissions has become of paradigm importance to most nations in the world today. Perhaps the biggest contributor to reaching carbon emission goals is through the development and utilization of renewable energy. Despite its good intentions, increasing renewable energy capacity will require more ways to balance this energy increase along national and international power grids.

An electricity grid must be kept properly in balance to ensure a safe and secure supply of electricity to end-users. In theory, a perfectly functioning grid maintains stability by matching electricity produced to the amount demanded in a particular grid system. For example, a European TSO must maintain the nominal 50 Hz frequency across a grid system as closely as possible to ensure smooth transmission and distribution. It is of course impossible to perfectly forecast energy demand profiles since daily fluctuations in consumer and industrial behavior often shift due to unforeseen circumstances.

In cases where a grid is not in balance or a deviation from the nominal frequency occurs, a grid operator must have mechanisms, like DSM techniques, at their disposal to correct the fluctuation and restore harmony as quickly and smoothly as possible. These options generally include power generators able to increase or decrease production or energy intensive industries able to reduce their output or take on excess energy in the grid and increase production. Depending on the scenario, and the tactic deployed to restore grid harmony, energy is purchased, sold or traded in energy spot markets developed by the energy authorities in that particular region.

In the next sections, an economical analysis will be detailed and analyzed to estimate hydrogen production prices in Iceland for different capacity electrolysis plants. The main goal of the analysis will be to determine the feasibility of an electrolysis plant in lowering manufacturing costs by participating as a DSM technology in Iceland's regulating power market.

2.2 Hydrogen in today's society

Current worldwide hydrogen production is around 600 billion m³/year, and is used in a variety of industrial and chemical processes. Such processes include hydrogenation of foods and oils, mixing with nitrogen to produce ammonia for fertilizers and also as coolants in power plants because of hydrogen's high heat capacity. Almost all of hydrogen is produced from processes using fossil fuels, natural gas and coal as feedstock.

In more recent times, hydrogen focus has shifted toward its potential as an energy carrier. Hydrogen production from techniques like electrolysis and hydrogen storage for electricity production via fuel cells are examples of such technologies that can help make the switch towards sustainable energy and fuels. While our understanding of fuel cells is not yet sophisticated enough for global deployment, electrolysis is well understood and can be performed sustainably when using renewable energy sources to power it. Recent focus has also shifted towards electrolytic hydrogen production as an energy balancing mechanism in electrical grids.

2.3 Electrical Network Balancing

Using the simple supply and demand theory, electrical grid operators attempt to balance power consumption with power generation amongst a given transmission and distribution system. This is done by energy forecasting, and attempts to use mathematical models, historical data and operator experience to predict the short-term and long-term changes in electricity demand. To do this perfectly is of course unrealistic, because energy consumption can be sporadic and energy production can become sporadic as well. Unpredictable changes in supply and demand behavior then cause deviations from the designated 50 Hz frequency needed to be maintained in a European electrical grid.

Whenever there is a deviation, or a change in frequency, a number of electrical exchanges happens simultaneously in attempt to correct the imbalance as quickly and coordinated as possible. Frequency deviations can change in both positive and negative directions. A positive frequency refers to a situation when power production exceeds demand at that point in time. A negative frequency therefore refers to when power demand exceeds the power being supplied.

Failures in the power system, such as large power plant going offline, would represent a large negative frequency deviation. When a situation like this arises, the TSO must deploy reserve power in order to restore the grid to the nominal 50 Hz. Reserve power can be broken into four categories and must be initiated in a timely manner to minimize the impact of the frequency deviation. Each of the four categories will be further explained along with requirements for these reserves as described by European regulatory framework regarding reserve power²⁵.

2.3.1 *Instantaneous Reserves*

As the name indicates, this reserve acts immediately to restore the nominal frequency, and is triggered by energy monitoring equipment that can relay quick signals. This energy comes from the kinetic energy associated with the large rotating masses still spinning yet slowing down (i.e. turbines and generators). Under normal operating conditions, every single “large rotating mass” is synchronously spinning in a given interconnected system. Therefore the available power in the instantaneous reserve is restricted to the size of the overall system.

2.3.2 *Primary Reserves*

Also known as *frequency containment reserves (FCR)*, primary reserves are typically provided by large power generators. These reserves need to respond to a TSOs signal within seconds, and must be able to provide both positive and negative grid balancing depending on the TSOs request. FCR must be initiated within seconds and must provide back up generation for up to 15 minutes.

The primary reserve aims to replace the lost frequency and restore the grid to nominal conditions as quickly as possible. It does this by not only producing power from large generators, but also by distributing the total reserve needed in equal proportion to all power generators to ensure a synchronous power restoration amongst all power producers in the overall system. Primary reserves are needed to establish a steady rate constant amongst all generators to fulfill the imbalance.

2.3.3 Secondary Reserves

Also known as *frequency restoration reserves (FRR)*, is next in line if the frequency imbalance is not solved within 15 minutes. FRR take about 3-5 minutes to start up and therefore are triggered during FCR to ensure smooth transition between reserves. Typical FRR technologies include hydropower applications and are needed to last at least 60 minutes.

FRR are selectively activated by TSOs in secondary control subsystems depending on the location of the frequency imbalance. FRR takes over by calculating the total work needed by the overall system to restore the imbalance and then distributing this workload proportionally amongst its external neighboring secondary control subsystems. Internally, the secondary control subsystems adapt either positive or negative control power generation as turbine rates are calculated and adjusted to match the rate of frequency increases from the secondary control subsystems. This allows for primary reserves to be ready again for quick deployment if necessary.

2.3.4 Tertiary Reserves

By the time a tertiary reserve or “replacement reserve” is needed, offline or idle power plants have had ample time (<60 minutes) to become operational. These plants then take over and are required to provide balancing power for up to 4 hours or until the original problem has been identified and appropriately dealt with.

The previous explanations of power reserves were used to illustrate an example in which a negative frequency situation occurs and power is needed to be restored in order to return the frequency to the nominal 50 Hz operating frequency.

It is important to understand that the opposite can occur as well. In a positive frequency deviation, differing rates of consumption will lead to power supply being greater than demand. These can be attributed to deviations from expected consumption estimates all across an electrical grid area, and during positive frequency times, a TSO must be able to reduce consumption across a grid area in order to restore equilibrium.

It is important that these reserves are well maintained and functioning properly because of how quickly they can be called upon and at varying degrees. All together, these reserves must have enough capacity to withstand the longest expected grid failure, in order to keep a secure supply of electricity flowing to end users. Figure 5 shows the general principle in which power reserves are called upon and summarizes the above sections on reserve power. It is important that at the end of a reserves capacity, the next reserve is already functioning properly enough to take the responsibility from that point.

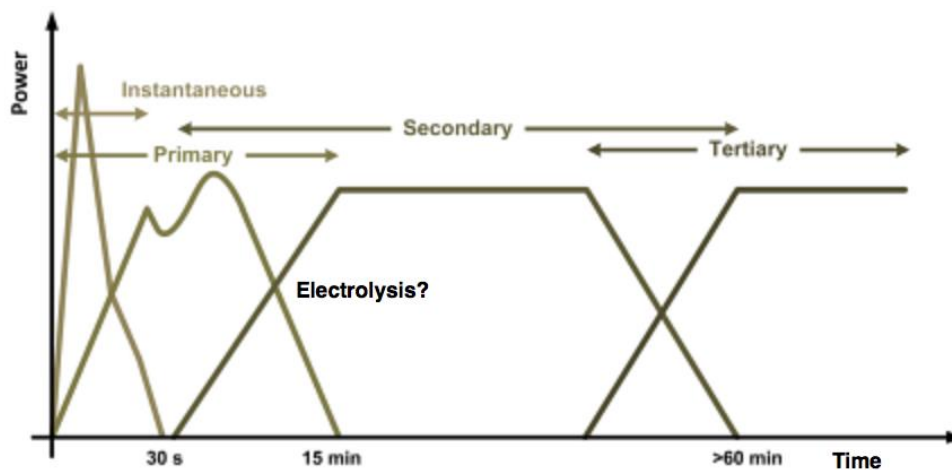


Figure 5: Evolution of power reserves over time and where water electrolysis might could potentially fit into this evolution²⁵.

2.4 Iceland's Electricity Market

In 2003, Iceland's Electricity Act was initiated and aimed to reform current conditions by opening up the electricity market to free competition for generation and supply. In Iceland, transmission and distribution are under the regulatory oversight of the National Energy Authority. Transmission is operated exclusively by Landsnet, and distribution is provided by several different companies. Landsnet's grid includes more than 3,000 km of transmission lines and approximately 70 substations and transformer stations. Overhead transmission lines are the most abundant and are designed with Iceland's harsh climate in mind. With the current infrastructure, transmission lines in Iceland can operate at voltages between 30 and 220 kV.

Landsnet's System Operations' Role is to manage the secure control of Iceland's electricity market by meeting quality standards put forth by the National Energy Authority. Some components of this include ancillary services and regulating power markets for reserve power.

Iceland's ancillary services include spinning reserves, reserve power and reserve reactive power (*landsnet.is*).

- Spinning Reserves – refers to the additional capacity of the electricity system's generators beyond their normal output. These are generally used for frequency control or to counteract large imbalances following a disturbance
- Reserve Power – refers to the generating capacity of certain power stations typically fueled by gas or diesel and are only used when a disturbance occurs or maintenance is being performed on the transmission system. Reserve power is not immediately available and can be broken into fast and slow reserves. Fast reserves are required to be available within 15 minutes,
- Reserve Reactive Power – refers to reactive power activated during a short deviation from normal operating conditions and can be activated automatically by monitoring equipment or manually by a system operator.

Iceland operates a regulating power market to offset imbalances between projected and actual power consumption across the country. In this market, generating companies and suppliers, known as "Balancing Responsible Parties" (BRPs) submit schedules to Landsnet for the next day with expected generation and consumption profiles. This schedule is then used to determine the projected output needed to satisfy consumers across the grid. Landsnet is able to rectify imbalances by increasing or

decreasing power output from BRPs. The balancing energy is traded in the regulating power market and priced at market rates for each hour throughout the day.

BRPs submit bids into the market for either up-regulation (increasing generation) or down-regulation (reducing generation) or both depending on the capacity and capability of the BRP entity. The bids are valid for one hour and are accepted in merit order. In the case of up-regulation, a BRP specifies a price to be paid by Landsnet to the power generator. For down-regulation, a BRP states a price that will be payable to Landsnet.

Historic regulating power prices are presented in Figure 6 for a five-year period (2010-2015). This study used only prices from 2015, and it can be seen that prices for up-regulation typically were higher than 4000 ISK/MWh and around 2000 ISK/MWh for down-regulation.

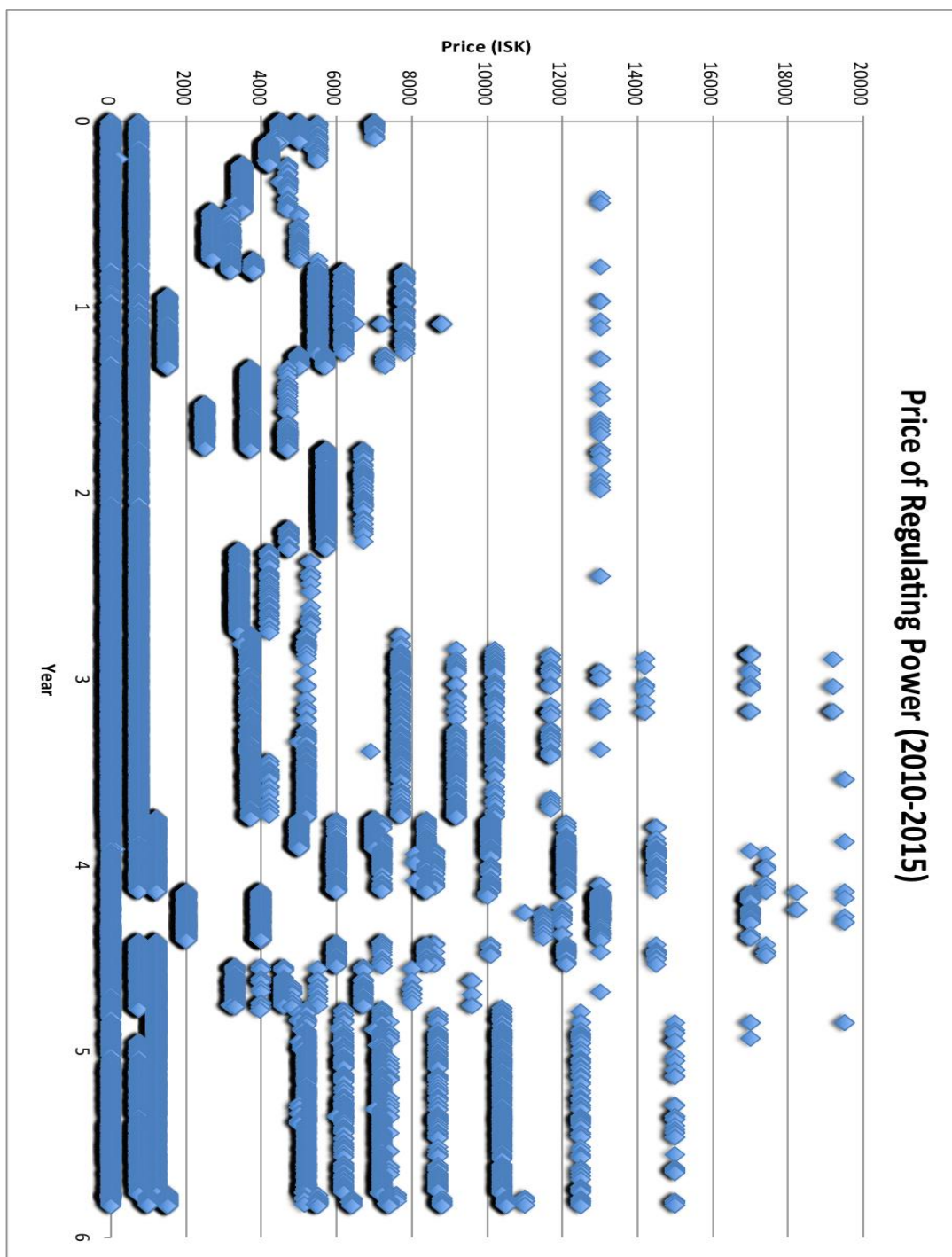


Figure 6: 5 year historical data on regulating power prices from Landsnet's regulating power market

2.5 Renewable Energy Installed Capacity

If we think about the supply and demand theory of energy further, it is important to factor in forecasts for renewable energy installed capacity. Driven by the idea of global decarbonization, many more renewable energy technologies are slated to come on line. When referring to solar and wind power technologies, it is crucial to remember that these technologies are primarily dependent on weather conditions and therefore are not always producing electricity at constant rates like generators using other feedstock like coal, natural gas, hydro or geothermal. This means that more balancing power will be needed to account for weather dependent production variations that are seen in these technologies. Nevertheless, the increased capacity can be dealt with in two ways: Increase infrastructure for larger electrical grids or by implementing storage capacity to manage future installed capacity. The first would be to build additional transmission and network infrastructure, which would result in more power lines, transformers, sub stations etc. This option may face public resistance and can often be costly as the price of a 380 kV power line can be up to 1 million €/km²⁶. The second way is through the use of fuel cells or flexible technology like electrolysis that can be used as energy storage and also produce a valuable product like hydrogen during times of electrical grid stabilization. The latter is known as a DSM technique, and is of growing interest amongst energy managers all across the world for managing electricity efficiently.

2.6 Water Electrolysis

In 2014, the United States Department of Energy (DOE) Hydrogen and Fuel Cells program conducted a study to estimate the hydrogen production cost from PEM electrolysis. Prior to this, the DOE created a Hydrogen Analysis (H2A) model for estimating production costs, and used this model to analyze the economics of four case studies.

The four case studies were based off of current (2013) and future (2025) electrolyzer technologies and distributed forecourt (500-1,500 kg/day) and centralized (50,000 kg/day) plant capacity schemes. The current electrolyzer case assumed operation at 1,500 mA/cm² and 450-psi outlet pressure. The future case assumed 1,600 mA/cm² and 1000-psi outlet pressure. The hydrogen production costs for each case are summarized below. The prices were reported in 2007 dollars and converted using a web-based inflation calculator to the price in 2015 dollars.

Current Forecourt - \$5.90 kg/H₂
Future Forecourt - \$4.85 kg/H₂
Current Centralized - \$5.87 kg/H₂
Future Centralized - \$4.82 kg/H₂

The H2A model also included sensitivity analyses, and showed that H₂ costs could be reduced \$0.08-\$0.09/kg for every 1 kWh/kg net energy reduction. Tornado charts examined the impact of individual parameters on H₂ costs as a single variable sensitivity analysis, and in all four cases suggested that electricity price is the single most impactful parameter for H₂ production²⁷.

It is interesting to note that the DOE did not use renewable electricity in this report. Therefore, it is fair to assume some reduction in these prices if they had used a renewable energy source. Another way to possibly reduce production prices for

hydrogen is to compete in electricity spot markets where energy can be purchased, sold or traded. Depending on a number of factors particularly geographic location, transmission and distribution guidelines, it can be possible to compete in electricity spot markets as a Demand Side Management (DSM) technique.

2.7 Demand Side Management (DSM)

The idea of DSM has been around since the 70s and is now more important than ever due to the evolution and coupling with smart grid technology. Being hooked into a network of sophisticated metering and analysis tools, electricity customers can really take into account their energy consumption and use information from smart grids to make decisions about energy use. The idea of being able to control end usage is a fundamental pillar in DSM.

DSM broadly refers to two principal activities, which gives end users more involvement in their energy consumption by allowing them to shift their own demand

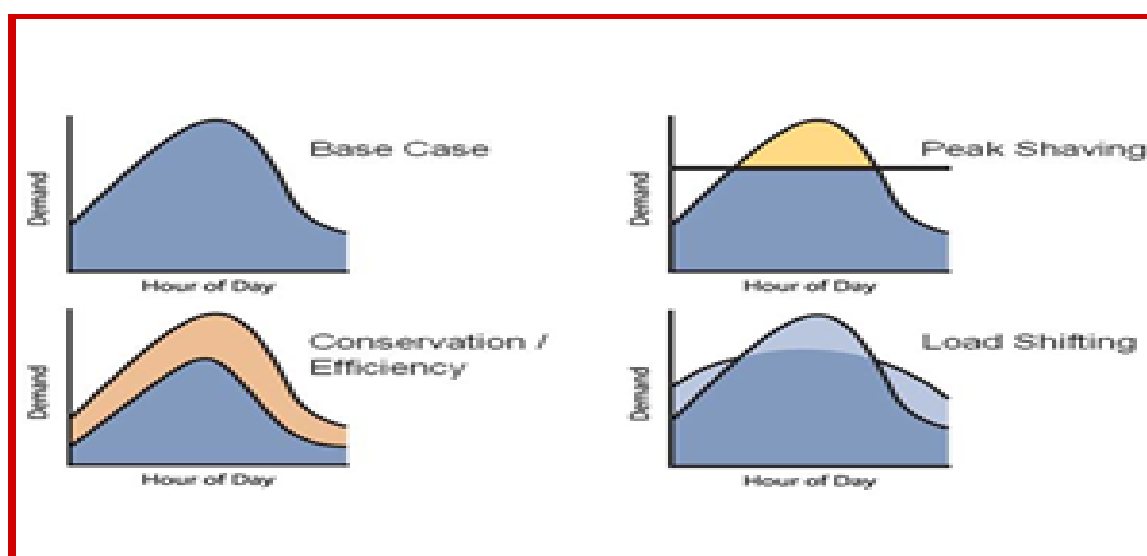


Figure 7: Graphical representations of DSM techniques (powerwise.gov.ae)

during peak periods and/or reduce their overall consumption. These two principals are ‘load shifting’ or energy efficiency and conservation programs²⁸.

Load shifting is a demand response technique where consumers can offer up their individual electrical load during high demand periods. This shift can be daily or during high demand periods throughout a year, depending on the willingness of the consumer to curtail their personal demand. Load shifting therefore flattens the overall load curve and allows for electricity to be generated by the least expensive suppliers.

Load shifting can be done in primarily three ways be reducing, increasing or shifting consumption. When a load is reduced, this is commonly known as “peak clipping.” When a load is increased, this is known as “valley shifting.” The three types of load shifting are illustrated in Figure 7 and these variations provide alternatives to storing electricity²⁵.

Energy efficiency and conservation programs also work as DSM techniques and aim to have customers reduce their electricity consumption and save money by doing so. These programs target appliances like air-conditioning units or refrigerators to reduce overall yearly consumption. Coupling smart grid technology with DSM techniques like energy efficient refrigerators etc. is propelling these technologies

towards further global integration. Smart grid technology can allow for real time monitoring of energy consumption, and can allow customers and other energy conscious entities to make smart and informed decisions about reducing consumption, and ultimately save money.

DSM in the form of load shifting has the potential to be used in grid balancing, frequency stabilization and in other facets in order to maintain electrical grid balance and harmony. An economic analysis of electrolysis DSM in Germany has been performed and suggested that DSM operations such as electrolysis would be competitive in tertiary reserve power markets²⁹. Currently, the wood pulp industry performs the majority of load shifting in Germany to meet grid-balancing needs due to its low opportunity costs and load bearing flexibility.

Spanish researchers investigated grid balancing by large-scale integration of hydrogen technologies in the underutilized Spanish electrical grid. The study identified a 'critical ratio' to determine the power generation for given demands according to daily demand curve profiles and how much of this can be regulated by hydrogen. The results suggested that as much as 42% of energy in the Spanish system could be regulated by decarbonized sources such as large-scale hydrogen production³⁰. A related study suggested that in using electrolysis to produce hydrogen as a grid balancing technique, Spanish utilities could multiply the amount of electricity regulated without adding capacity³¹. Future scenario analyses performed by British researchers looked at possible UK energy supply pathways up until 2050. All of the scenario results suggested that if the UK were to avoid being heavily dependent on imported fossil fuels, then large amounts of hydrogen would need to be produced by electrolysis using excess energy from the UK's electrical grid. The UK therefore views electrolysis as a beneficial DSM technique and predict it could be a common practice by 2030³². Applying DSM in the UK electrical grid opens up opportunities to reduce generation margin, improve transmission and distribution functions and drive investment costs downward. It is also expected that applying DSM in the UK will lead to more improvements in communication technology along the grid and relieve stress on the aging grid and infrastructure in place³³. NREL was able to demonstrate the effectiveness of electrolyzers acting as demand response devices due to fast response rates and long durations. The exceptional operational performance led the researchers to claim that at least all PEM electrolyzers should qualify to participate in all regulation and reserve energy markets²⁴.

A MATLAB SIMULINK model was developed of a steam turbine generation unit and simulated a scenario in which a sudden loss of generation occurred and an electrolysis unit was used to stabilize the grid's frequency. The results showed that a pressurized alkaline electrolysis unit could respond sufficiently, even without a spinning reserve as a backup in the system. The same research team also suggested that pressurized alkaline electrolysis when used as a dynamic demand response technology could help in the reduction of spinning reserves required to support an electrical power system³⁴. Life cycle assessments were performed on two power to gas scenarios being considered in Canada. Hydrogen storage systems linked to wind and hydroelectric power were proposed and their global warming potential (GWP) was calculated. It was noted that emissions are only accumulated in the construction/production portion of the project, as emissions are negligible during operation. The total GWP for the wind dependent system was 152×10^6 kg CO₂ equivalent over its entire lifetime (20 year assumption) compared to a measured GWP for a typical coal power plant is 964 g CO₂ eq/kWh³⁵.

The above examples from previous research demonstrate that electrolytic hydrogen production is a clean and sustainable DSM or grid balancing technique. Hydrogen is an easily produced medium with the capability to generate and regulate electricity through load shifting. Research from European countries suggest that electrolysis, regardless of the hydrogen's end use will be pivotal in future energy infrastructure. The implementation of electrolysis will strongly depend on regulatory energy authorities and the available spot markets for DSM technologies like electrolysis to be competitive in. Expected challenges for DSM include lack of advanced metering, control and communication methods as well as undeveloped or inadequate market structures. There is also a notion that DSM technologies will add a degree of complexity to the system operation as compared to traditional operating standards³³.

METHODS

2.8 Electrical Grid System Boundaries

In order to discuss methods to assist electrical grids, it is important to first understand the European electrical grid in general and highlight some challenges that need to be addressed for a continued secure electrical network. An electrical grid can be broken down into transmission networks and distribution networks, and European electrical grids are kept at a constant 50 Hz. The task is to manage this 50 Hz effectively between the transmission and distribution networks in order to maintain complete system balance. The transmission system boundaries are defined by the transmission lines and the substations where transformers step the power down to the lower voltage distribution lines. Europe's transmission networks are typically operated at 400 kV and can span across many regions or countries. The distribution system is then responsible for taking the lower voltage power from the transmission lines and carrying it on to the end consumer. The system boundary for this can be defined as the entire infrastructure necessary to move energy from the physical connection with the transmission system to the furthest expected customer in the distribution systems coverage area. These include low, medium and high voltage distribution lines.

2.8.1 Electrolysis Review

A literature review was performed to collect information on hydrogen production processes from renewable energy including geothermal. Electrolysis was selected as the focus due to its wider applicability, mature technology and also emerging potential. Other hydrogen production processes considered were thermochemical cycles and hydrogen liquefaction however these were dismissed due to high heat requirements that geothermal cannot regularly produce. The literature review revealed that three electrolysis techniques were the most researched and documented, and therefore they were chosen as the primary focus of the research. These include Alkaline, PEM and HTE electrolysis. Other specialized technologies like Anion Exchange Membrane (AEM) were not included because there was a lack of information and recognition as a useful electrolysis technique. During the research on the different types of electrolysis, sources were analyzed for performance

parameters, cost and real world applications. Special emphasis was placed on performance in order to be candidates as an applicable DSM technique.

2.8.2 Case Study

Essentially, a model was created using Excel, to show hydrogen production prices per kg as a function of bidding additional capacity in Iceland's regulating power market. The control variable was considered as each case's hydrogen production price as a function of not participating in the regulatory power market and therefore not generating revenue. Other models exist such as the Department of Energy's H2A model, however it was determined that a simpler model would be sufficient to estimate production hydrogen production prices. The H2A model considered revenue from hydrogen selling and also assumed either compression or storage for hydrogen vehicle gas stations. There was no profit from hydrogen sales calculated into the model and neither end use assumed in the H2A was comparable to the hydrogen's end use intended in this study.

A constant dialogue was maintained with companies involved in this research including Landsvirkjun, Landsnet and the Iceland Innovation Center, all located in Reykjavik, Iceland. Data was obtained from a publicly available database on Landsnet's website. Relevant data included the price of electricity per MWh for each hour of an entire year (November 1, 2014 to October 31 2015). These values were plotted in Excel and graphed with a scatterplot to visually see the prices per year and any correlations that may be associated. Another scatter plot, Figure 6 was also created with five years (2010-2015) worth of price data to be analyzed for up and down regulation trends.

2.8.3 Electrolysis Methods

From the literature review, it was determined that an atmospheric pressure alkaline electrolyzer would be the most appropriate technology for this analysis, because of its demonstrated ability to increase capacity within the required timeframe defined by Landsnet to be a regulating power entity and its lower capital cost than PEM. The electrolyzer's specifications can be seen in Table 4. Designed by NEL Hydrogen, the electrolyzer has a rated production capacity of 485 Nm³/h of hydrogen and operates at atmospheric pressure. Pressurized systems were taken into consideration, however decided against due to increased capital costs.

Table 4: Characteristics of NEL atmospheric pressure alkaline electrolyzer.

Max Capacity (Nm³/h of H₂)	485
Electrical energy consumption (kWh/Nm³ H₂)	4.1-4.75
Electrical energy consumption (kWh/kg H₂)	49.0
Power consumption (MW)	2.2
Operating range (%)	20-100%
Start up time (min)	<10
Expected parts lifetime (electrodes and membrane)	10 years

Operation is assumed to remain at 80 C and use 25% KOH electrolyte solution in the cell. The four cases studied, described in Table 5 were then identified on the based on the number of electrolyzers.

Table 5: Cases studied for analysis.

Number of electrolyzers	1	5	10	20
Power consumption (MW)	2,3	11,5	23	46
Production capacity (Nm ³ /h)	485	2.250	4.500	10.000

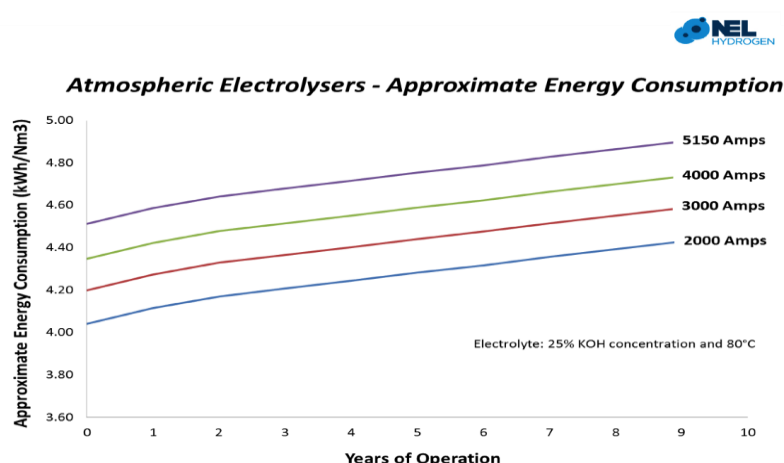


Figure 8: NEL electrolyzer approximate energy consumption.

Using both Excel models in conjunction, arbitrary prices were entered to show a hypothetical scenario in which it would be favorable for the electrolysis plant to bid in the regulating power market for either up or down regulation. During periods in which the electrolysis plant is not submitting bids, or a submitted bid is not accepted, capacity was assumed to be at 100%, and therefore producing 485 Nm³ hydrogen gas per hour and consuming on average 4.75 kWh/Nm³ for the single electrolysis unit case. If a bid is accepted, the capacity is assumed to be 20%, thus producing 97 Nm³ hydrogen per hour and consuming on average 4.10 kWh/Nm³ for the single electrolysis unit case. Figure 8 shows the electricity consumption rates assumed through different operating electric currents over the electrolyzer's expected lifetime. From Figure 8, it is assumed that energy consumption in year 5 will be used as an average for the lifetime of the electrodes and membranes in the electrolysis unit.

The NEL alkaline electrolyzer was partly chosen because of its relatively quick start up time and its demonstrated ability to perform at 20-100% capacity. This then allowed the analysis to utilize the 80% capacity in between for regulating power via submitted and accepted bids. It is assumed that production will be continuous and therefore never lower than 20% operation.

2.8.4 Capital Cost

Capital cost was calculated by taking the sum of the electrolyzers and the building necessary to house the equipment. Electrolyzer cost was calculated on a

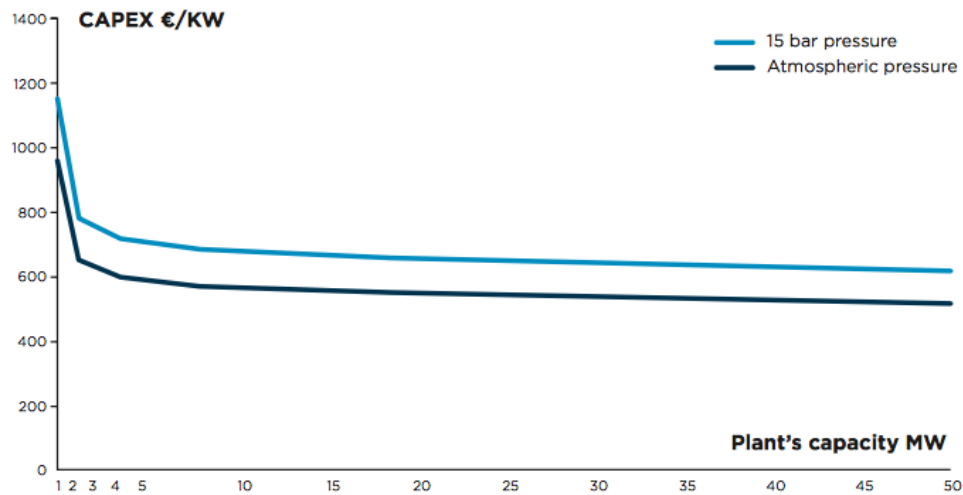


Figure 9: Electrolyzer CAPEX (€/kW) compared to plant capacity (MW)

€/kW basis following Figure 9 from NEL Hydrogen manufactures specifications sheet. From this figure, it is clear that after about 10 MW plant capacities, the price per kW becomes relatively fixed for both atmospheric and pressurized plants. Included in the electrolyzer cost is all auxiliary equipment. Auxiliary equipment includes the water supply with deionizer, gas processing equipment and small storage tank. Table 6 summarizes the capital costs assumed for each scenario in the economic model.

Table 6: Cost assumptions used for each case including auxiliary equipment.

Number of electrolyzers	1	5	10	20
Power consumption (MW)	2,3	11,5	23	46
Price assumed (€/kW)	680	550	530	515

2.8.5 Total Manufacturing Costs

Total manufacturing costs were calculated as the sum of electricity costs, fixed costs and annualized capital cost. A full year of operation (8760 hours) is assumed. Revenue from bids were then included and/or not included depending on any of the analyses' objectives. The total manufacturing costs was then divided by hydrogen production totals respective to each production totals (either 20% or 100%).

2.8.6 Electricity Costs

The transmission fees are based on the amount of power drawn from the grid by distributors and power-intensive industries at specified delivery points. There are two types of charges: a capacity charge and an energy charge and both are independent of distance traveled by the power through the grid. The capacity charge is calculated on the basis of the average of the four highest 60-minute monthly power

peaks of the year for each delivery point. The energy charge is calculated from each MWh transmitted via Landsnet's grid. A fixed annual delivery charge is payable for all supply/delivery points connected to the grid, whether for power supplied into or drawn from it. There is also a charge for ancillary services and transmission losses, at a fixed amount per each kWh drawn from the grid. The purpose of this charge is to cover the expense of Landsnet's purchasing of these services at any given time. The tariff for consumption by power-intensive industries is in US dollars. Table 7 shows the electricity costs and tariffs assumed in the financial model. All tariff prices were publicly available online at Landsnet's website, and electricity price was assumed to be about 43\$/MWh.

Table 7: Electricity costs and tariffs assumed in financial model

Electricity from grid (€/MWh)	40
Transmission capacity charge (\$/year)	55.395
Transmission delivery charge (\$/MW/year)	32.268
Transmission energy charge (\$/MWh)	1.63
Ancillary service charge (€/MWh)	0.33
Transmission losses charge (€/MWh)	0.63

2.8.7 Fixed Costs

Fixed costs assumed were for maintenance, insurance and permits, as well as operating personnel. Maintenance and permitting costs were assumed to be 1.5% of total CAPEX based on EU recommendations. Personnel costs were assumed to be €55,000 fixed salary to each operator. At maximum 4 operators were assumed to be necessary for the larger plants to maintain round the clock operation. Annualized capital cost was calculated and numerically describes the cost to purchase, install, maintain and later dispose of the asset over its lifetime. A 6% interest rate over a 20-year period was assumed and taken into consideration for this calculation, which was then added to the total production cost. Revenue is also generated from simply agreeing to be a regulating power entity, and therefore an additional 436 ISK/MWh for remuneration is included in calculations.

2.8.8 Model Limitations

One of the problems with the methodology is that the excel model assumes that all bids are accepted in the calculations. This presents then a most optimistic analysis of these electrolysis cases. It is of course, inappropriate to assume that the regulatory power market will accept every bid submitted from this particular electrolysis plant. Therefore it is necessary to factor some real world scenarios into this economic evaluation. One way to do so is to say that a percentage of bids would be accepted. Calculations were made to show the prices if 75%, 50%, and 25% of the bids were actually expected. These percentage scenario approaches were used in this research to add more realism to the cases studied and as a comparison to the most optimistic scenario, which is the main focus of this research. It is also assumed that Iceland's regulating power market has enough room to absorb the addition of capacity up to the largest case study at 46 MW, which may be unrealistic since up regulating power is seldom more than 20 MW.

Results

2.9 CAPEX

From the NEL capital costs graph mentioned above, see Figure 9, CAPEX was calculated for each scenario. Table 8 shows the associated CAPEX for the four size scenarios studied in this analysis.

Table 8: CAPEX associated with the different proposed case studies

No. of electrolyzers	1	5	10	20
Electrolyzer max power (MW)	2,3	11,5	23,0	46,1
Area of building (m2)	150	667	1334	2668
Cost of installed electrolyzer with auxiliary equipment (€/kW)	680	550	530	515
No. of operators	1	2	2	4
CAPEX eletrolyzers				
Electrolyzers with auxiliary equipment (€)	1.566.550	6.335.313	12.209.875	23.728.625
Building* (€)	160.256	712.607	1.425.214	2.850.427
Total CAPEX electrolyzers	1.726.806	7.047.919	13.635.089	26.579.052
* Building cost of 150.000 ISK/m2 is assumed				

As would be expected, larger capacity plants with more electrolysis units will have a higher capital cost and will need more personnel on site to maintain constant operation. What is unique to these scenarios is that there is a very small benefit from scaling up in terms of the price of electrolyzer per kW. There is a large decrease between one unit and five units, however after five units, the price does not reduce much with added capacity. This suggests that the five to ten unit range may be ideal candidates for further evaluation. It is also important to notice that the majority of the capital costs are in the electrolyzer and not in the building or other infrastructure needed. More specifically, the majority of the electrolyzer cost is in the cell, and it is anticipated that these costs will go down in the future with further cell development. The numbers indicate that an electrolyzer plant with 5 electrolyzers is also more in line with the regulating power needed in the Icelandic context.

2.9.1 Electricity Charges

The price of electricity from the grid is kept constant at 40€/MWh from Landsvirkjun. Table 9 presents the amount expected for wholesale electricity from the grid for each scenario for an entire year of operation.

Table 9: Wholesale electricity costs for each case assuming operation at 100% capacity and 8760 hours per year and electricity price of 40€/year

Number of electrolyzers	1	5	10	20
Electricity cost €/year	805.920	4.029.600	8.059.200	16.118.400

Other electricity charges associated are presented in Tables 10 and 11. These prices are unavoidable and will be charged by Landsnet throughout the lifetime of the operation. The delivery charge is the same for all the scenarios and the rest of the

costs increase as capacity increases. From the table it can be seen that as the number of electrolysis units increases, the total amount of tariff's decreases per MWh.

Table 10: Additional electricity charges expected for each case assuming operation at 100% capacity and 8760 hours per year

Number of electrolyzers			1	5	10	20
Rated Capacity (MW)			2,3	11,5	23	46
Transmission charges						
Delivery charge	55.395	USD/year	55.395	55.395	55.395	55.395
Capacity charge	32.268	USD/MW/year	74.216	371.082	742.164	1.484.328
Energy charge	1,632	USD/MWh	32.882	164.408	328.815	657.631
SUM		USD/year	162.493	590.885	1.126.374	2.197.354
		EUR/year	153.442	557.974	1.063.638	2.074.965
		EUR/MWh	7,62	5,54	5,28	5,15

Table 11: Ancillary Service and Transmission losses charges for each case assuming operation at 100% capacity and 8760 hours per year

Rated Capacity (MW)		2,3	11,5	23	46
Ancillary Service (45,64 ISK/MWh)*		6.550	32.748	65.495	130.991
Transmission Losses (87,87 ISK/MWh)*		12.610	63.049	126.097	252.194
Sum (€)		19.159	95.796	191.593	383.185
*Prices calculated in ISK then converted to €					

Manufacturing Costs		1 electrolyser	5 electrolyzers	10 electrolyzers	20 electrolyzers
Operating hours/year	8.760				
Electricity costs					
Electric energy cost	40 €/MWh	807.234 €/year	4.036.170 €/year	8.072.340 €/year	16.144.680 €/year
Transmission capacity charge	55.395 \$/year	52.310 €/year	52.310 €/year	52.310 €/year	52.310 €/year
Transmission delivery charge	32.268 \$/MWh/year	70.197 €/year	350.985 €/year	701.970 €/year	1.403.939 €/year
Transmission energy charge	1,632 \$/MWh	31.101 €/year	155.504 €/year	311.007 €/year	622.015 €/year
Ancillary service charge	0,33 €/MWh	6.195 €/year	30.974 €/year	61.948 €/year	123.896 €/year
Transmission losses	0,63 €/MWh	11.927 €/year	59.634 €/year	119.268 €/year	238.536 €/year
Fixed Costs					
Maintenance	1,5% of CAPEX	25.902 €/year	105.719 €/year	204.526 €/year	398.686 €/year
Insurance/Permits	1,5% of CAPEX	25.902 €/year	105.719 €/year	204.526 €/year	398.686 €/year
Personnel	55.000 €/operator	55.000 €/year	110.000 €/year	110.000 €/year	220.000 €/year
Annualized Capital Cost	Interest Rate				
Electrolysis plant	6%	150.551 €/year	614.470 €/year	1.188.769 €/year	2.317.283 €/year
Revenue from balancing market					
From bids	X	- €/year	- €/year	- €/year	- €/year
From regulating power option	436 ISK/MWh	(50.136) €/year	(250.680) €/year	(501.359) €/year	(1.002.718) €/year
Total Manufacturing Cost		1.186.182 €/year	5.370.804 €/year	10.525.305 €/year	20.917.312 €/year
Hydrogen Production					
		4.248.600 Nm3/year	21.243.000 Nm3/year	42.486.000 Nm3/year	84.972.000 Nm3/year
		382 tonne/year	1.910 tonne/year	3.819 tonne/year	7.639 tonne/year
Manufacturing Cost/Unit H2					
		0,279 €/Nm3 H2	0,253 €/Nm3 H2	0,248 €/Nm3 H2	0,246 €/Nm3 H2
		3,106 €/kg H2	2,812 €/kg H2	2,756 €/kg H2	2,738 €/kg H2
		93,2 €/MWh	84,4 €/MWh	82,7 €/MWh	82,1 €/MWh

Table 12: Excel spreadsheet including all parameters used for cost analysis and displaying manufacturing costs without revenue (highlighted in yellow)

2.9.2 Hydrogen Production Prices

The Excel model was designed in a way to be able to enter a hypothetical bid price and display the corresponding manufacturing price in €/kg. Table 12 shows all of the variables included in the calculation of the manufacturing price. 'X' is entered in the "revenue from bids" cell to show prices without any income from the regulating market. The results show that manufacturing costs range from 2,7 – 3,1 €/kg with the 20 unit electrolysis plant case having the lowest expected cost of 2,74 €/kg.

The regulating power market works by bids being submitted each hour of the day and the price per MWh of regulating power can vary significantly throughout the day, month or year. Entering different values into the "revenue from bids" cell in the Excel spreadsheet changed the production totals and manufacturing costs. Figure 10 shows the manufacturing price of each case at different bid prices. The 2,3 MW case with only one electrolyzer has the highest cost and this can be attributed to the annualized capital cost taken into consideration in Table 12. All scenarios show a positive upward trend from a minimum at about 6000-7000 ISK/MWh in manufacturing cost due to a higher bid price, and this is inversely correlated with frequency of bids at those higher prices. The 11,5 MW case seems to show the most promising economics out of all the cases. Even though it does not have the lowest production price, it displays the same price trends as the other cases but has the second lowest capital cost, considering also that the volume of the regulating power is about 20 MW for upward regulation. Figure 11 looks at production costs specifically related to the 11,5 MW case as a function of electricity price per MWh. As electricity price increases, production price increases as well going up to as much as 3,00€/kg hydrogen without including revenues from accepted bids. In Landsvirkjun's 2014 annual report, it is stated that the average electricity price for industries in Iceland was 24,5€/MWh. This would then correlate to an average price production cost at about 2 €/kg whereas it would be about 2.8€/kg if the electricity price is the same as in new industry contracts as stated by Landsvirkjun.

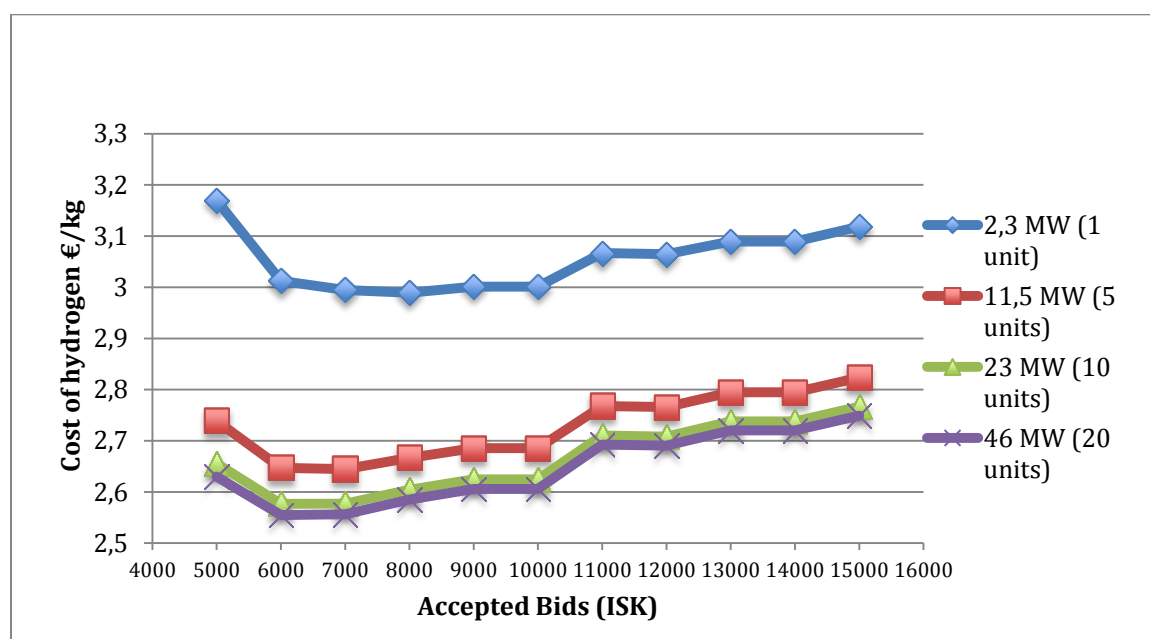


Figure 10: Manufacturing cost of hydrogen for each case including revenue from bids

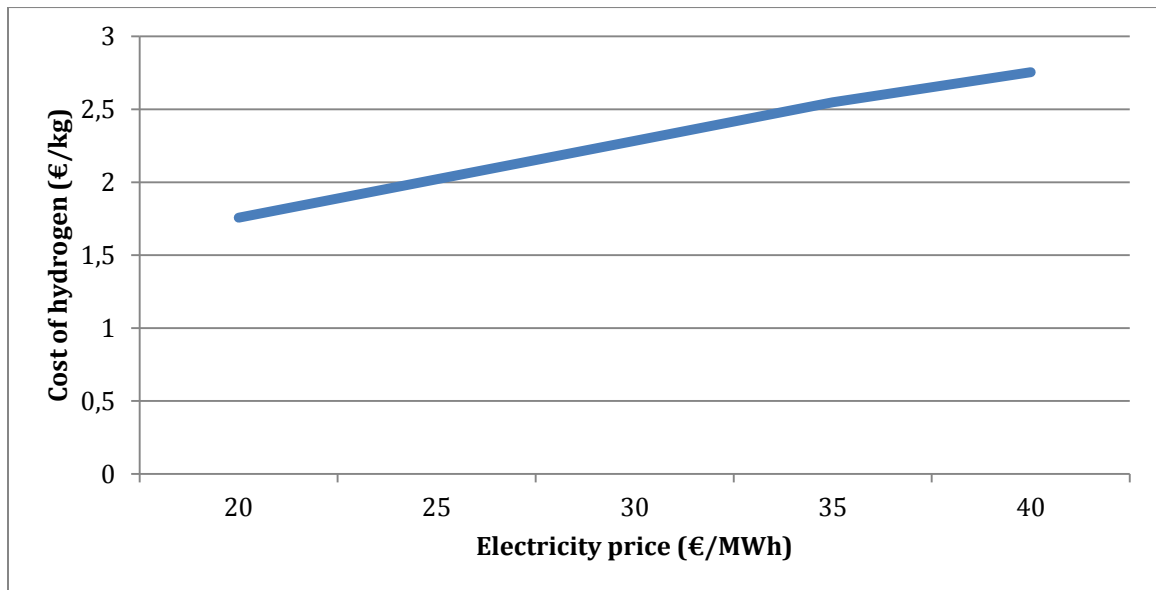


Figure 11: Production price as a function of electricity price per MWh for the 11,5 MW (5 unit) case

2.9.3 75%, 50%, 25% Scenarios

Figure 12 shows the results of the scenarios that were applied in an attempt using a self-developed method to make the data more realistic. As expected, the larger the percentage of bids submitted that are accepted yields the lowest manufacturing costs at a 6000 ISK bid scenario. All of the scenarios still resulted in prices being mainly below 3€/kg.

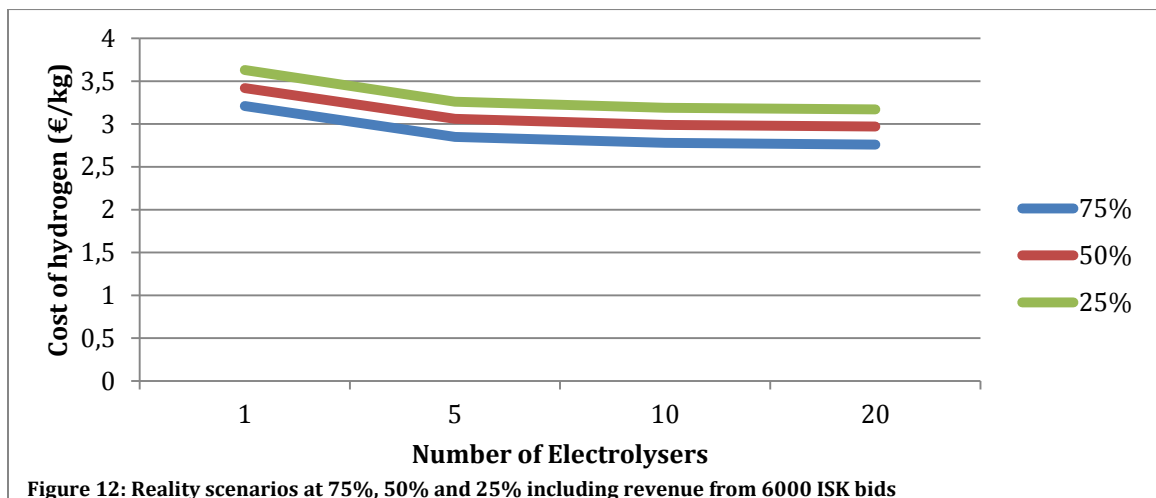


Figure 12: Reality scenarios at 75%, 50% and 25% including revenue from 6000 ISK bids

2.9.4 Wholesale Electricity Price

Manufacturing costs including bid revenue are presented in Figure 13 from a wholesale electricity cost point of view. All of the electricity prices show a distinct rise around the 10.000 ISK mark and exhibit positive slopes as bids become higher. The two highest electricity price cases (35 and 40 MW) show decreasing prices between the 5000 and 6000 ISK bid prices due to the frequency of bids at this price indicating cheap up-regulation.

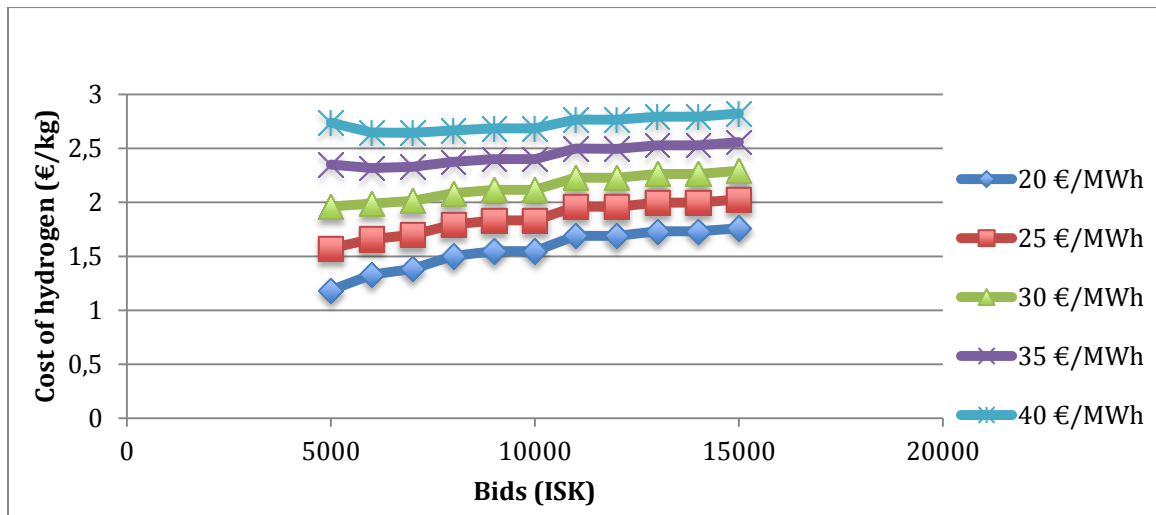


Figure 13: Manufacturing price at different wholesale electricity prices including revenue from bids

2.9.5 Historical Regulating Power Market Prices and Trends

Regulating power market prices are provided on Landsnet's website in a database. Figure 14 shows the prices for each hour for five years (2010-2015). Two separate trends from the data can be observed. Two zones can be seen clearly in the scatterplot. The first zone includes lower prices <3000 ISK and these are attributed to bids for down regulation, or when the electrical grid has too much supply and not enough demand. Higher prices >3000 ISK indicate bids for up regulation where there is not enough supply to match demand. In this up-regulation scenario, the electrolyzers in this study would send power back into the grid with a submitted bid into the regulating power market. From this scatterplot it is clear that over the years the prices for regulating power have been increasing especially in the up-regulation market. This suggests that as bid price increases, frequency of bids at that price may increase as well, and this would significantly benefit the electrolysis plants in this case study by having lots of high price bids available for the regulating power market.

2.10 Discussion/Conclusion

In the future, as renewable energy penetration increases and hydrogen demand increases as well, water electrolysis technologies could serve as flexible energy balancing mechanisms that simultaneously produce gaseous hydrogen.

Alkaline electrolysis has shown capability as a DSM technique, and it is very likely that DSM techniques will be necessary in the future as society aims to reduce consumption. The IEA Demand Side Management Program (IEADSM) is a task force program that was developed by the IEA under the framework of the Economic Cooperation and Development (OECD). The program currently consists of 25 member countries and its primary aim is to research, develop and demonstrate new and energy efficient end use schemes. Participating countries acknowledge goals in the form of Energy Efficiency Obligations (EEO) contracts. An EEO therefore operates as a regulatory mechanism that pushes a country to meet energy saving targets by implementing end-use energy efficiency measures. Currently, Iceland is not involved in the IEADSM. Despite Iceland's exceptional renewable energy profile,

participating in such a program could still be beneficial particularly in efficient end-use schemes.

A financial model of water electrolysis as a DSM technique has been created to estimate hydrogen production costs from alkaline electrolysis while competing in Iceland's regulatory power market. A literature review of current electrolysis technologies was also performed in order to select an appropriate electrolysis technology for the financial assessment. Atmospheric alkaline electrolysis was chosen over PEM and HTE because of its lower capital cost and fast start up and response times. Landsnet defines that an energy regulating entity must be able to meet TSO requests in less than 10 minutes, and the chosen technology has proven to be able to do so. Results indicate that without revenue from bids, manufacturing costs range from 2,7-3,1 €/kg. Including revenue from bids can bring the costs to be lower than 2€/kg. This suggests that participating in the regulatory power market can be beneficial in driving costs down. Wholesale electricity prices need to be lower in order to drive down production prices and correlates positively to production price, and this can be achieved by coupling with renewable energy. The analysis mainly took into consideration up-regulation bid because of the allure of higher profits, however with the frequency of less expensive bids for down-regulation, it could be worthy to approach this research again focusing on down-regulation. Of all the cases, the 11,5 MW case shows the most promise and realism for future consideration due to the second lowest capital cost and the fact that the volume of the regulating market can currently support this.

Iceland currently regulates its power with hydropower reserves leaving not a lot of diversity in the regulating power market. These reserves can be called upon much quicker than alkaline, but about the same time as PEM electrolysis. With competition lacking, there is really only a primary regulating power market in Iceland compared to the rest of Europe that has secondary and tertiary regulating power markets with different start up time regulations in each. It could be informative to investigate PEM electrolysis further with this analysis because PEM capital costs are expected to decrease in the future, and it could be competitive with Iceland's hydropower reserve as a regulating power entity.

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