3-2021

An Analysis of Various Hydrogen Production Methods for Fleet Vehicle Fuel

Eugene J. Denezza II

Recommended Citation

Denezza, Eugene J. II, "An Analysis of Various Hydrogen Production Methods for Fleet Vehicle Fuel" (2021). *Theses and Dissertations*. 4941.
https://scholar.afit.edu/etd/4941

AN ANALYSIS OF VARIOUS HYDROGEN PRODUCTION METHODS FOR FLEET VEHICLE FUEL

THESIS

Eugene J. DeNezza, II, Second Lieutenant, USAF

AFIT-ENV-MS-21-M-216

DEPARTMENT OF THE AIR FORCE
AIR UNIVERSITY

AIR FORCE INSTITUTE OF TECHNOLOGY

Wright-Patterson Air Force Base, Ohio

DISTRIBUTION STATEMENT A.
APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED.

AFIT-ENV-MS-21-M-216

AN ANALYSIS OF VARIOUS HYDROGEN PRODUCTION METHODS FOR FLEET VEHICLE FUEL

THESIS

Presented to the Faculty

Department of Systems Engineering and Management

Graduate School of Engineering and Management

Air Force Institute of Technology

Air University

Air Education and Training Command

In Partial Fulfillment of the Requirements for the

Degree of Master of Science in Systems Engineering

Eugene J. DeNezza, II, BS

Second Lieutenant, USAF

December 2020

DISTRIBUTION STATEMENT A.
APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED.

AFIT-ENV-MS-21-M-216

AN ANALYSIS OF VARIOUS HYDROGEN PRODUCTION METHODS FOR FLEET VEHICLE FUEL

Eugene J. DeNezza, II, BS

Second Lieutenant, USAF

Committee Membership:

Major John X. Situ, PhD
Chair

Lieutenant Colonel John E. Stubbs, PhD
Member

Lieutenant Colonel Clay M. Koschnick, PhD
Member

AFIT-ENV-MS-21-M-216

Abstract

As conflict, the environment, and politics cause changes around the world, the United States Air Force is pursuing a diversification of drop-in and alternative fuel sources. Hydrogen fuel cells for vehicles are gaining popularity worldwide. Yet, how to best produce hydrogen gas still remains a question. This thesis will provide an overview of various hydrogen production methods and their respective environmental impacts, costs, efficiencies, and viability; and will perform sensitivity analysis to determine an optimal solution. Analysis was performed utilizing Excel enabled with macros, with decision analysis weights determined from the current United States Air Force energy goals from the Energy Flight Plan: 2017-2036 [1]. The optimal production method is Thermolysis followed by Steam Reformation of Landfill or Natural Gas, Coal Gasification, and PEM Electrolysis. Based on varying requirements the recommended options for U.S. Air Force consideration are Thermolysis if nuclear power is available, Steam Reformation of Landfill Gas, and PEM Electrolysis. Steam Reformation of Natural Gas is only recommended for use in non-contested environments. PEM Electrolysis is extremely promising due to its portability and required inputs of only water and electricity.

Acknowledgments

I would like to thank Lieutenant Colonel Torrey Wagner for his guidance during the Spring Semester, and Major John Situ for his guidance once Lt Col Wagner retired starting Summer of 2020. The expertise, review, and feedback of both Lt Col Wagner and Maj Situ was invaluable. I would also like to thank the Department of Systems Engineering and Management faculty that have taught me the past year and a half which provided an incredible foundation for critical thinking, insight into systems engineering and small unmanned air system design, and an introduction to scholarly research.

Eugene J. DeNezza, II

Table of Contents

Page

List of Figures

Page

List of Tables

Page

AN ANALYSIS OF VARIOUS HYDROGEN PRODUCTION METHODS FOR FLEET VEHICLE FUEL

I. Introduction

Background

The Department of Defense (DoD) is researching new methods of sustainably fueling its warfighting capabilities at home and abroad. The US Air Force is the largest consumer of fuel in the Department of Defense at an average rate of 2 billion gallons per year, with roughly 4 million gallons devoted to ground vehicles [2]. The massive consumption of fuel has resulted in a Pentagon lead effort under Air Force Operational Energy organization to champion energy-informed solutions that increase combat capability across the force [2]. Hydrogen gas can be produced using only water and electricity providing a new source of fuel with environmental benefits, a possible long-term solution to the inevitable exhaustion of Earth's oil reserves, and a continuous method of worldwide fuel production. Despite its low volumetric density, H_2 (hydrogen gas) has a high gravimetric energy density or more energy per unit of mass when compared with hydrocarbon fuels, making it a promising replacement for fossil fuels. Hydrogen technology provides a source of ground vehicle fuel that can be produced anywhere with a feedstock of only electricity and water, with no emissions from use, has a refuel time similar to gasoline, and is a proven technology [3]. Manufacturers like Toyota are producing hydrogen vehicles like the *Mirai*, and the industry is starting to build hydrogen stations throughout California. Although the combustion of H_2 gas produces water and no greenhouse gases (GHG), certain productions methods of H_2 gas produces varying amounts of Greenhouse Gas Emissions, depending on the means of production and power source utilized.

Hydrogen's Problem

Why has hydrogen fuel cell technology not widespread with these benefits? Numerous authors site that hydrogen is limited by the supply and demand cycle. There are 8,486 hydrogen cars in California and 46 hydrogen stations in highly populated areas as of December 1, 2020 [4]. This means economies of scale do not exist and ownership of hydrogen vehicles is limited to those who both can afford a near $50,000 vehicle and live in highly populated areas of California where stations exist. Limited hydrogen stations also result in low demand for hydrogen, which in turn leads to a lack of investment in new hydrogen technology. Politically there is little interest in hydrogen, while the lobbying power of the oil industry is significant. Companies like Nikola have received Department of Energy grants for their work to build a hydrogen economy, but in the United States the oil industry holds immense political power. On average each Republican Senator received a donation of $88,533 while their Democratic counterparts received on average $10,122, with 96 Senators from both parties receiving donations from the oil industry [5]. In the House, 382 out of the 435 members have received contributions from the oil industry [5]. In 2019, the total expenditures in contributions of the oil industry into lobbying was $125,733,359, with $19,212,899 going to campaign contributions [5].

Growth of Hydrogen

Even with these obstacles, the consumer use of hydrogen ground vehicles has begun expanding especially in the freight industry. American startup, Nikola, is heavily investing in hydrogen freight truck production releasing two prototype designs which received over 13,000 advanced orders [6]. Nikola plans to build over 700 hydrogen stations across the United States and Canada by 2028, and will be releasing a fuel cell pickup truck in early December 2020 [7] [6]. California plans to open 100 hydrogen fueling stations by 2024 and have one million fuel cell vehicles on the road by 2030 beginning the growth of American residential fuel cell vehicles, Japan is building 80 new hydrogen refueling stations, Hyundai is launching a fleet of freight trucks and a car powered by hydrogen, and Germany is building a hydrogen refueling station for hydrogen powered buses [8]. With companies like Nikola, Toyota, Hyundai, and Honda investing in hydrogen technologies; the cycle of supply and demand issues with hydrogen appears like it will break in the coming decade. The histogram below shows the cumulative sales of hydrogen residential cars in the US markets, demonstrating an increasing trend in purchases of hydrogen fuel cell vehicles.

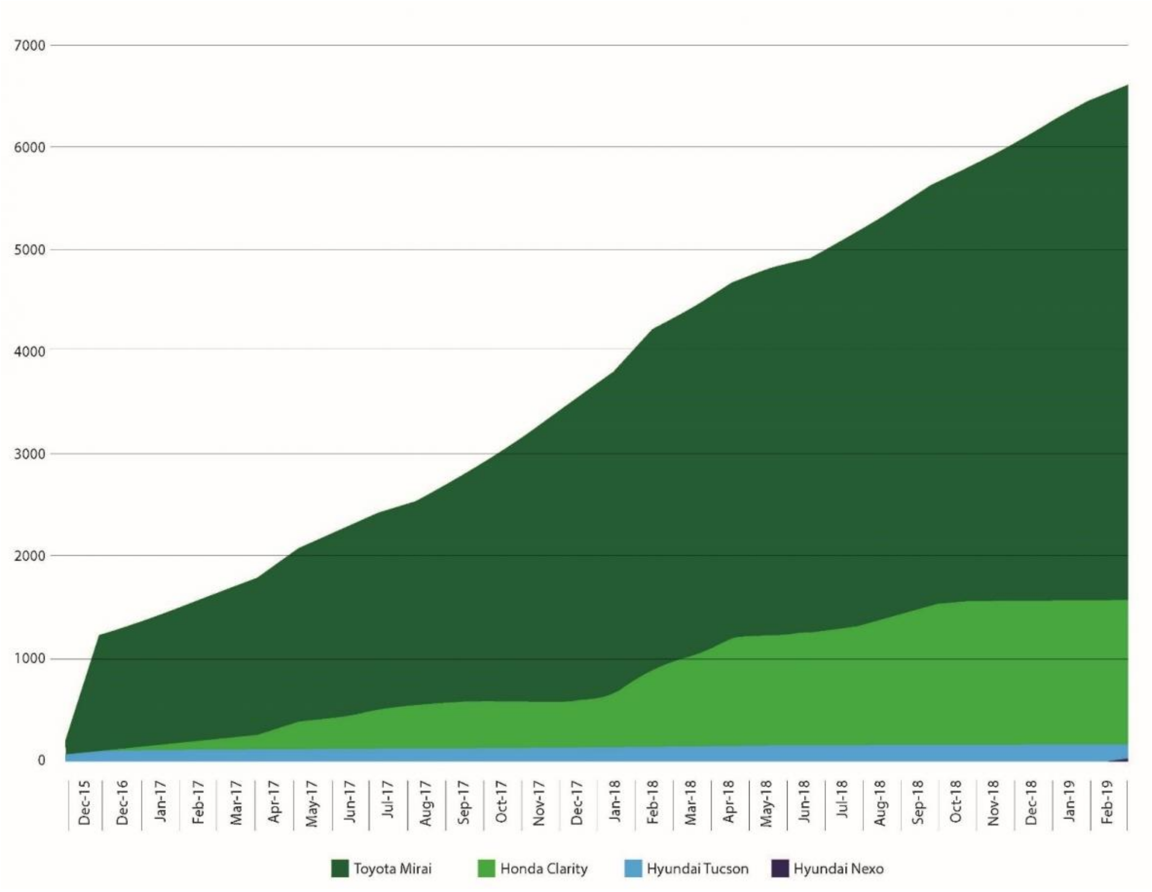


Figure 1: Cumulative Sales in the US from December, 2015 to February, 2019 [8]

H_2 is not just a possibility for cars, it is becoming the frontrunner for zero emission flight. Airbus, who is pushing for zero emissions flight by 2035, recently released three concepts it has for hydrogen powered aircraft shown in Figure 2 [9].

Figure 2: Concepts of Hydrogen Planes Released by Airbus [9]

The largest is a turbofan jet, much like the current A321neo, and a flying-wing concept both with a range of 2,000 nautical miles and a capacity of 200 souls [10]. Additionally, a smaller turboprop design was released with a 1,000 nautical mile range and a capacity of 100 souls [10]. Chief Executive Officer Guillaume Faury stated, “I strongly believe that the use of hydrogen – both in synthetic fuels and as a primary power source for commercial aircraft – has the potential to significantly reduce aviation’s climate impact” [10]. In an interview with CNN, Airbus’s chief technology officer Grazia Vittadini stated regarding hydrogen turbines, “it’s particularly important to combine…direct combustion of hydrogen through modified gas turbines, with an embedded electric motor, powered by fuel cells…to accelerate on this path, we already have in the pipeline a zero-emission demonstrator, which will be fundamental, especially to de-risk concepts such as refueling of such an aircraft and safe storage and distribution of hydrogen on board an aircraft” [11]. Airbus plans to test the aircraft in 2025 and have the aircraft enter service by 2035. Yet, the success of hydrogen powered aircraft is dependent on hydrogen manufacturing and the buildup of hydrogen infrastructure.

Problem Statement

The expansion of hydrogen's potential market to both residential and commercial ground vehicles, and aerial vehicle leaves the question: How should hydrogen be produced? This thesis will perform an analysis on various hydrogen production methods utilizing a decision analysis method to determine if there is an optimal solution or, at minimum, what solutions should be pursued.

Research Objectives and Questions

Hydrogen productions methods vary in their degrees of readiness to enter full production. This thesis will examine which production methods are currently viable and which production methods are not viable due to limited production ability, incomplete technical research, or extreme cost. Since the Air Force has not released a specific decision criterion for the pursuit of alternative fuels a question this thesis will answer two key questions: (1) What are the critical aspects of the decision analysis from an U.S. Air Force perspective? (2) What parameters, and weights of the aforementioned parameters will be utilized in the Decision Analysis portion? Finally, through the utilization of Sensitivity Analysis to determine robustness, is there a general optimal solution for the U.S. Air Force that stands out even with varying value hierarchies?

Research Methodology

First, research into current hydrogen production methods will be performed to gather key values such as cost, efficiency, and environmental impacts for each method utilizing a SMART method. Second, these values will be normalized. Third, analysis will be performed. The analysis will consist of both a user inputted weight calculation to find the optimal method based on value focused thinking, and sensitivity analysis for each weighted category to determine robustness of the result. Finally, an examination of the results and sensitivity analysis along with U.S. Air Force specific needs will determine if there is an optimal solution or what solutions should be pursued.

Limitations and Assumptions

Hydrogen as an alternative fuel has many varying areas of research such as the production of hydrogen, transportation, storage, comparison to other fuel sources, and numerous other subsets of research. This thesis will only compare hydrogen production methods. It will not compare hydrogen to electrical or petroleum-based fuels, the storage of hydrogen, the safety of hydrogen fuel cells, or the transportation of hydrogen gas. A critical assumption in this thesis is that each weighted category is independent from the other weighted categories. This assumption is primarily utilized in this thesis’s sensitivity analysis.

Expected Contributions

Although individual hydrogen production methods have been researched, there is incomplete research on a total comparison between the numerous production methods considered in the energy community. First, this thesis will provide an initial and baseline approach of the various methods available to date. Second, the research from this thesis will provide the first Air Force specific analysis of hydrogen production to date. Third, this thesis will also provide a universally available and easy to utilize framework for future users to modify and compare hydrogen production methods utilizing their own decision criteria.

II. Literature Review

Chapter Overview

The purpose of this chapter is to provide an overview of various hydrogen production methods and determine their cost, efficiency, and environmental impacts. First, this chapter will introduce the various forms of Hydrogen Production that will be analyzed and provide insight into the production methods used today. Second, a description of technologies will provide a technical outline of how each method produces hydrogen. Third, the cost, efficiency, global warming potential, acidification potential, and water consumption of each production method will be determined. Finally, these values will be normalized to a scale suitable for analysis.

Various Production Methods for Hydrogen Fleet Vehicle Fuel

H_2 has the highest energy content per unit weight of any known fuel source at 142kJ/g or 2.75 times the energy density of biofuels [12]. Even though H_2 has poor volumetric energy density, the high gravimetric energy density coupled with the relative abundance of elemental hydrogen on Earth is driving significant research into producing and harnessing H_2 as a fuel source to supplement and replace fossil fuels. 50% of the world's H_2 is produced by steam reformation of natural gas, 30% from oil reformation, 18% from coal gasification, 3.9% from water electrolysis, and 0.1% from other methods [13]. Presently, the United States generates 95% of its hydrogen gas through the process of steam reforming of natural gas, which will be described, along with the following H_2 production methods:

1. Steam Reformation based processes
2. Gasification of Coal

3. Pyrolysis
4. Electrolysis based processes
5. Thermolysis
6. Biological and Photobiological processes
7. Photonic processes

The chart below shows selected energy sources and their production method organized by the three main prime energy sources.

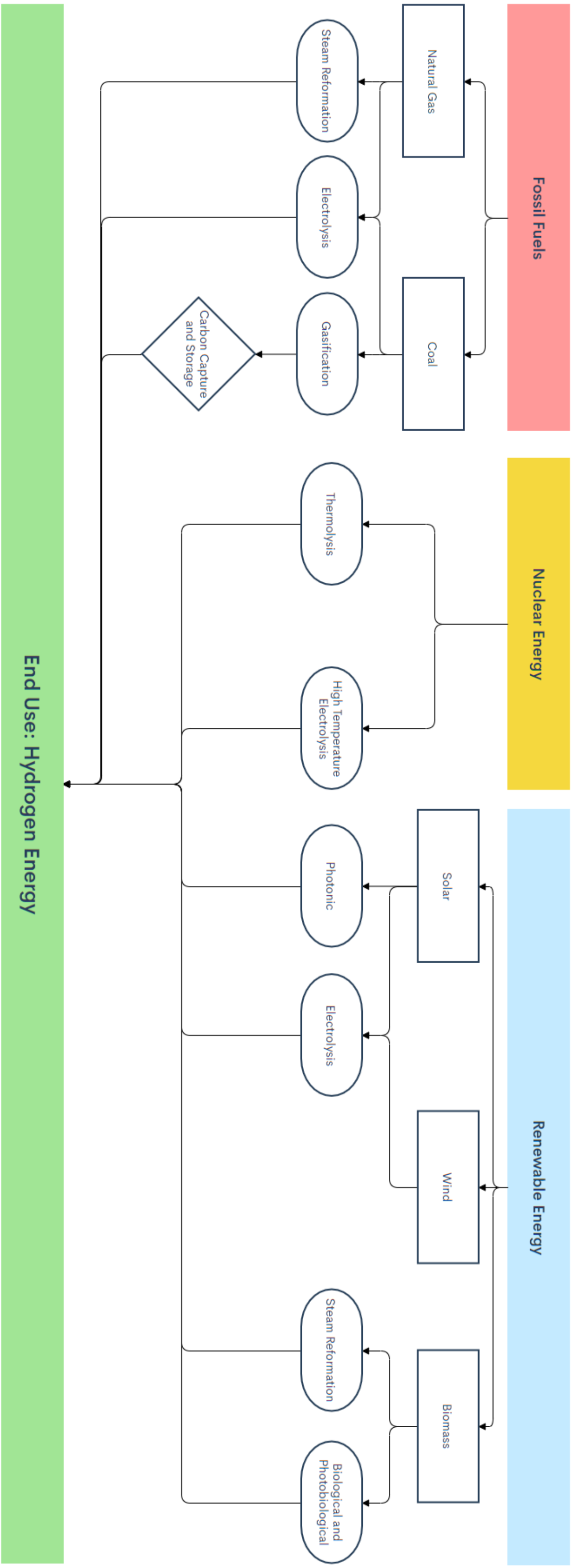


Figure 3: Selected Production Methods based on Prime Energy Source: Fossil Fuels, Nuclear Energy, or Renewable Energy – for larger diagram refer to Appendix A

Description of Technologies

Steam Reformation of Natural Gas

Steam reforming of natural gas is the most common method of hydrogen production. First, natural gas is filtered from its impurities. It is then mixed with steam and passed over an externally heated reactor, where carbon monoxide (CO) and H_2 are produced as shown in Equation 1 [14]. The temperature of the steam is between 700°C and 1000°C. The CO and H_2O undergo a catalytic water-gas shift reaction to produce H_2 and carbon dioxide (CO_2) as shown in Equation 2.

$$CH_4 + H_2O\ (+heat) \rightarrow CO + 3H_2 \tag{1}$$

$$CO + H_2O \rightarrow CO_2 + H_2\ (+small\ amount\ of\ heat) \tag{2}$$

Finally, a pressure swing adsorption process are used to separate H_2 from various gaseous impurities at a purity rate of 99% [15]. The CO_2 bi-product is filtered through a carbon capture system to limit Green House Gas, referred to as GHG, emissions.

Steam Reformation of Landfill (Methane) Gas

According to the EPA, landfill gas is the third largest producer of greenhouse gas emissions in the United States, accounting for 14.1% of all emissions in 2017 [16]. Approximately 67% of landfill emissions consist of methane gas which has a more potent effect on ozone depletion and greenhouse effects in the atmosphere than CO_2 [17]. In this process, methane gas and water react together under high temperature (700 – 1000 °C) and pressure (3 – 25 bar) to generate hydrogen gas and carbon monoxide. The addition of high pressure is required for methane gas steam reformation which is not required in natural gas steam reformation.

Gasification of Coal

The widespread availability of coal makes gasification of coal practical for large plants. At high temperature and pressure coal is partially oxidized with steam and oxygen; producing a mixture of mainly H_2 and CO, then combined with steam and CO_2 [14]. Like reformation, the CO undergoes a water-gas shift reaction producing H_2 and CO_2. This method releases elemental Sulphur which must be removed from the gases by various means.

Pyrolysis

Pyrolysis is a thermochemical decomposition of biomass in the absence of oxygen at moderate temperatures to produce bio-oil, bio-char, and gaseous compounds. Common plastics like polyethylene and polypropylene produce a mixture of various hydrocarbons that serve as a feedstock for producing H_2 gas upon thermal decomposition [18]. Slow pyrolysis utilizes temperatures around 400 degree Celsius for a long period of time, maximizing biochar at 35%, bio-oil at 30%, and 35% gaseous products. Rapid pyrolysis uses 1,000 to 10,000 degrees Celsius temperatures to rapidly heat the biomass's temperature to between 650 to 1,000 degrees Celsius, depending on whether gas or oil products are preferred, yielding 50-70% bio-oil, 10-30% bio char, and 15-20% syngas by mass [19]. The gaseous byproducts contain H_2, CO, CO_2, and various CH compounds.

Electrolysis

An improved technology for hydrogen production is the process of electrolysis. The process of electrolysis uses an anode and cathode separated by a membrane – such as plastic in the case of polymer electrolyte membrane (PEM) located within an electrolyzer [20]. This method's water temperature ranges between 70 and 90 degrees Celsius. Oxygen and positively charged hydrogen particles are formed at the anode. Gaseous oxygen moves towards the surface, while the positively charged hydrogen moves towards the negatively charged cathode. At the cathode, due to the negative charge, the positive hydrogen (H+) combines with the electrons to produce molecular hydrogen or H_2 as demonstrated by Figure 4 [20].

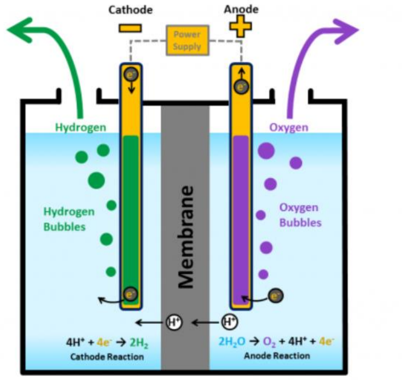


Figure 4: Typical PEM Cell [20]

The second main type of electrolysis is performed between 650 and 850 degrees Celsius using solid oxide electrolysis cells (SOEC) informally known as high temperature electrolysis. SOEC works by splitting steam into pure O_2 and H_2 molecules utilizing a cathode-electrolyte interface under an applied voltage. The H_2 diffuses through the cathode while the O_2 is transported across the dense electrolyte as demonstrated by Figure 5 [21].

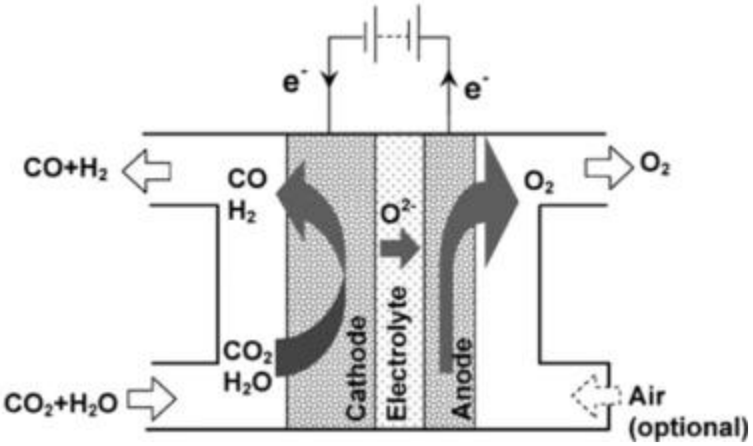


Figure 5: Typical SOEC [21]

Both PEM and SOEC systems can utilize renewable energy. Wind powered PEM and SOEC will be referred to as PEM-RW and SOEC-RW respectively. Photovoltaic powered PEM electrolysis will be referred to as PEM-SV.

Thermolysis

Thermolysis is designed for use in nuclear reactors. Thermolysis relies on heat to break apart water molecules into its component elements. The stable conditions of a nuclear power plant make it ideal for hydrogen production since production can be near continuous [22]. Nuclear-hydrogen power is most simply explained in two equations [22]:

$$2H_2O + Nuclear\ Energy\ \rightarrow 2H_2 + O_2 \tag{3}$$

$$2H_2 + O_2 + Heat\ \rightarrow Energy + 2H_2O \tag{4}$$

Yet, pure thermolysis requires a temperature of 2,200 degrees centigrade; this temperature can be reduced using a thermochemical cycle [13]. There are over 200 thermochemical production methods mentioned in literature, most nothing more than theoretical calculations [23]. Eight have commercial significance, with the Copper-

Chloride (Cu-Cl) and the Sulphur-Iodine (S-I) considered the most promising and both cycles benefit from their components being able to be recycled [13] [23]. The S-I cycle consists of three main steps that occur concurrently. During the Hydrolysis step in Equation 5, iodine (I_2), sulfur dioxide (SO_2), and water (H_2O) react at 120°C to form hydriodic acid (HI) and sulfuric acid (H_2SO_4), which are separated. The Oxygen production step in Equation 6, consists of the sulfuric acid is heated to over 800°C and decomposes into sulfur dioxide, water, and oxygen (O_2). Then hydrogen is separated from hydrogen iodide at 300°C in the hydrogen production step in Equation 7 [23].

$$I_2 + SO_2 + 2H_2O \rightarrow 2HI + H_2SO_4 \tag{5}$$

$$H_2SO_4 \rightarrow H_2O + SO_2 + \frac{1}{2}O_2 \tag{6}$$

$$2HI \rightarrow H_2 + I_2 \tag{7}$$

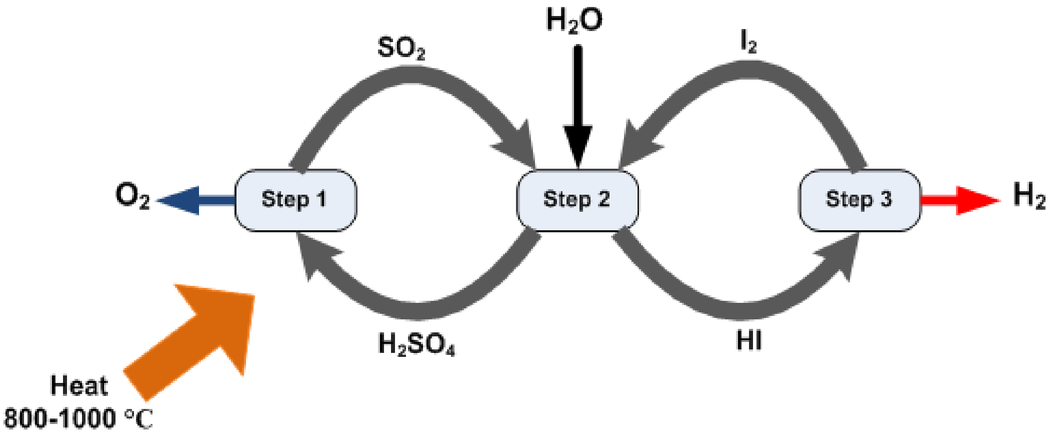


Figure 6: S-I Cycle 3 Step Process [22]

The Cu-Cl cycle is five steps in a closed loop that reuses all compounds on a continuous basis. Additionally, the max necessary temperature in the Cu-Cl cycle is 500°C, a cooler cycle than the S-I Cycle [23]. Step 1, Equation 8 reacts H_2O and $CuCl_2$ at roughly 450°C to produce Cu_2OCl_2 for and HCl for step 5 [22]. Step 2, Equation 9 reduces Cu_2OCl_2 to O_2 and CuCl at 500°C [22]. Step 3, Equation 10 reduces molten CuCl to Cu at 25°C [22]. Step 4, Equation 11 dries aqueous $CuCl_2$ to solid $CuCl_2$ at 90°C [22]. Step 5, Equation 12 reacts solid copper particles from step 1 and HCl from step 4 at 450°C to produce the final products of H_2 and CuCl [22].

$$2CuCl_2(s) + H_2O(g) \rightarrow Cu_2OCl_2(s) + 2HCl(g) \tag{8}$$

$$Cu_2OCl_2(s) \rightarrow 2CuCl(l) + \frac{1}{2}O_2(g) \tag{9}$$

$$4CuCl(aq) \rightarrow 2CuCl_2(aq) + 2Cu(s) \tag{10}$$

$$2CuCl_2(aq) \rightarrow 2CuCl_2(s) \tag{11}$$

$$2Cu(s) + 2HCl(g) \rightarrow 2CuCl(l) + H_2(g) \tag{12}$$

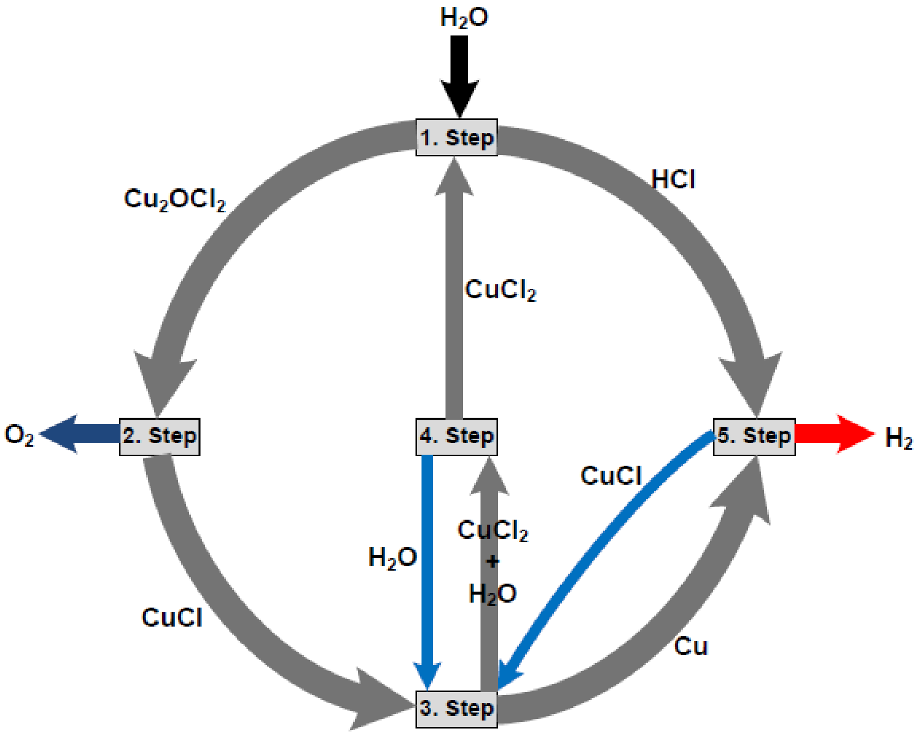


Figure 7: Cu-Cl 5 Step Process [22]

Biohydrogen

Biological hydrogen production utilizes the power of microorganisms to break down feedstock and produce H_2. The basic concept of biohydrogen or biological hydrogen production revolves around selection and preparation of feedstock delivered to one or more microorganisms for digestion in a controlled environment. Biohydrogen consists of numerous concepts including biphotolysis, indirect biophotolysis, photo-fermentation, and dark fermentation [24]. Hydrogen is produced as a biproduct of that digestion. Critical parameters to observe when evaluating biological hydrogen production methods include dependence and sensitivity to light, temperature sensitivity and range, rate of production, cost of feedstock pre-treatment, and cleanliness. Some literature proposed the combination of food waste and sewage within a bioreactor as a biological hydrogen production technique [25]. While biological hydrogen production methods, such as using fermentation or enzymes provide a relatively low impact production process, current methods are challenged by their production rate and financial viability.

Photonic

Photonic energy is carried by protons making solar energy the only natural source for photonic systems. Photocatalytic, photoelectrochemical, and photovoltaic-electrolysis are the three main types of photonic hydrogen production systems.

First, Photovoltaic-Electrolysis (PV-E) is identical to electrolysis except photovoltaic cells produce the electricity used to reduce water molecules. Second, photocatalytic hydrogen production relies on specialized photocatalysts to convert photonic energy into chemical energy in the form of hydrogen [26]. The catalyst creates a band gap that is overcome by certain high energy protons, like those found in UV light.

These protons collide with the catalyst and electrons jump from the valence band into the conduction band creating an electron-hole pair. The excess of electrons in the conduction band allow for the reduction of H_2 and the oxidation of O_2 by the holes. The highest energy level of the valence band must be more positive than 1.23 Volts and the lowest energy level of the conduction band must be more negative than 0 Volts [27]. This requires the catalysts to have a minimum requisite energy gap of 1.23eV [27]. The equations for photocatalysis are shown below:

$$H_2O + 2h^+ \rightarrow 2H^+ + \frac{1}{2}O_2 \quad E^{\circ}_{oxidation} = -1.23V \tag{13}$$

$$2H^+ + 2e^- \rightarrow H_2 \quad E^{\circ}_{reduction} = -0.00V \tag{14}$$

$$H_2O \rightarrow H_2 + \frac{1}{2}O_2 \tag{15}$$

The two main types of catalysts are oxides or sulfides. The oxides catalysts could be TiO_2, Fe_2O_3, SnO_2, ZnO, ZrO_2, CeO_2, WO_3, and V_2O_5; while the sulfide catalysts could be CdS, ZnS, and WS_2 [26]. Even if a catalyst meets the energy potential requirement it might fail due to photo-corrosion; which occurs, “if the anion from the catalyst is oxidized instead of H_2O by photogenerated holes” [27]. The catalyst is dissolved in water as a heterogeneous, homogeneous, or a hybrid mixture which determines the type of photonic production system as shown in Figure 8.

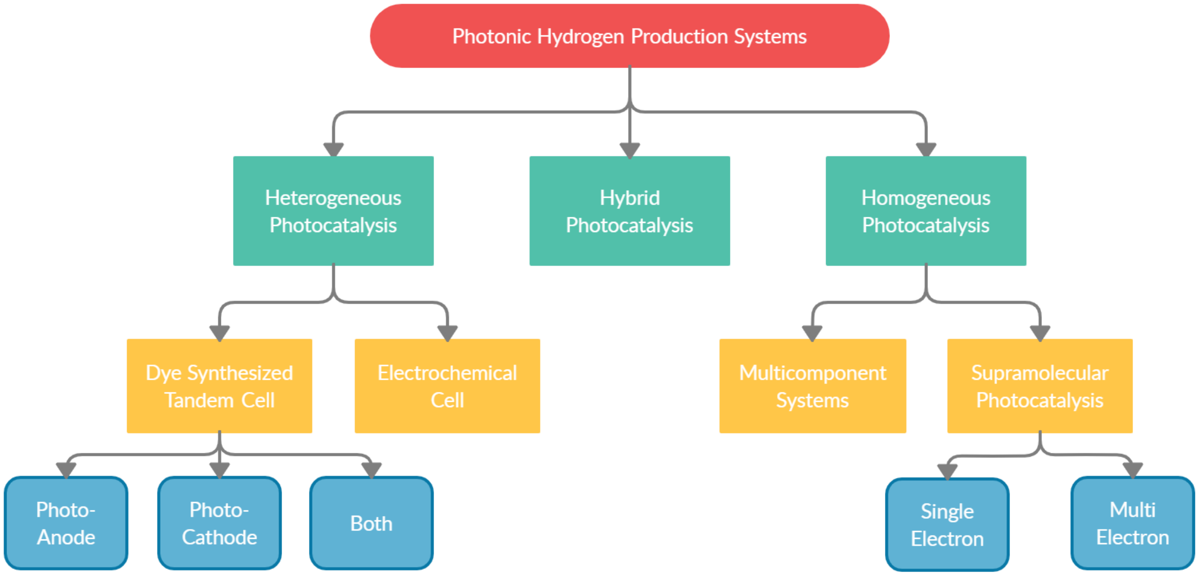


Figure 8: Categories of Photocatalytic Hydrogen Production Systems [25]

Photocatalysis is in the early research stage but has growing interest in the scientific community for a number of reasons. Photocatalytic reactions require two of the most abundant materials on Earth: sunlight and water. The only carbon emissions are from the initial construction cost and lifecycle emissions of the catalyst used. Current catalysts only generate an electron-hole pair from UV or high energy frequency visible light spectrum protons meaning only 4% of photons entering the atmosphere will cause a reaction [26]. Much of current research is devoted to expanding the usable photon spectrum to that of visible light spectrum by, “the discovery of a cheap, active, abundant, efficient, and stable photocatalysts” [28]. Acar et. al. determined there are ten requirements for an effective photocatalyst shown in Figure 9. To note is (1) the suitable band gap needed to harness the visible light spectrum, (2) stability in the reduction environment, (3) corrosion resistance, (4) large scale production potential, (5) the proper valence and CB band placement which drive reduction reactions, (6) low cost of production and operation, and (7) abundance of photocatalyst material [28]. These five were selected by C. Acar et. al. due to their overall necessity for an efficient process. The remaining factors: (1) recyclability, (2) long life, and (3) efficiency in production are desirable traits but not significantly defining for production efficiency of hydrogen.

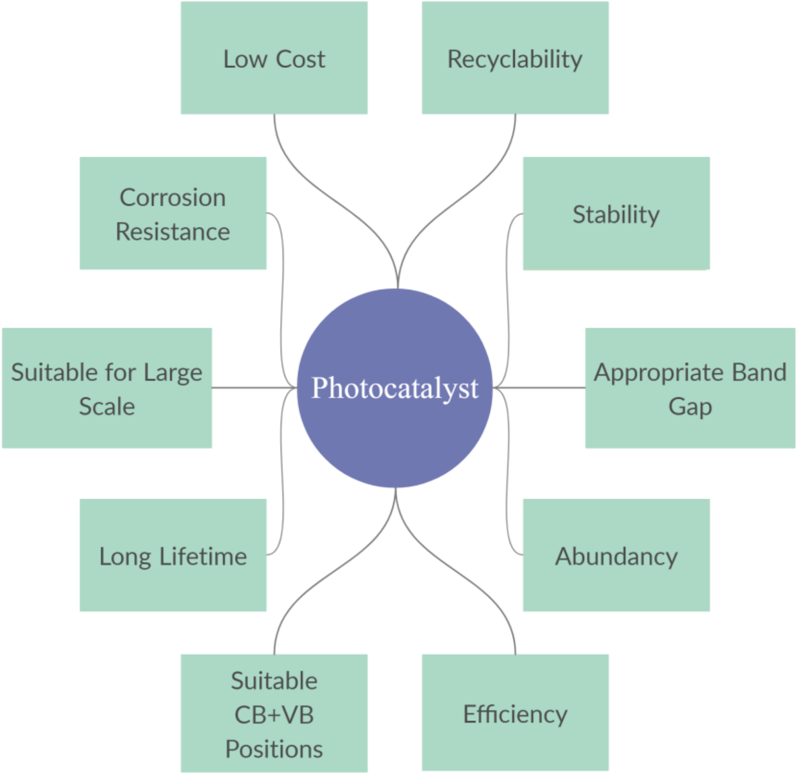


Figure 9: Requirements for an effective photocatalyst [27]

Third, Photo-electrochemical (PEC) cells essentially integrate a photovoltaic cell with a water electrolyzer. PEC cells consist of photosensitive semi-conductors submerged in an aqueous electrolyte [29]. When photons collide with the semi-conductor, electron-hole pairs are formed creating an electric field which is used to oxidize or reduce water. This process is demonstrated in Figure 10.

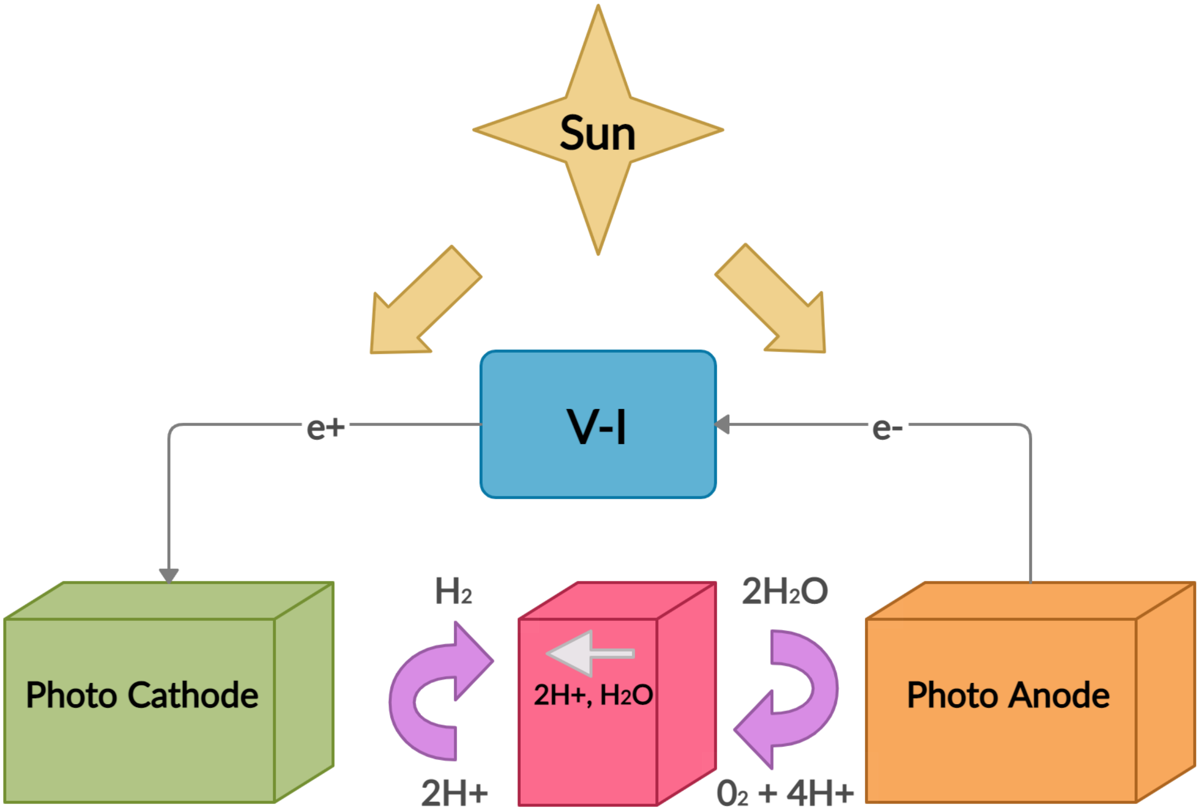


Figure 10: Photoelectrochemical Process [26]

Photo-biological

The ability to convert seemingly useless waste-water into hydrogen energy is enticing. Microalgae and cyanobacteria use light as an energy source to perform water photolysis under anaerobic conditions, producing H_2.

$$4H_2O + light \rightarrow 2O_2 + 4H_2 \tag{16}$$

Bioreactors must be enclosed in order to capture H_2, practical to sterilize, and distribute light over the entire volume or distribute the material by stirring of the substrate. Additionally, as H_2 is produced O_2 generation occurs slowing the reaction to a mere 1.5% efficiency [30]. Oxygen must be removed from the photobioreactor continuously for efficiencies of 3-10% to be achieved [30]. Unlike photovoltaic panels, where high light intensity is desired, low but continuous light intensity is ideal for photobiological processes; too much light and H_2 production slows [30]. Photo-biological methods are challenged by the slow efficiency rate, demanding reactor conditions, and expensive reactor designs. Currently, photo-biological methods have never been tested on a large scale. Even the largest reactors are simply a number of small, connected reactors [30].

Environmental Impact

Environmental impact will be defined by CO_2 production, and ReCipe 2016 standards including global warming impact (GWP), acidification potential (AP), and water consumption (WC); the ReCiPe 2016 model is a lifecycle assessment of the pressure a certain production method places on the environment [31]. These environmental indicators satisfy the three main impact areas of an energy source as seen in Figure 11.

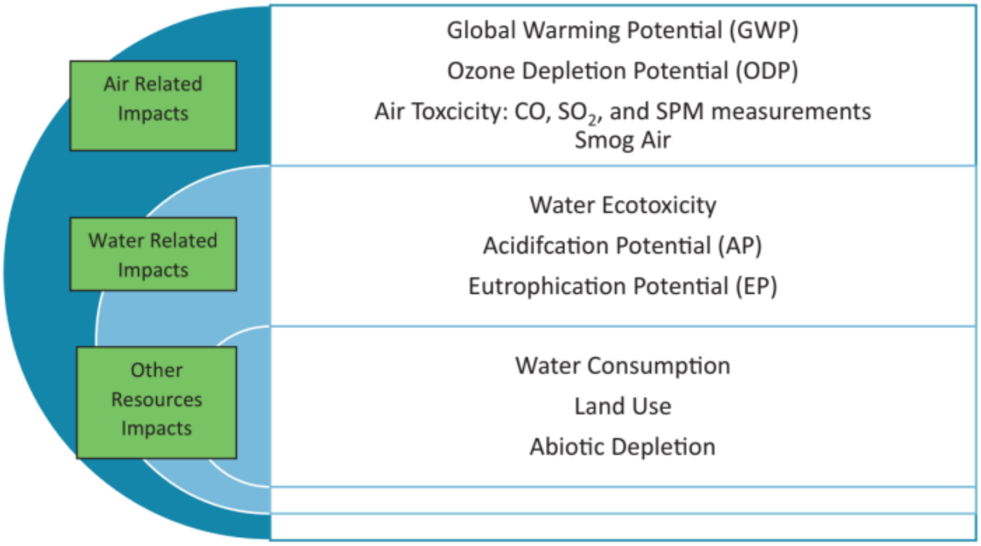


Figure 11: Environmental Indicators for Sustainability Assessment Modeling [31]

Global Warming Potential

GWP is the measure of the affect that a specific GHG contributes to global warming. In order to understand GWP, radiative forcing (RF) must be understood. RF describes the affect GHG have on absorbing solar radiation and containing outgoing solar radiation in the atmosphere meaning any net increase in RF will force warming of the measured system [32]. RF is numerically described as the rate of energy change per unit area of the globe measured in the tropopause (upper layer of the troposphere) as W m^{-2} [32]. The larger the RF, the greater the expected change in the Earth's temperature; this change can be positive or negative dependent on the sign of the RF. The effect of a specific GHG on RF change is determined by the initial concentration of the gas in the atmosphere, the radiative absorption characteristics, the temperature and thickness of the atmosphere, and the effects of other gases present; this measure is well understood and is calculated with a high degree of confidence [32]. GWP combines the effects of RF with the atmospheric lifetime of the GHG to produce the total lifetime affect. A molecule that has a large RF that persists for many years would have a high GWP value. The calculation for GWP is shown in Equation 17:

$$GWP = \frac{\int_0^Y \Delta F_{GHG} f_{GHG}(t) dt}{\int_0^Y \Delta F_{CO_2} f_{CO_2}(t) dt} \tag{17}$$

Where the numerator calculates the total RF for a specific GHG (ΔF_{GHG}) over a period of time, while the demoniator express the same for CO_2 [32]. ΔF_{GHG} reflects the RF caused by 1 kg of the GHG introduced at t = 0. $f_{GHG}(t)$ describes the fraction of the GHG remaining at any time after t=0. GWP will be calculated using a 100-year time frame per mid-term outlook referred to in the ReCipe2016 standards. The decay of common GHG's is shown below in Figure 12 and 13.

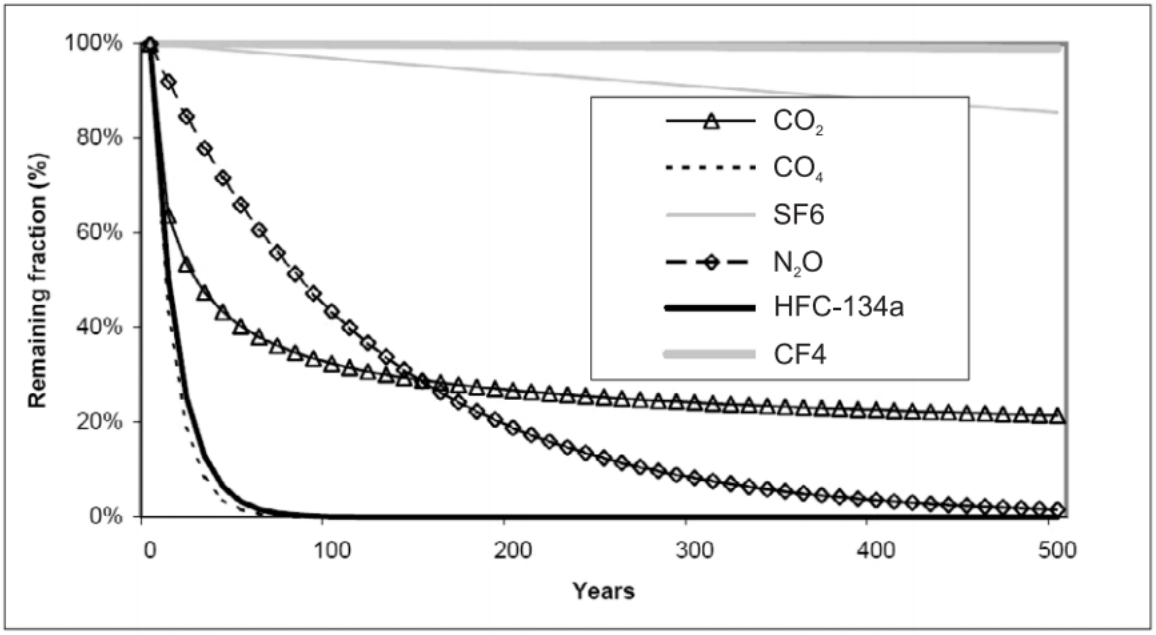
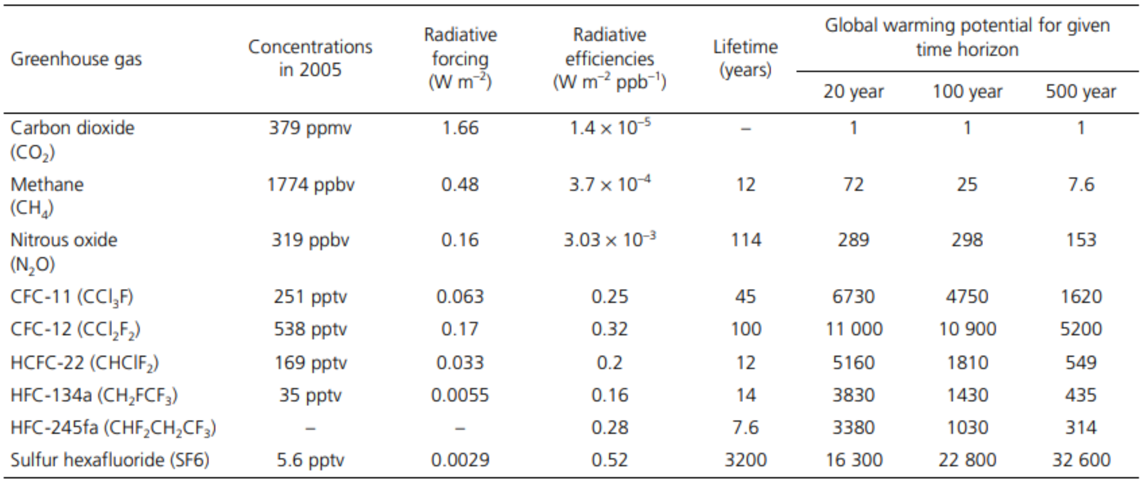


Figure 12: Comparison of Common GHG Decay Curves in Relation to CO2 [32]



Greenhouse gas	Concentrations in 2005	Radiative forcing (W m^{-2})	Radiative efficiencies (W m^{-2} ppb^{-1})	Lifetime (years)	Global warming potential for given time horizon		
					20 year	100 year	500 year
Carbon dioxide (CO_2)	379 ppmv	1.66	1.4×10^{-5}	–	1	1	1
Methane (CH_4)	1774 ppbv	0.48	3.7×10^{-4}	12	72	25	7.6
Nitrous oxide (N_2O)	319 ppbv	0.16	3.03×10^{-3}	114	289	298	153
CFC-11 (CCl_3F)	251 pptv	0.063	0.25	45	6730	4750	1620
CFC-12 (CCl_2F_2)	538 pptv	0.17	0.32	100	11 000	10 900	5200
HCFC-22 ($CHClF_2$)	169 pptv	0.033	0.2	12	5160	1810	549
HFC-134a (CH_2FCF_3)	35 pptv	0.0055	0.16	14	3830	1430	435
HFC-245fa ($CHF_2CH_2CF_3$)	–	–	0.28	7.6	3380	1030	314
Sulfur hexafluoride (SF6)	5.6 pptv	0.0029	0.52	3200	16 300	22 800	32 600

Figure 13: Common GHG Concentrations, RFs, Radiative Efficiencies, Lifetimes, and GWPs [32]

Figures 12 and 13 demonstrate how lifetime and RF affects GWP. To note, the effects of a long persisting GHG with a low RF is demonstrated by sulfur hexafluoride while the effects of a high RF GHG with a low persistence is demonstrated by CH_4 methane and SF_6 sulfur hexafluoride which have GWP of 289 and 16,300 respectively over a 20-year time horizon.

GWP will be normalized to a scale of 0 to 10, the former has the worst GWP of all production methds and the latter the least GWP utilizing the formula below:

$$Rank\ for\ Method\ i = \frac{Maximum - GWP\ of\ Method\ i}{Maximum} \times 10 \tag{18}$$

Acidification Potential

AP is a measure of SO_2-equivalence that refers to compounds that are precursors of acid rain. The predominate compounds in AP measurement are sulfur dioxide, nitrogen oxides, nitrogen monoxide, and nitrogen dioxide [33]. The mathematical calculation for AP is:

$$Y_{AP} = \frac{X_{AP(T)}}{X_{AP}} \tag{19}$$

Where $X_{AP(T)}$ is the EPA's standard for ambient air quality set at -190 µg m^{-3}, and X_{AP} is the concentration of SO2 in the local environment called the calculated acidification potential. X_{AP} is calculated below:

$$X_{AP} = SO_{2,0} + \frac{SO_2}{Area_{Community} + MH_{SO2}} \times \frac{\tau_{SO2}}{8760} \tag{20}$$

Where $SO_{2,0}$ is the background concentration, SO_2 is annualized life cycle emissions, τ_{SO2} is the resident time, and MH_{SO2} is the vertical mixing height of SO_2 [33].

AP will be normalized to a scale of 0 to 10, the former has the most AP and the latter the least AP utilizing the formula below:

$$Rank\ for\ Method\ i = \frac{Maximum - AP\ of\ Method\ i}{Maximum} \times 10 \tag{21}$$

Water Consumption

Water consumption (WC) is an important metric for arid regions and a main cause of ecosystem destruction [34]. WC is measured by the volume of water needed to produce one kilogram of H_2. WC will be normalized to a scale of 0 to 10, the former having the great water use and the latter the least water use utilizing the formula below:

$$Rank\ for\ Method\ i = \frac{Maximum - WC\ of\ Method\ i}{Maximum} \times 10 \tag{22}$$

Steam Reformation of Natural Gas

Steam Methane Reforming (SMR) emissions are dependent on the scale of production. Large-scale SMR plants produce an estimated 13.7 kg CO_2/kg of H_2, while small-scale SMR united generate an estimated 7.67 kg CO_2/kg of H_2 [35]. Implementation of a Carbon Capture System would reduce GWP to an estimated 3.4 kg CO_2-eq/kg of H_2 [34]. Estimated emissions do not consider plant construction and assume electrical power is provided by a coal power plant as seen in Figure 14.

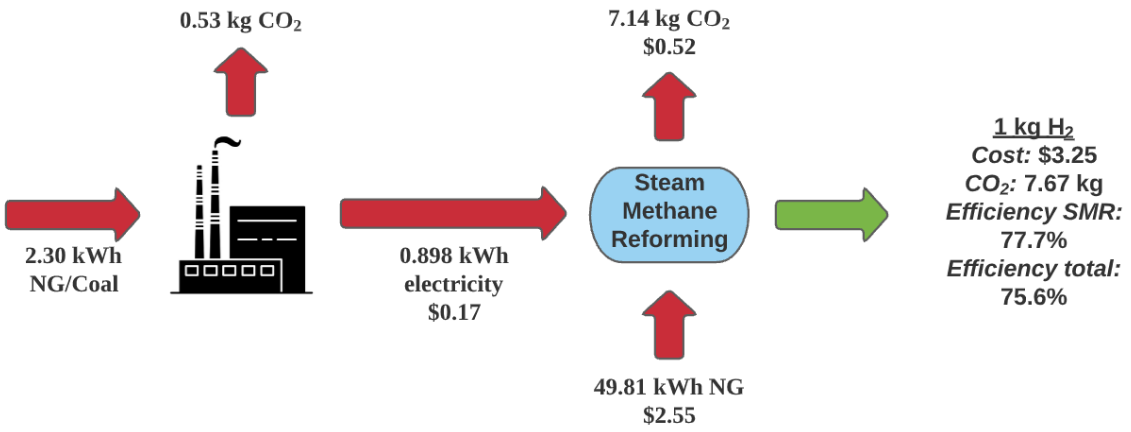


Figure 14: SMR Emissions from Helbio APS 1000 Unit in the United Kingdom, cost converted to U.S. Dollars [34]

The WC of Steam Reformation is overall very low at 5.57 cubic meters of water per kilogram of hydrogen produced [34]. The normalized GWP of Steam Reformation is 2.94 [14]. The normalized AP of Steam Reformation is 5.71 [13].

Gasification of Coal

This is the worst possible option scoring a 0 on the weighted GWP and AP scale. This is due to the various GHG produced from carbon heavy coal, and Sulfur Oxides produced for every molecule of H2. Below is a common total reaction equation for coal gasification [34]:

$$CH_{0.8} + O_2 + H_2O \leftrightarrow CO + CO_2 + CH_4 + H_2 + other\ species \qquad (23)$$

Most current research promotes coal technologies with carbon capture and storage options but the technology is not mature and investment cost is high. Even with high efficiency Carbon Capture (90% capture rate), gasification of coal scores lower than all other options. The normalized GWP and AP of Coal Gasification is 0 [14]. Gasification of coal is considered moderate for WC utilizing 13.1 cubic meters of water per kilogram of hydrogen produced [34].

Steam Reformation of Landfill Gas

Currently, there have been no studies into the environmental impacts of utilizing landfill gas for H_2 production. What is known is that the methane produced in landfills, if not converted, will dissipate into the atmosphere. For every molecule of methane converted, four H_2 molecules are formed and one CO_2 molecule:

$$CH_4 + H_2O \rightarrow CO + 3H_2 \tag{24}$$

$$CO + H_2O \ \rightarrow H_2 + CO_2 \tag{25}$$

$$CH_4 \rightarrow CO_2 + 4H_2 \tag{26}$$

CO_2's GWP is 1, while CH_4's GWP is between 28 and 36 [36]. Therefore, landfill gas reforming is cleaning the air. The main source of pollutant is the energy source. Figure 14 shows that even under coal power, the amount of CO_2 released is 0.53kg/kg of H_2. This number would be significantly lower if renewable energy from wind or solar provides electrical power. Further research will determine the GWP and emissions lifecycle assessment (LCA) for photovoltaic panels and wind turbines. Additionally, for every 1kg of H_2, 0.022 kilograms of CO_2 is produced according to the above reaction. Without considering the LCA of wind or solar power, the carbon emissions are 0.0552kg of CO_2/kg of H_2. This does not consider the net benefit of removing methane from the atmosphere. If a fossil fuel fueled power plant is utilized the emissions per kg of hydrogen produced would be 0.53 kg of CO_2/kg of H_2 [35] The removal of methane from the atmosphere coupled with the low carbon emissions results in the best normalized GWP of 9.75. Acidification potential is unknown. A conservative estimate would be to place it at the same weight as steam reformation although the true is most likely much lower. WC is also unknown but since the process is near identical to steam reformation of natural gas the conservative estimate would be to place WCP at 5.57 cubic meters of water utilized per kilogram of water produced.

Pyrolysis

Utilizing pyrolysis, for every one kilogram of H_2 produced, 12 kilograms of CO_2 are produced from plastics [18]. This number varies with differing plastics, for example, PET only produced 8.8 kilograms of CO_2 per kilogram of H_2. Current research is examining new catalysts for the reaction that decrease the amount of CO_2 produced per kilogram of H_2. Although there is no current research available for the LCA of pyrolysis from municipal waste as the feedstock, there is LCA data available for feedstocks consisting of biomass. The normalized GWP of biomass pyrolysis is 2.67, and WC is 4.94 m^3 of H_2O/kg of H_2 [34]. There is no current data on the AP of pyrolysis.

Electrolysis Emissions (PEM, PEM-R, SOEC, SOEC-R, PV-E)

All electrolysis derived production methods' GWP, AP, and WC values are found in the table below:

Table 1: Electrolysis Types and Environment Impact for one kg H2

	GWP (kg CO_2-eq)	**AP (equivalent SO_x)**	**WC** (m^3 of H_2O)
PEM	3.33 [13]	8.86 [13]	18.04 [34]
PEM-RW	9.43 [14]	9.16 [14]	16.40 [34]
SOEC	8.82 [14]	8.42 [14]	146.82 [34]
SOEC-RW	2.10 [34]	9.43 [34]	8.82 [34]
PEM-PV	8.53 [14]	7.37 [14]	16.40 [34]

Thermolysis Emissions

In both the S-I and Cu-Cl cycles, the sole input required is water, and the only outputs are oxygen and hydrogen. The other chemical components that undergo reaction return to their original compositions and are reutilized to create more hydrogen gas (14). Because of this, thermolysis is a relatively clean process, producing few harmful emissions through the cycles themselves. However, the fabrication of the equipment and facilities needed to perform thermolysis still produces CO_2 emissions. There are numerous methods of thermolysis utilizing various thermochemical cycles and due to the wide variation of possible modifications needed for a nuclear power plant to host the addition of a Thermolysis facility there an assortment of assumed values for GWP, AP, and efficiency. For example, GWP of a nuclear facility producing hydrogen through the S-I cycle is expected to be 9.64 [14]. A nuclear facility using the Cl-Cu cycle will result in slightly more emissions at 9.49, while one utilizing SOEC is valued at 8.60 [14]. Both thermochemical processes produce corrosive acids that are recycled continuously to other compounds, evaluated using acidification potentials (APs). Dincer and Acar provides a conservative estimate of 9.17 for general Thermolysis GWP, and an AP of 9.43 for general Thermolysis [13]. WCP is 14.9 due to the amount of water utilized by the nuclear reactor providing heat and power for hydrogen production [22]. The WC of thermolysis is considered moderate at 14.9 cubic meters of water utilized for one kilogram of hydrogen produced [22].

Biological Emissions

Despite the focus of this research on quantifying the differences between legacy hydrogen production methods and biological production methods, relatively little literature is available to quantify the emissions in biological methods. This is most likely due to the large amount of feedstock needed to produce even one kg of H_2. Utilizing dark fermentation Dincer and Acar estimate the normalized GWP to be 9.58 and the AP to be

9.71 [14]. The WC of the biological emissions process is 84.9 cubic meters of water to produce one kilogram of hydrogen [34]. This is due to the large amount of aqueous feedstock necessary for this production method.

Photo-biological

The ability to utilize wastewater as an energy could help alleviate the negative effects of wastewater GHG emissions. Due to the natural energy source, fuel, and micro-organism converters in photo-biological process it scores 9.58 for GWP and 9.71 AP [13]. These numbers make photo-biological methods one of the least impactful on the environment of all methods. Although these numbers are promising, the lack of non-laboratory testing questions the reliability of data on the process. Specifically, without a defined design or material, it has hard to determine the lifecycle environmental impact of bioreactors [30]. Like the biological emissions method, photo-biological methods have an equivalent WC of 84.9 cubic meters of water to produce one kilogram of hydrogen [34].

Photonic

Photocatalytic hydrogen production has a normalized GWP of 9.58, and an AP of 9.71 [13]. Photoelectrochemical methods have a normalized GWP of 9.58 kg of CO_2/kg H_2 and an AP of 9.71 [13]. There appears to be no current research on the WC of photonic methods but will be estimated to utilize an equivalent volume of water as photo-biological which is commonly grouped under photonic methods in research.

Summary of Environmental Impact Scores

GWP score is based on the percentage of CO_2 produced per kilogram of hydrogen. The results were then normalized on a scale of 1 to 10.

Table 2: Normalized GWP on a Scale of 0 (worst) to 10 (best)

Hydrogen Production Method	**GWP**
Ideal Production Method	*10.0*
Renewable Steam Reformation of Landfill Gas with Methane Reduction Considered	9.75
Photocatalysis	9.58
Biological and Photo-Biological	9.58
Wind PEM Electrolysis	9.43
Thermolysis	9.17
High Temperature Electrolysis	8.82
Photovoltaic PEM Electrolysis	8.53
Photoelectrochemical	8.33
Landfill Gas Reformation from Coal Plant without Methane Reduction Considered	6.63
PEM Electrolysis	3.33
Steam Reformation of Natural Gas	2.94
Pyrolysis	2.67
High Temperature Wind Electrolysis (SOEC-RW)	2.10
Coal Gasification	0.00

Table 3: Normalized Acidification Potentials on a Scale of 0 (worst) to 10 (best)

Hydrogen Production Method	**AP**
Ideal Production Method	*10.0*
Photoelectrochemical	9.71
Photocatalysis	9.71
Biological and Photo-Biological	9.71
High Temperature Wind Electrolysis (SOEC-RW)	9.43
Thermolysis	9.43
Wind Generated PEM Electrolysis	9.16
PEM Electrolysis	8.60
High Temperature Electrolysis (SOEC)	8.42
Photovoltaic PEM Electrolysis	7.73
Steam Reformation of Natural Gas	5.71
Steam Reformation of Landfill Gas	5.71
Coal Gasification	0.00
Pyrolysis	Unknown

Table 4: Normalized Water Consumption on a Scale of 0 (worst) to 10 (best)

Hydrogen Production Method	**WC**
Ideal Production Method	*10.0*
Steam Reformation of Landfill Gas	9.62
Steam Reformation of Natural Gas	9.62
High Temperature Wind Electrolysis (SOEC-RW)	9.39
Coal Gasification	9.11
Thermolysis	8.99
Photovoltaic PEM Electrolysis	8.88
Wind Generated PEM Electrolysis	8.88
PEM Electrolysis	8.77
Biological and Photo-Biological	4.21
Photocatalysis	4.21
Photoelectrochemical	4.21
High Temperature Electrolysis (SOEC)	0.00
Pyrolysis	Unknown

Cost

Costs will be normalized in Table 5; the pre-normalized values are below. SMR costs vary from \$1.25/kg of H_2 to \$3.50/kg of H_2 depending on size of the plant and cost of natural gas set at \$6/GJ for this estimate [37]. Gasification of Coal is estimated to cost \$1.63 with CCS [38]. Landfill gas reforming is estimated to cost less than \$3.50/kg of H_2 [37]. Pyrolysis' cost lies between \$1.25 and \$2.20 dependent on the fuel [38]. PEM electrolysis averages \$5.12/kg of H_2 [39]. PEM electrolysis costs are dependent on electrical cost which account for 75%-80% of total cost [40]. Photovoltaic electrolysis costs \$5.78 [13], wind electrolysis (PEM-R) lies between \$5.89 and \$6.03/kg of H_2 [38]. Photovoltaic and Solar Thermal electrolysis utilizing SOEC is estimated at \$10.36/kg of H_2 [38]. Thermolysis is estimated between \$2.17 and \$2.63/kg of H_2 [38]. Biological methods do not have usable cost estimations Biomass pyrolysis estimated cost lies between \$1.25 and \$2.20/kg of H_2 [38]. For Biohydrogen, most of the reviewed literature clearly highlighted claimed production cost but failed to quantify the production rates other than production is qualitatively slow; accurate production cost cannot be determined without production quantity. Further, details concerning pretreatment costs were not clearly noted. This is likely due to biohydrogen only being tested in laboratory settings. For future comparisons, attention must be given to collect more granular details regarding pretreatment materials and quantities for a more detailed cost breakout. The additional detail would facilitate updates as the costs of pretreatment materials mature. Photo-Biological utilizing algae claims a rate of \$2.80/kg of H_2 but does not clarify if this is cost including the price of the plant and algae ponds or simply production cost [38]. Photocatalysis methods have a normalized cost of \$5.19/kg of H_2 [13]. Electrochemical methods have a normalized cost of \$10.25/kg of H_2 primarily due to its limited technological maturity has only led to lab testing.

Cost will be normalized to a scale of 0 to 10, the former the most expensive and the latter the least expensive utilizing the formula below:

$$Rank\ for\ Method\ i = \frac{Maximum - Cost\ of\ Method\ i}{Maximum} \times 10 \tag{27}$$

Where $Maximum$ is the most expensive option and $Cost\ of\ Method\ i$ is the average cost for the specific production method. Table 5 was constructed using the values and equation above.

Table 5: Normalized Cost on a Scale of 0 (worst) to 10 (best)

Hydrogen Production Method	Cost
Ideal Production Method	*10.0*
Gasification of Coal	8.43
Pyrolysis	8.34

Steam Reformation of Natural Gas	7.71
Thermolysis	7.69
Biological and Photo-Biological	7.30
Steam Reformation of Landfill Gas	6.63
High Temperature Electrolysis (SOEC)	6.63
PEM Electrolysis	5.06
Photocatalysis	5.00
Photovoltaic PEM Electrolysis	4.43
Wind Generated PEM Electrolysis	4.25
Photoelectrochemical	0.11
High Temperature Wind Electrolysis (SOEC-RW)	0.00

Efficiency

Efficiency in hydrogen production must be considered for military application. High efficiency limits the amount of energy used for the same task and reduces the need for energy generation imports. Some efficiencies are well known due to the widespread use of the production method. For others, efficiency is estimated in lab tests and are currently provide the best estimates for a full-sized hydrogen production system. For PEM electrolysis efficiency varies from 70% to 95% due to variances in temperature and water purity [13]. For the purposes of this paper, the conservative estimate of 70% will be used. The table below contains the efficiency of each production method:

Table 6: Normalized Efficiency on a Scale of 0 (worst) to 10 (best)

Hydrogen Production Method	**Efficiency**
Ideal	*100%*
Steam Reformation of Natural Gas	77% [35]
PEM Electrolysis	70% [13]
Pyrolysis	Less Than 80% [41]
Thermolysis	72% [14]
Steam Reformation of Landfill Gas	70% [37]
Gasification of Coal	46% [13]
High Temperature Electrolysis (SOEC)	29% [13]
Photovoltaic PEM Electrolysis	23% [13]

Photoelectrochemical	12.4% [42]
Biological and Photo-Biological	3-10% [30]
Photocatalytic	4% [14]
Wind Generated PEM Electrolysis	Unknown
High Temperature Wind Electrolysis (SOEC-RW)	Unknown

Viability

Steam Reformation of Natural Gas

SMR has the greatest viability since it is used to produce 95% of all hydrogen gas in the United States [43]. As such, it is a very low risk option.

Gasification of Coal

Gasification of coal is possible with today's technology but is limited by carbon capture and storage technology. For every molecule of H_2 produced a molecule of CO, CO_2, CH_4, and various other species [34]. Although the most environmentally impactful of the production methods, gasification of coal is proven and a currently viable option.

Steam Reformation of Landfill Gas

Viability of the Landfill Gas reformation is proven especially since it uses and identical process as SMR. A Methane to H_2 process has been successfully tested by BMW at their plant in Greer, South Carolina utilizing landfill gas. H_2 is produced from methane gas utilizing a steam reformation process. BMW organized the project into three separate stages. The first phase of the Landfill Gas-to-Hydrogen Project showed that a viable business case can be made for large scale operation. At BMW's test site in South Carolina, H_2 was produced at a purity of 99.99988% which, "*Successfully proved the technical ability to recover sufficiently pure methane from an incoming stream of LFG to* *permit follow-on hydrogen recovery using traditional steam methane reformation technology"* [44].

Additionally, the research study found that, *"At the 500 kg/day level, with the existing landfill gas (LFG) supply and equipment at the host facility, onsite production of hydrogen using LFG as the hydrocarbon feedstock appears to be cost competitive, if not advantageous, over hydrogen sourced from vendors, produced offsite and transported to the facility"* [44].The second phase of the project confirmed that commercially-available technologies are available to recover fuel cell-quality hydrogen from a landfill gas source. The third stage tested several of BMW's fuel cell forklifts that were fueled with hydrogen from the project equipment with no detectable difference in performance compared to that achieved when fueled by delivered hydrogen at BMW (26). BMW states that this has saved them five million dollars annually at their South Carolina plant. Additionally, BMW decreased their carbon emission by over 92,000 tons per year. Currently, over 100 BMW forklifts are powered by H_2 gas which increases their efficiency over the charge times of electric forklifts [45]. Although they have not released details on the specifics of their plant, BMWs plans to release a training program in the future [46].

Pyrolysis

Current research performed cannot find examples of scaled production but current testing seems limited to lab results. This is a high-risk approach since large scale production would demand significant initial research capital and unproven production methods. This large-scale viability is not guaranteed, and research costs are currently unmeasurable; therefore, this method is deemed not viable.

Biohydrogen

Biological methods are not viable due to the large reactor size and low hydrogen output. Table 7 demonstrates various biohydrogen production methods and the size of the bioreactor needed to power a 1.0 kW fuel cells:

Table 7: Size of Bioreactor for 1.0 kW fuel cell [23]

Biohydrogen Production Method	Bioreactor size in liters for 1.0 kW fuel cell
Direct photolysis	341,000
Indirect photolysis	67,300
Photo-fermentation	149,000
Dark-fermentation (mesophilic, pure strain)	1,140

Assuming the 1kW fuel cell utilizes 13 liters of hydrogen per minute or 18,720 liters of hydrogen per day, and 1 kg of hydrogen is equivalent to 14.132 liters of hydrogen; over 380 liters of substrate would be needed per day. Although seemingly viable in laboratory experiments, biohydrogen production is greatly diminished in the real world. A 100,000-liter distillery produced only 21.28 kg of H2 in 40 hours [47]. That would not even be enough H_2 to power the 1.0 kilo watt fuel cell for a single hour. Due to the lack of experimental evidence supporting large scale biohydrogen viability; it is not a recommended technology for hydrogen production.

Electrolysis

Approximately 4% of the world-wide annual H_2 production is already accomplished with electrolysis in standard dark reactors that are driven with electrical grid power [48]. The current state of PV-E systems to generate H_2 is well understood due to the relative maturity of both halves of the system. Current research into primary power generation has driven significant research into PV, yielding current maximum demonstrated solar efficiency at production scale of 23% as of 2019 [49]. Joining the two technologies could allow an increase in overall efficiency due to the negation of the inverter and rectifier inefficiencies when converting direct current power from a PV array to alternating current for long-distance transmission, and then back to direct current to power the disparate anode and cathode for electrolysis. Currently, Nikola plans to utilize PV Electrolysis for their system of hydrogen semi tractor-trailer truck filling stations to produce eight tons of hydrogen per day with a planned future expansion of up to 32 tons per day [50]. PEM Electrolyzers are also extremely portable and small, over 3,500 of these small electrolyzers have been produced by NEL Hydrogen [51]. High Temperature Wind Electrolysis is an extremely expensive option and many of the key metrics like efficiency are unknown; therefore, it is deemed non-viable.

Thermolysis

Thermolysis is available for utilization in nuclear reactors and is viable [22]. Thermolysis has been considered for focused solar radiation towers since the required temperatures can be achieved which is not a viable solution. This is due to the immense amount of wear put on internal parts of a solar tower especially in comparison to a nuclear plant system [52]. There has been significant research into the safety of thermolysis for nuclear power generation and areas of concern have been resolved by numerous research efforts [53].

Photoelectrochemical and Photocatalytic Methods

This method is currently in the research and development phase and has not been tested at a large scale. It holds potential for flexible use through numerous potential application areas but without large scale testing it cannot be deemed viable [13]. Current catalysts only generate an electron-hole pair from UV or high energy frequency visible light spectrum protons meaning only 4% of photons entering the atmosphere will cause a reaction [26]. Much of current research is devoted to expanding the usable photon spectrum to that of visible light spectrum by, “the discovery of a cheap, active, abundant, efficient, and stable photocatalysts” [28]. Although photocatalytic methods are promising; they are currently non-viable until a more efficient catalyst is discovered.

Photo-biological

Large scale photo-biological reactors do not exist. Limitations consist of completely sealing the system, material to be utilized, ease of sanitation, and resistance to clumping of biological feed material [54]. This coupled with low efficiency, untested designs, and limited data makes photo-biological hydrogen production not viable.

Summary of Viability

Table 8: Current Viability of Hydrogen Production Methods

Viable Options:	**Non-Viable Options:**
Ideal Production Method	Pyrolysis
Gasification of Coal	Biological and Photo-Biological
Steam Reformation of Natural Gas	Photocatalysis
Thermolysis	Photoelectrochemical
Landfill Gas Reformation	High Temperature Electrolysis
High Temperature Electrolysis (SOEC)	
PEM Electrolysis	
Photovoltaic PEM Electrolysis	
Wind Generated PEM Electrolysis	

III. Methodology

Objectives

The purpose of Methodology is to provide future users with a guide for reproducing the decision analysis framework provided, detail the determined weights and reasoning for a probable USAF weighting framework, and detail the construction of the analysis tool.

Overview of Air Force Specific Goals

The initial analysis will be performed using weights that would align with the Air Force's goals. The United States Air Force Energy Flight Plan: 2017-2036 lists three strategic goals: Improve Resiliency, Optimize Demand, and Assure Supply [1]. Assure Supply consists of three main intents and expected results that directly tie into the use of hydrogen and other renewable energy sources:

1. "Integrate alternative source of energy compatible with mission requirements" resulting in, "access to clean energy resources and supply chains based on asset and mission priorities" [1]. By 2025 the Air Force hopes to reduce 20 percent of its single points of failure [1]. Hydrogen fuel cell technology fits the Energy Flight Plan 2017-2036 and this goal by providing po.
2. "Diversify drop in sources of energy," resulting in, "increased flexibility in all operations" [1]. Since Hydrogen product simply needs water and electricity, it could be utilized and produced in any area that has accept to these two resources.
3. "Increase access to reliable and uninterrupted energy supplies," resulting in, "increased ability to sustain mission" [1]. Assuming water and electricity are

abundant, hydrogen is a resource that can be produced continuously without interruption. If electricity is fully generated by renewable energy, then the only resource needed is water.

Variables that affect design areprobabilistic. This randomness constantly changes the optimal solution depending on environmental factors, cost, and overall efficiency goals.

Independent Variable Weight Determination

The analysis will consist of a value hierarchy to organize the various specification of each hydrogen production method based on weights in three major categories: Cost, Efficiency, and Environmental Impact. Environmental Impact will have three subcategories: Global Warming Potential (GWP), Acidification Potential (AP), and Water Consumption (WC). Figure 15 shows the category hierarchy.

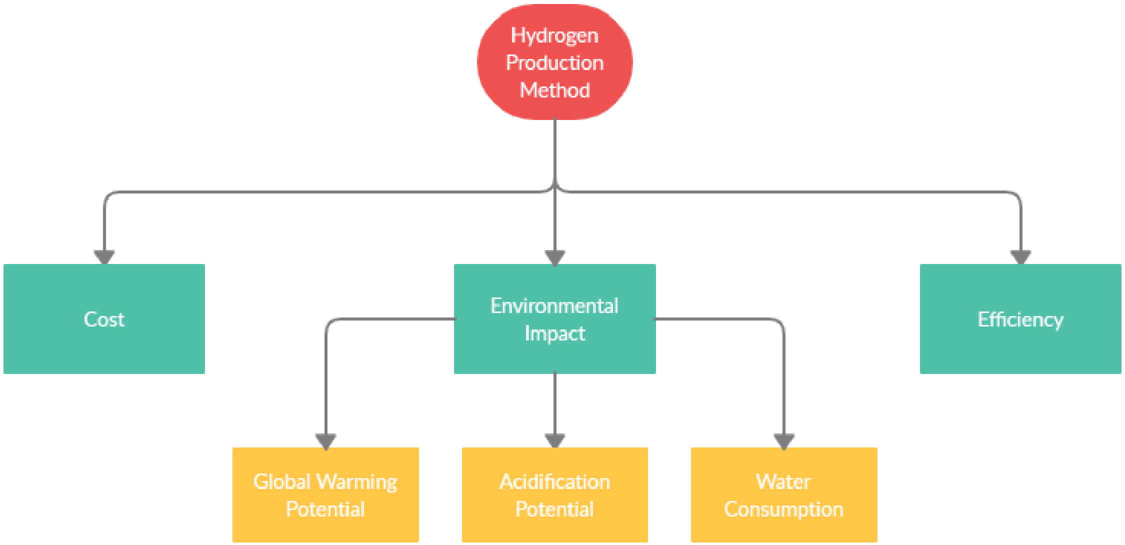


Figure 15: Hierarchy of Weight Categories

Cost was chosen a major consideration for the Air Force since clean energy must be affordable compared to fossil fuel options or bridge the gap utilizing the, “inherent value in the resilience clean energy can provide" [55]. This is stark change from previous years where renewables would only be accepted if they were cheaper than their fossil fuel alternatives [55]. Efficiency is chosen as a variable since higher efficiency limits the amount of energy waste, which in a contested environment, may be precious. Finally, environmental impact is critical for all systems claiming to be part of clean energy. Additionally, a Distinguished Visitors surrey, weapon loader, and U-30 aircraft tow tractor were developed and tested by AFRL in Hawaii; Brigadier General Stan Osserman stated, "the Air Force will want this kind of reliable, quiet, pollution free gear in its support equipment arsenal," this can only be achieved by analyzing the environmental impacts of claimed clean energy solutions [56]. There is no available information on the decision criteria for USAF hydrogen production; hence, the initial weights will be determined from previous USAF energy production projects and guidelines.

The initial weights determined for preliminary analysis will be as follows:

1. 50% Cost: Clean energy solutions must be either comparative in cost to fossil fuel options or provide inherent value through energy resiliency [55].
2. 30% Environmental Impact: integrating alternative sources of energy is a an Air Force goal and ensuring these alternative sources pose the least environmental impact is politically beneficial [57].
    a. 60% Global Warming Potential: the primary method of examining the effect on climate change and the reduction of greenhouse gases by 26-28%, measured directly by GWP, is the United States pledge during the Paris Climate Accords [58]. This makes the reduction of GWP extremely important both politically and environmentally.

    b. 30% Water Consumption: Water is finite resource, is expensive to transport, and is utilized by numerous other venues in the military. Conserving water is paramount and required by U.S. Code 2866 for all military installations [59].
    c. 10% Acidification Potential: A long term measure that must be considered but does not have the same level of damaging potential as greenhouse gases or large water consumption. Prolonged exposure to acid rain can prevent photosynthesis in plants, leaches calcium and magnesium from the soil, and increases chances for lung cancer in humans [60].
3. 20% Efficiency: Conserving energy is critical to relieving energy supply lines and may allow for smaller production plants in areas where land area and energy is limited.

Assumptions

The first assumption is that the weights chosen are correct for the U.S. Air Force. Since there is no specific weight structure provided in any strategic document released, it is still ambiguous what the specific weight of each main component would be. To minimize the effect of this assumption, Sensitivity Analysis must be utilized to account for various focuses on the six different weighted areas. A second major assumption throughout the sensitivity analysis is that each weight being swung is independent. Meaning that a decrease or increase of the importance of a specific weight has no role in affecting the value of another weight. For example, it is assumed that a decrease or increase in the weight of cost will not have an effect on the efficiency of the system.

Current research has not analyzed the independence or dependence of various factors on the various hydrogen production methods.

Production Method Final Values

First, all non-viable options from Table 8, Chapter 2 must be removed. This leaves eight remaining production methods: steam reformation of natural gas, steam reformation of landfill gas, gasification of coal, thermolysis, PEM electrolysis, photovoltaic PEM electrolysis, wind generated PEM electrolysis, and high temperature electrolysis. These methods will be compared in the five categories described and normalized in Section 2: Cost, Global Warming Potential (GWP), Acidification Potential (AP), Water Consumption (WC) and Efficiency. These values for each of the nine viable production options will be evaluated utilizing sensitivity analysis in Excel. Excel was chosen due to the commonality of the software worldwide and Excel's availability on Department of Defense computers. Below is a summarized chart of all values being considered for each of the nine remaining production methods:

Table 9: Complete Table of Values Utilized for Analysis

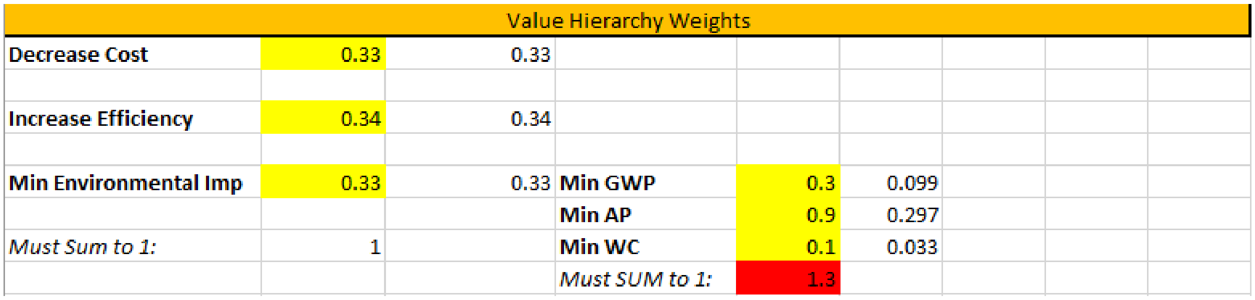
Production Method	GWP	AP	WC	Cost	Efficiency
Ideal	*10*	*10*	*10*	*10*	*100%*
Steam Reformation of Natural Gas	2.94	5.71	9.62	7.71	77%
Steam Reformation of Landfill Gas	9.75	5.71	9.62	6.63	70%
Thermolysis	9.17	9.43	8.99	7.69	72%
PEM Electrolysis	3.33	8.60	8.77	5.06	70%
Photovoltaic PEM Electrolysis	8.53	7.73	8.88	4.43	23%
Wind Generated PEM electrolysis	9.43	9.16	8.88	4.25	4%
High Temperature Electrolysis	8.82	8.42	0.00	6.63	29%
Gasification of Coal	0.00	0.00	9.11	8.43	70%

A production method to note is thermolysis. It is only utilized in nuclear power plants. Nuclear power only provides roughly 20% of the electric load for the United

States' electric grid [58]. This is a limiting factor that must be considered, but for areas that have access to nuclear power it is a viable option. Additionally, small nuclear reactors are being developed for deployed environments making the utilization of Thermolysis a possibility soon [62]. Hence, it will remain part of this analysis and will be considered viable for both domestic and deployed use.

Analysis Tool Design

The analysis tool utilized is Excel. This allows for a wide range of users due to the commonality of the software and ease of understanding. First, the user will determine the three main category's weights; then the user will determine the weights for the three Environmental Impact sub-categories—see Figure 16.. The user will only change the values found in yellow highlighted blocks. Directly below the three main categories and the Environmental Impact sub-categories is a block labeled "*Must SUM to 1:*". If the resulting value is highlighted in red then the weights entered are either above or below 1, meaning the user must revise them as demonstrated in Figure 16.



Value Hierarchy Weights								
Decrease Cost	0.33	0.33						
Increase Efficiency	0.34	0.34						
Min Environmental Imp	0.33	0.33	**Min GWP**	0.3	0.099			
			Min AP	0.9	0.297			
Must Sum to 1:	1		**Min WC**	0.1	0.033			
			Must SUM to 1:	1.3				

Figure 16: Demonstration of User Determined Weights with Error for Environmental Impact

The system utilized for analysis is Multi-Criteria Decision Making (MCDM) through the Simple Multi-Attribute Rating Technique (SMART) due to its commonality and accuracy. In order to utilize Sensitivity Analysis in Excel by determining single dimensional values, one must utilize equations that automatically calculate exponential and piecewise linear values. Excel does not have these functions built in. It is possible to add them to Excel through use of macros. The macros utilized in my analysis allow the inclusion of the exponential single dimensional value function, referred to as ValueE; and the piecewise linear value single dimensional value function, referred to as ValuePL. Appendix B contains the code in text format.

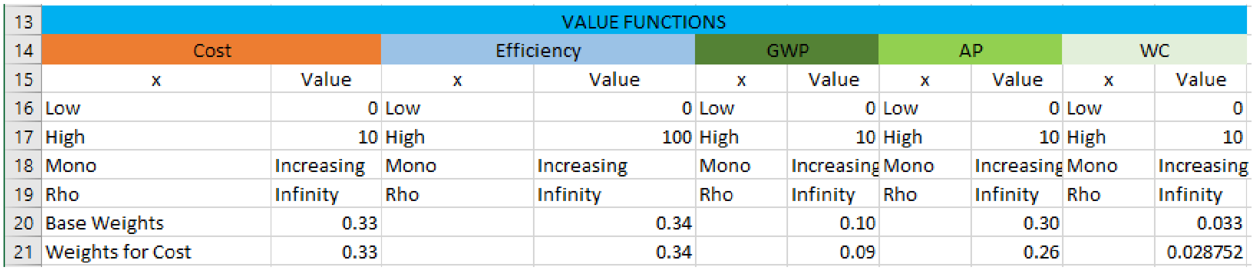
Once the macro is properly loaded, ValueE and ValuePL can be utilized as a standard Excel function. Their Excel formulas are below:

$$ValueE(x, Low, High, Monotonicity, Rho) \tag{28}$$

$$ValuePL(x, X - List, V - List) \tag{29}$$

Where *x* is the score or level of the option, *Low* denotes the lowest possible value, *High* denotes the highest possible score, *Monotonicity* describes if the scale increases or decreases, *Rho* is the exponential coefficient,

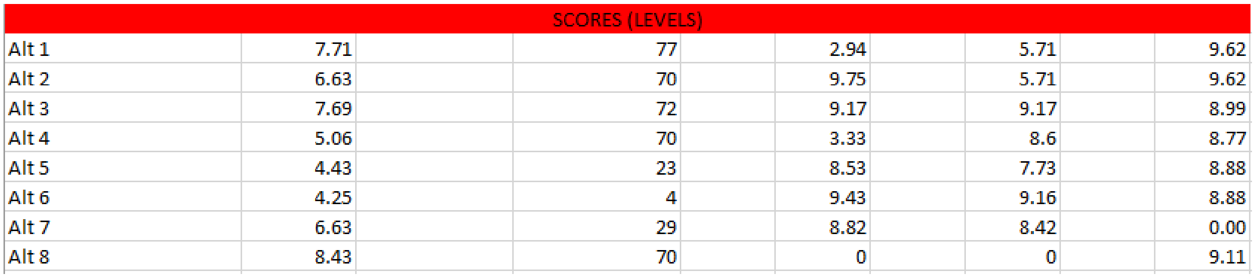
The section, *Value Functions*, sets up the information to be used by the ValueE and ValuePL functions. Since the values were standardized to a scale of 0 to 10, with the exception of Efficiency which is a percentage scale from 0 to 100, all values are ready to be utilized in the Excel calculations without any further revision. The program accounts for the input range of scores from 0 to 10 or 0 to 100 and calculates the scores accordingly. Additionally, the user provided weights are recopied and the Environmental Impact sub-category weights are calculated in row 20 while row 21 is utilized for sensitivity analysis as shown in Figure 18.



13	VALUE FUNCTIONS									
14	Cost		Efficiency		GWP		AP		WC	
15	x	Value	x	Value	x	Value	x	Value	x	Value
16	Low	0	Low	0	Low	0	Low	0	Low	0
17	High	10	High	100	High	10	High	10	High	10
18	Mono	Increasing	Mono	Increasing	Mono	Increasing	Mono	Increasing	Mono	Increasing
19	Rho	Infinity	Rho	Infinity	Rho	Infinity	Rho	Infinity	Rho	Infinity
20	Base Weights	0.33		0.34		0.10		0.30		0.033
21	Weights for Cost	0.33		0.34		0.09		0.26		0.028752

Figure 17: Value Functions

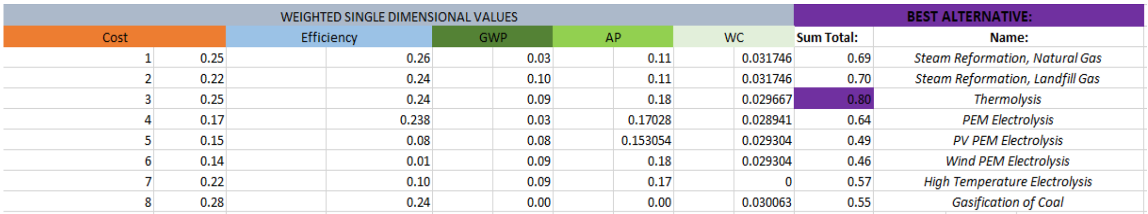
The section, *Scores (Levels),* inserts the scores found in the Figure 19 for each alternative production method as shown in Figure 19.



SCORES (LEVELS)									
Alt 1	7.71		77		2.94		5.71		9.62
Alt 2	6.63		70		9.75		5.71		9.62
Alt 3	7.69		72		9.17		9.17		8.99
Alt 4	5.06		70		3.33		8.6		8.77
Alt 5	4.43		23		8.53		7.73		8.88
Alt 6	4.25		4		9.43		9.16		8.88
Alt 7	6.63		29		8.82		8.42		0.00
Alt 8	8.43		70		0		0		9.11

Figure 18: Scores (Levels)

The results will be displayed first by '*Weighted Single Dimensional Values'* that show a comparison of all eight methods in each specific weighted category. The calculations used are all ValueE since it provides the smoothest analysis by utilizing a continuous curve. The results are displayed as decimal values between 0.00 and 1.00. The worst solution would be 0.00, while the ideal solution would be 1.00. Ideal means lowest cost, highest possible efficiency, and lowest environmental impact. At the far-right hand side of this section, under the purple 'BEST ALT' section; the best alternative given the user provided weights is highlighted in purple as shown in Figure 20.



WEIGHTED SINGLE DIMENSIONAL VALUES						BEST ALTERNATIVE:	
Cost		Efficiency	GWP	AP	WC	Sum Total:	Name:
1	0.25	0.26	0.03	0.11	0.031746	0.69	*Steam Reformation, Natural Gas*
2	0.22	0.24	0.10	0.11	0.031746	0.70	*Steam Reformation, Landfill Gas*
3	0.25	0.24	0.09	0.18	0.029667	0.80	*Thermolysis*
4	0.17	0.238	0.03	0.17028	0.028941	0.64	*PEM Electrolysis*
5	0.15	0.08	0.08	0.153054	0.029304	0.49	*PV PEM Electrolysis*
6	0.14	0.01	0.09	0.18	0.029304	0.46	*Wind PEM Electrolysis*
7	0.22	0.10	0.09	0.17	0	0.57	*High Temperature Electrolysis*
8	0.28	0.24	0.00	0.00	0.030063	0.55	*Gasification of Coal*

Figure 19: Weighted Single Dimensional Values with Highlighted Best Option

Yet, this result does not account for sensitivity analysis. Below, each specific hierarchy category will display a sensitivity analysis chart and graph which shows the user at what weight a different production method may be preferred. Each specific weight is swung from 0% value to 100% in each subsequent sheet. The label of the sheet denotes the weight being swung. The graph demonstrates the best option at different percentage weights of the swung weight with labelled increments of 10%. The other weights will stay in proportion to the weights provided by the user. Figure 21 is an example of the provided graph of the generated Sensitivity Analysis with *Efficiency* being the swung weight.

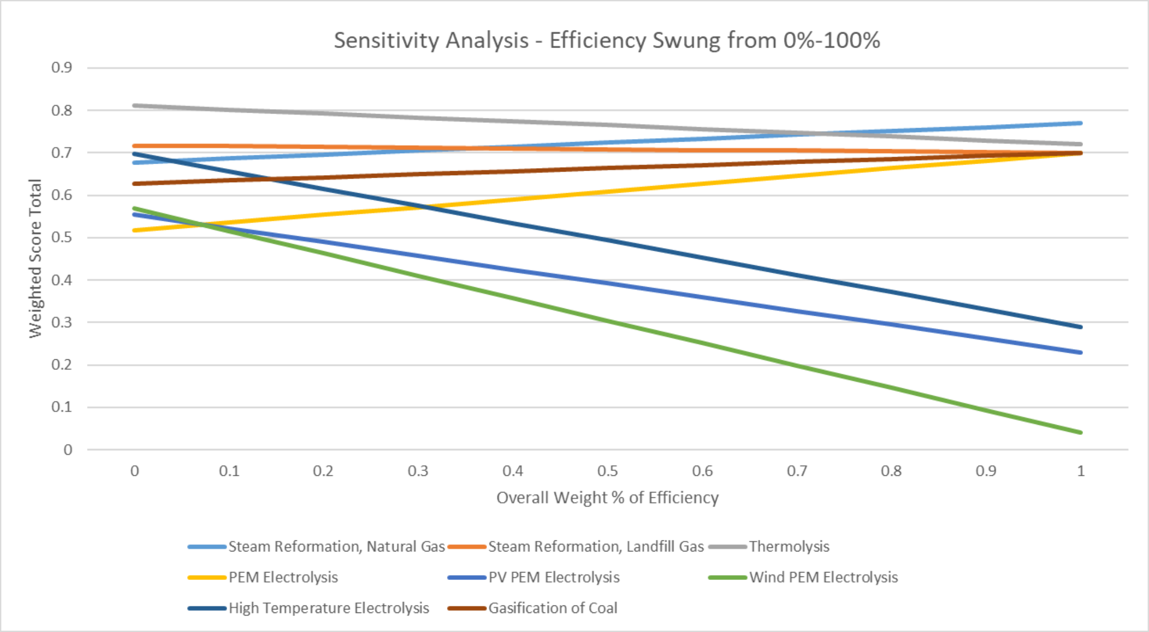


Figure 20: Example of Sensitivity Analysis Performed as Weight Efficiency

IV. Analysis

Analysis Overview

The purpose of the analysis portion is to determine if a general production method is superior to other methods for the U.S. Air Force. This will be done first by comparing the various production methods on the pre-determined weights. Further analysis to determine if there is an optimal solution will be done by through Sensitivity Analysis by swinging the weight of each performance measure and detailing both graphically and numerically the highest scoring solution as the weight is swung.

Results Scoring Based on Initial Weights

Utilizing the determined weights of 50% Cost, 30% Efficiency, 20% Environmental impact with sub-weights of 60% GWP, 30% AP, and 10% WC the scoring of all viable hydrogen production methods is shown in Table 10:

Table 10: Best to Worst Method with Predetermined Weights

Production Method – Best to Worth	Score out of 1.00
Ideal	*1.00*
Thermolysis	0.78
Steam Reformation, Landfill Gas (tied)	0.71
Steam Reformation, Natural Gas (tied)	0.71
Gasification of Coal	0.65
PEM Electrolysis (tied)	0.57
High Temperature Electrolysis (tied)	0.57
PV PEM Electrolysis	0.46
Wind PEM Electrolysis	0.41

Interpretation of Scoring Based on Initial Weights

1.00 would be the ideal solution. The optimal method is Thermolysis with a sum total of 0.78 out of 1.00. Of interest, is the large gap between Thermolysis and the other options. It appears that Thermolysis will remain the dominate production method even if there are changes to the decision weights, but this assumption will only be verified by sensitivity analysis. Following thermolysis is Steam Reformation of Natural Gas and Landfill Gas at 0.71. Of great surprise, due to its low scores for Environmental Impact, Gasification of Coal scores fourth highest. Next, another tie follows Gasification of Coal with PEM Electrolysis and High Temperature Electrolysis holding the exact same score.

Sensitivity Analysis

As a weight is being swung during sensitivity analysis, all other weights will remain in a similar proportion to each other.

Cost

Sensitivity analysis while swinging the weight of cost demonstrates that Thermolysis, from 0% weighted Cost to 83% weighted cost, achieves a higher overall score than the other production methods. When the weight of cost exceeds 83%, the highest scoring option becomes Gasification of Coal. Assuming a nuclear power plant is unavailable making Thermolysis non-viable, when cost is swung from 0% to 52% Steam Reformation of Landfill Gas is the highest scoring production method, then from 53% to 71% Steam Reformation of Natural Gas scores highest, and finally from 72% to 100% Gasification of Coal scores highest. Figure 22 displays these results graphically.

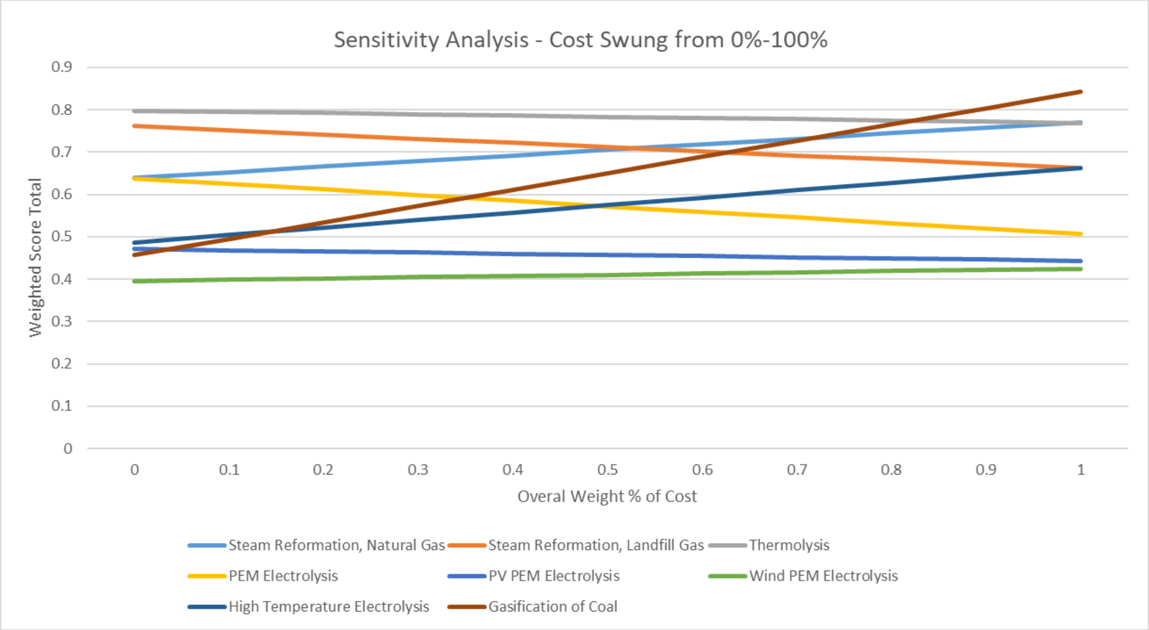


Figure 21: Graph of Sensitivity Analysis of Cost's weight swung from 0% to 100% Efficiency

Sensitivity analysis while swining the weight of efficiency from 0% to 100% demonstrates that Thermolysis from 0% to 72% weighted efficiency, acheives a higher overall score than the other production methods. When the weight of efficiency exceeds 72%, the highest scoring option becomes Steam Reformation of Natural Gas. Assuming thermolysis is non-viable, when efficiency is swung from 0% to 35% Steam Reformation of Natural Gas scores highest, then finally from 36% to 100% Steam Reformation of Landfill Gas scores highest. Figure 23 displays these results graphically.

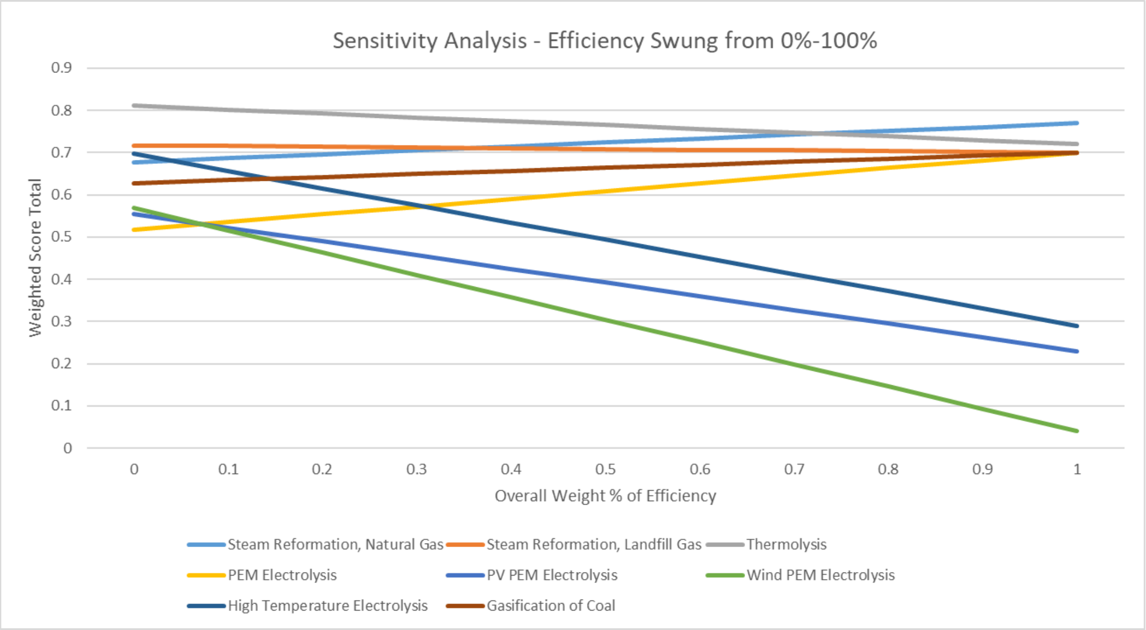


Figure 22: Graph of Sensitivity Analysis for Efficiency's weight swung from 0% to 100%

Environmental Impact

Sensitivity analysis while swining the weight of environmental impact from 0% to 100% demonstrates that Thermolysis from 5% to 98% weighted environmental impact, acheives a higher overall score than the other production methods. When the weight of environmental impact exceeds 98%, the highest scoring option is Wind PEM Electrolysis. When the weight of environmental impact drops below 5%, the highest scoring option is Gasification of Coal. Assuming thermolysis is non-viable, when environmental impact is swung from 0% to 5% Gasification of Coal scores highest, then from 6% to 18% Steam Reformation of Natural Gas scores highest, then from 19% to 83% Steam Reformation of Landfill Gas scores highest, and finally from 84% to 100% Wind PEM Electrolysis is the highest scoring option. Figure 24 displays these results graphically.

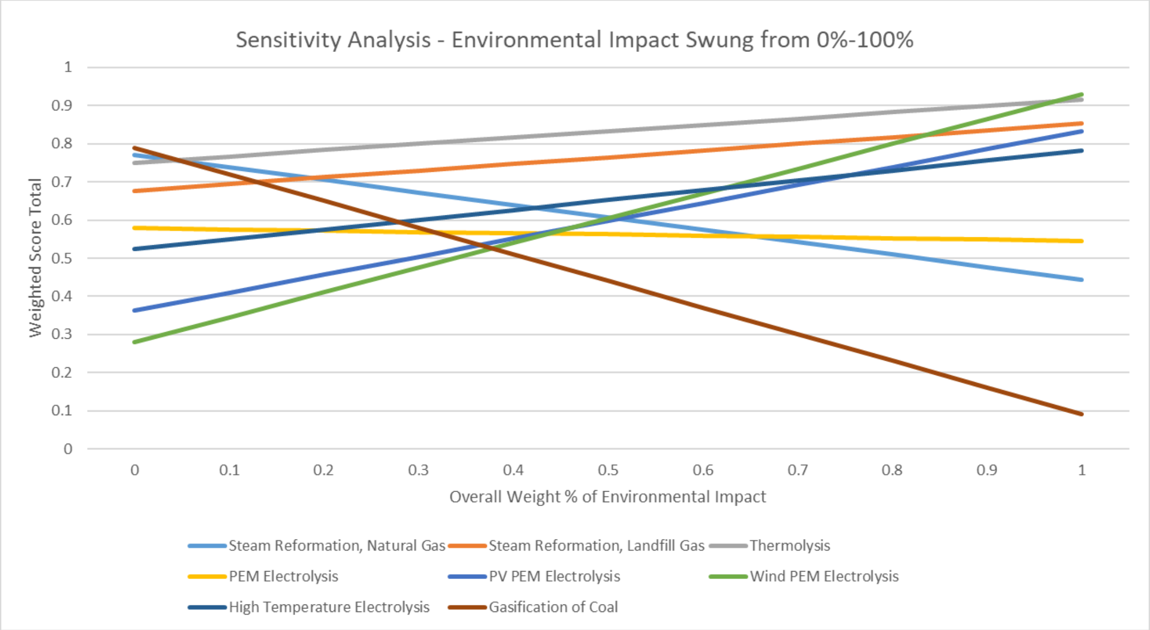


Figure 23: Graph of Sensitivity Analysis for Environmental Impact's weight swung from 0% to 100%

Global Warming Potential

Sensitivity analysis while swining the weight of global warming potential from 0% to 100% demonstrates that Thermolysis from 0% to 65% weighted GWP, acheives a higher overall score than the other production methods. When the weight of GWP exceeds 65%, the highest scoring option is Steam Reformation of Landfill Gas. Assuming thermolysis is non-viable, when efficiency is swung from 0% to 11% Steam Reformation of Natural Gas scores highest, from 12% to 100% Steam Reformation of Landfill Gas scores highest, then from 19% to 83% Steam Reformation of Landfill Gas is the highest scoring option. Figure 25 displays these results graphically.

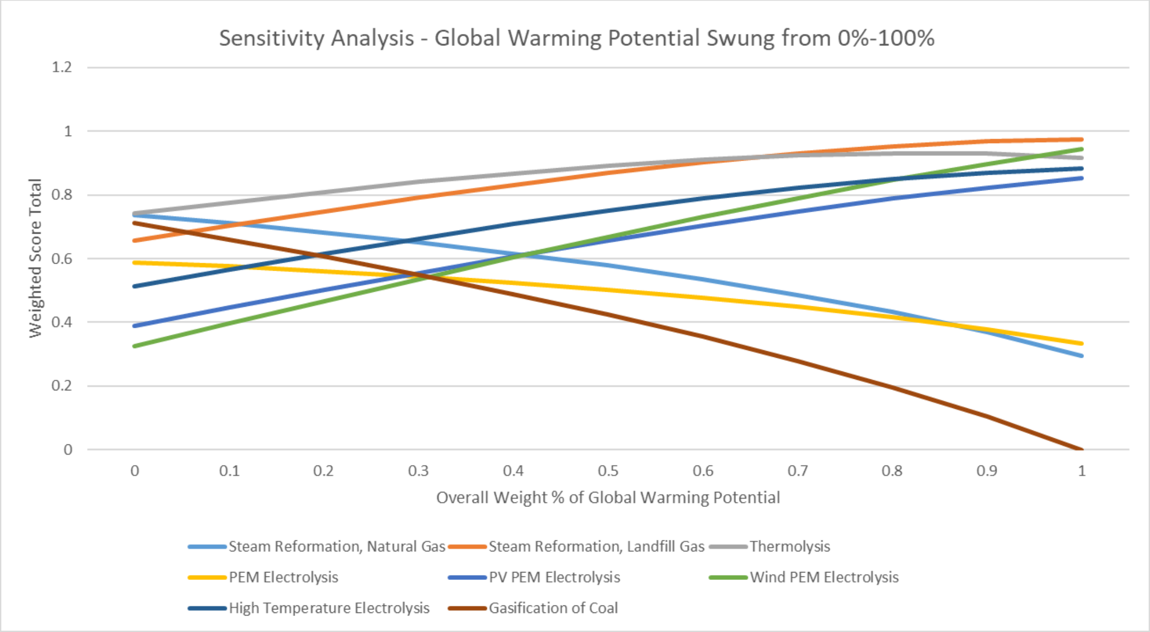


Figure 24: Graph of Sensitivity Analysis for Global Warming Potential's weight swung from 0% to 100%

Acidification Potential

Sensitivity analysis while swining the weight of acidification potential from 0% to 100% demonstrates that Thermolysis from 0% to 100% weighted AP, acheives a higher overall score than the other production methods. Assuming thermolysis is non-viable, when AP is swung from 0% to 29% Steam Reformation of Natural Gas scores highest, then from 29% to 37% Steam Refomation of Landfill Gas scores highest, from 38% to 70% High Temperature Electrolysis scores highest, from 71% to 78% PEM Electrolysis has the highest score, and finally from 79% to 100% Wind PEM Electrolysis is the highest scoring option. Figure 26 displays these results graphically.

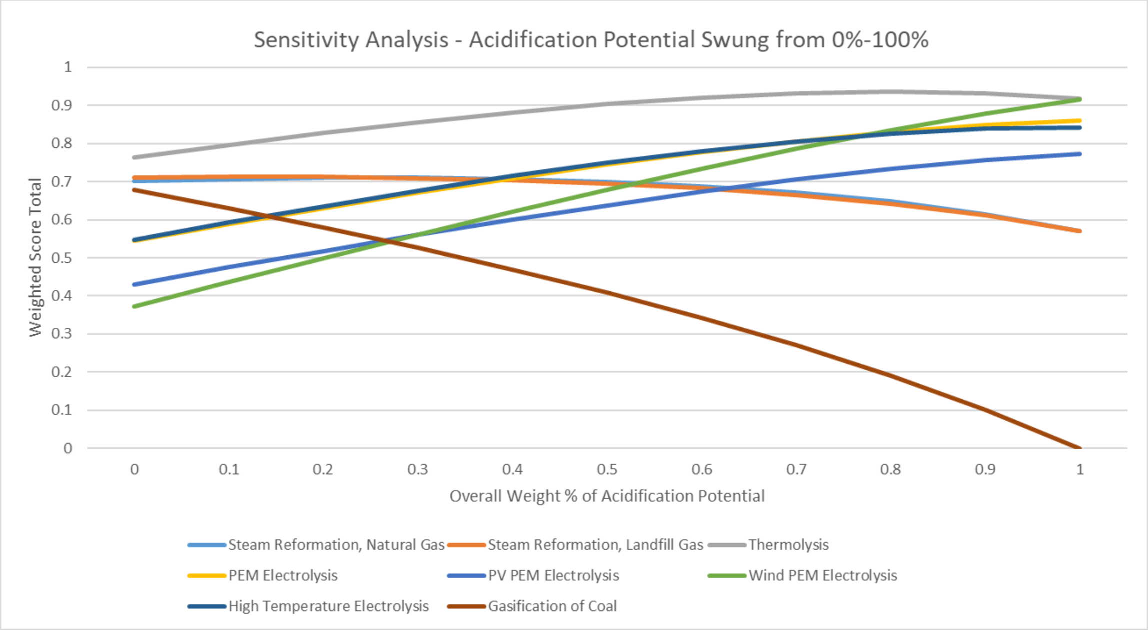


Figure 25: Graph of Sensitivity Analysis of Acidification Potential Weight Swung from 0% to 100%

Water Consumption

Sensitivity analysis while swining the weight of water consumption from 0% to 100% demonstrates that Thermolysis from 0% to 60% weighted water consumption, acheives a higher overall score than the other production methods. When the weight of environmental impact exceeds 60%, the highest scoring option is Reformation of Natural Gas. Assuming thermolysis is non-viable, when environmental impact is swung from 0% to 24% Reformation of Landfill Gas scores highest, then finally from 25% to 100% Steam Reformation of Natural Gas scores highest. Figure 27 displays these results graphically.

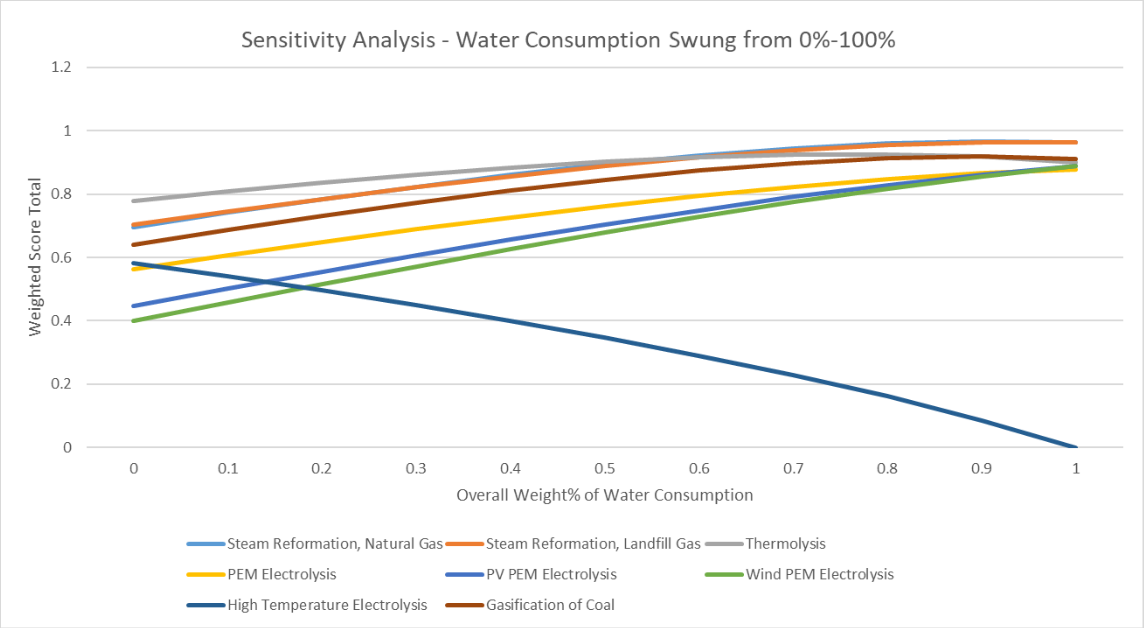


Figure 26: Graph of Sensitivity Analysis for Water Consumption's weight swung from 0% to 100%

Sensitivity Analysis Interpretation

In every case, thermolysis was the optimal solution for all weights for at least 50% of each weights swing from 0% to 100%. Thermolysis held this status near the center of the weights range and in every case was the optimal solution between 5% and 60%. No weight exceeded 50% of the total base weights for analysis. Above or below this range of values, especially toward the extreme limits of a weight's maximum or minimum value other options exceeded the score of thermolysis. This demonstrates that in most feasible cases where an individual weight will not exceed 60%, thermolysis will be the optimal solution. There is only one exception to this. If Environmental Impact is valued at less than 5%, then thermolysis is no longer optimal due to the low cost of Gasification of Coal. An Environmental Impact score below 5% is highly unlikely since one of the main draws to hydrogen is the concept of 'Green Hydrogen' meaning hydrogen as a low impact fuel on natural resources.

Although thermolysis is the optimal solution, it is dependent on the availability of nuclear power. This is a significant restraint. As the country pursues cleaner energy alternatives, nuclear energy has been found to, "be a feasible option for providing electricity to military installations" per a 24-million-dollar study funded by the U.S. Navy [63]. Nuclear options are not off the table. The two options predominantly featured after thermolysis are Steam Reformation of Landfill Gas followed by Steam Reformation of Natural Gas. Throughout the sensitivity analysis Landfill Gas exceeds thermolysis twice beyond 60% swung weighted value, and with thermolysis excluded gains the greatest amount of percentage points while being the optimal solution at 248. Natural gas follows Landfill gas at 180 points. Through the entire sensitivity analysis, the most stable scoring option, was PEM Electrolysis. It frequently retained a middle position and very rarely dropped significantly but did occasionally have impressive gains as weights moved above 70%.

Results with Provided Cost Values Changed

Chapter 2 normalized cost values were based on the 2019 costs per kilogram of H_2. In 2014, similar analysis was performed by Diner and Acar that greatly increases the cost per kilogram of hydrogen produced by thermolysis decreasing its normalized value from 7.69 to 6.12 [13]. Additionally, Dincer and Acar decreased the cost of both Steam Reformation of Natural Gas, Coal Gasification, and Electrolysis so that their normalized values changed from 7.71 to 9.28, 8.43 to 9.11, and 5.06 to 6.12 [13]. Detailed in Table 11, these changes in overall scores caused an overall small changes in the overall best to worst opinions except for the scores of Thermolysis and Electrolysis. Steam Reformation methods and Thermolysis remained the top options while High Temperature Electrolysis, PV PEM Electrolysis, and Wind PEM Electrolysis remained the worst options. To note is that under their cost analysis Steam Reformation scored higher than Thermolysis, and that PEM Electrolysis performed higher than Gasification of Coal. These results further verify that the 2019 results that were utilized in this document are realistic since the average change between the total score of the 2014 and 2019 production methods was 0.0375, with the 4 out of 8 methods having no change. The largest score change was for PEM Electrolysis at 0.12, a 17% change. This large change is most likely caused by the fluctuation of operating costs for PEM Electrolysis depending on plant size. Thermolysis decreased by 0.07 points primarily due to the 2014 analysis which focused on general thermolysis not specifically Cu-Cl or S-I cycle thermolysis. This change increases both the cost, GWP, and AP of thermolysis resulting in its overall lower scoring compared to Steam Reformation of Landfill and Natural Gas.

Table 11: Best to Worst Method with Predetermined Weights from 2014 Values

Production Method – Best to Worth (New)	**Score out of 1.0**
Ideal	*1.0*
Steam Reformation, Landfill Gas	0.79
Steam Reformation, Natural Gas	0.78
Thermolysis	0.71
PEM Electrolysis	0.69
Gasification of Coal	0.68
High Temperature Electrolysis (tied)	0.57
PV PEM Electrolysis	0.46
Wind PEM Electrolysis	0.41

Further Cost Analysis

The cost value utilized in the analysis overall analysis was total lifecycle cost of each various production cycle as detailed in Chapter 2. Further decomposition of cost into acquisition cost, and operating cost is required for full analysis of the major production types consisting of reformation, electrolysis, and thermolysis. Acquisition cost is the total capital cost including machinery, buildings, piping, electric, and installation. Operating cost is the total cost per kilogram of H_2 manufactured based on plant overhead and seed material value. Below is the acquisition cost and operating cost centralized (large) and decentralized (small) electrolysis and methane reforming plants, and a large nuclear thermolysis plant. To note is the thermolysis value is the minimum cost, the large methane reformation plant's capacity is 380,000 kilograms of H_2 per day while the large electrolysis plant's capacity is 52,300 kilograms of H_2 per day. One of the major advantages of PEM electrolysis is its small-scale distributed production yielding much smaller plants sizes distributed over a local area compared to other production options [38].

Table 12: Acquisition and Operating Cost of Major Production Types for Small and Large Plants

Production Type and Plant Size	Acquisition Cost ($M)	Operating Cost based on 1/2 total lifecycle ($/kg of H_2)
Methane Reformation Small	0.8 [59]	$3.83 [59]
Electrolysis Small	1.1 [59]	$4.30 [59]
Nuclear Thermolysis Large	39.6 [38]	$2.17-$2.63 [38]
Methane Reformation Large	111.2 [59]	$0.90-$3.50 [38] [59]
Electrolysis Large	38.1 [59]	$2.92 [59]

Table 12 demonstrates that the larger the plant, even with acquisitions cost, will produce hydrogen at a lower overall cost rate than a small plant. Larger, centralized plants have a 40-year expected lifespan compared to the 20-year lifespan of small, decentralized plants [59]. Yet, these larger plants require centralized production; hence, requiring transportation of hydrogen to the location of need. Even with this added transportation cost, Khzouz et. al. determined through, “the hydrogen transportation and dispensing model…outcomes showed that centralized production via methane reformation is still the most prominent alternative compared to the other decentralized methods” [59]. Yet, a stated assumption is that the maximum travel distance for the hydrogen is 300 kilometers which may be significantly shorter than the actual travel distance necessary if a centralized model is pursued. Although there is current research on what jobs are created by hydrogen, the personnel required for each type of hydrogen production plant is not. It is assumed that labor costs for a small production plant is roughly 40% the cost of a large production plant [59].

Conclusion and Recommendations

Summary of Results, Research Questions and Answers

For the weights selected, the greatest to least scoring options are as follows:

1. Thermolysis
2. Steam Reformation of Landfill Gas (tied)
2. Steam Reformation of Natural Gas (tied)
3. Gasification of Coal
4. PEM Electrolysis (tied)

4. High Temperature Electrolysis (tied)
5. PV PEM Electrolysis
6. Wind PEM Electrolysis

What are the critical aspects of the decision analysis for an U.S. Air Force perspective?

In summary, the goals listed in the Air Force Energy Flight Plan 2017-2036 is to acquire a drop-in, reliable, uninterruptable, and diversified sources of energy. Hydrogen accomplishes these tasks due to its zero-emission use producing only water as its by product from a fuel cell, ability to be produced universally with only water and electricity, and proven fuel-cell technology which can immediately be utilized for generator or ground vehicle production. Yet, to be a suitable candidate a stakeholder must consider cost, efficiency; and environmental impact which includes global warming potential, acidification potential, and water consumption. These quantities are measurable, well-researched, and cover critical criteria for future stakeholders.

What parameters and weights were utilized in decision analysis?

1. Cost at 50%.
2. Environmental Impact at 30%.
    a. Global Warming Potential at 60%.
    b. Water Consumption at 30%.
    c. Acidification Potential at 10%.
3. Efficiency at 20%.

Is there an optimal solution?

Throughout sensitivity analysis, thermolysis was the optimal solution. In every sensitivity analysis case, thermolysis scores highest for at least 50% of the weight's range. This demonstrates that for most cases, thermolysis is the best solution. The caveat is that nuclear power must be available for Thermolysis. Throughout sensitivity analysis cases, reformation of landfill gas or steam reformation of natural gas are predominantly featured behind thermolysis.

Challenges and Safety of Thermolysis

The greatest challenge with Thermolysis is necessary renovation of current nuclear power plants to accommodate hydrogen production. There are currently no active thermolysis production plants so determining an average cost of retrofitting a current nuclear power plant is not available. There have been three main studies on the safety of utilizing a Cu-Cl thermolysis cycle that, "developed control systems and safety precautions for various risk scenarios encountered in commercial operation of a nuclear hydrogen plant" [53]. These studies were performed in 2010 to prepare Canadian Type IV nuclear reactors to be retrofitted with a Thermolysis hydrogen generator and is considered to be a safe option for current nuclear power plants [53].

Consideration of PEM Electrolysis for Military Application

Although a mid-range scoring option, PEM Electrolysis is the most flexible option for demands less than 1,500 kilograms of H_2 per day. Nel hydrogen, a leader in the hydrogen market by manufacturing and installing over 3,500 hydrogen gas electrolyzers, produces modular hydrogen production plants that can operate completely autonomously. These electrolyzers are manufactured inside Conex shipping containers for ease of transport. Their smallest containerized plant produces 531 kilograms of H_2/day while their largest containerized plant produces 1,062 kilograms of H_2/day [51]. Both containerized plants can operate in temperatures ranging from -20 to 40 degrees centigrade with a total plant area of 45.75 square meters.

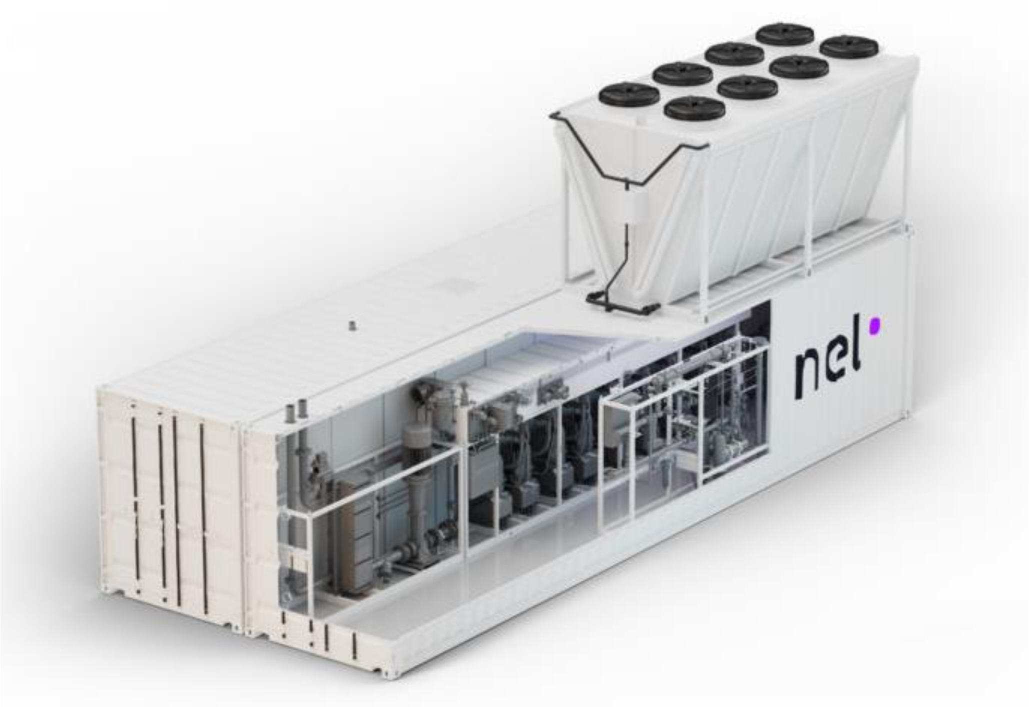


Figure 27: Example of Containerized PEM Electrolyzer [51]

Containerization should be of great interest for hydrogen production methods in remote or contested environments. Conex shipping containers are sturdy, easy to transport, have a 25-to-30-year lifespan with little care, and can be relocated indefinitely without compromising their structural integrity. The convenience of containerized electrolyzers makes PEM Electrolysis a feasible solution for proven and reliable H_2 production where a small, portable package is needed.

Study Limitations

There are potential areas where variations could be created that deviate the highest scoring options from my analysis. The first major area where this is possible is new research into the various hydrogen production methods, changing the values currently listed in this document. Many of the productions methods examined have not been massed produced and are simply lab based; these means that the technology may or may not exceed laboratory-based results.

As technology improves and utilization of hydrogen fuel cell technology increases; the development of various hydrogen production methods will improve. It is plausible that options listed as non-viable in my analysis may become viable in the coming years. Even the results from energy sources that are currently being utilized could also fluctuate depending on power source and as production efficiency improves over time.

Additional limitations in research may be found on the prescribed user weights for the United States Air Force. Since there is no available data on what the decision analysis criteria for alternate sources of fuel are for the USAF; the baseline utilized was determined from numerous sources as the most probable weight configuration. Mitigating steps included sensitivity analysis, utilizing numerous sources to compile weights and reasons for each criteria utilized, and providing an imbedded spreadsheet for user calculation in Appendix C. Finally, as mentioned in Chapter III: Methodology, it is assumed that each weighted category is independent. There is no current research to disprove this assumption but additional research may change this finding.

Recommendations for Action

If nuclear power is available thermolysis is the best production method to pursue. If it is not available, Reformation of Landfill Gas is recommended since it is a renewable fuel source as long as waste is being produced. Essentially, landfill gas can be produced anywhere waste is disposed of making it an uninterruptible energy source while simultaneously eliminating the need for natural gas shipments and cost. Although the fourth highest scoring option is gasification of coal, it cannot be recommended since it is the highest carbon producing option and requires continuous fuel inputs that eliminates hydrogen's ability from being an uninterrupted energy source. Finally, PEM electrolysis should be considered as a good alternative due to its production flexibility and stable performance throughout the Sensitivity Analysis. PEM Electrolysis scored below thermolysis and both steam reformations except when Acidification Potential's weight is pushed to over 35% of the total weighted value. This is of interest since PEM Electrolysis is the production method chosen by Nikola, the emerging leader in renewable trucking. This aligns with their goal of producing hydrogen at each one of their gas stations along U.S. highways with room for supplementation of renewable power sources. PEM electrolysis is a proven, simple, and universally viable method since it does not rely on landfill gas, nuclear energy, or natural gas which may be location dependent. For this reason, PEM Electrolysis plants could be used to provide on-site and on-demand hydrogen in a small package for a variety of USAF locations. For small application of hydrogen production less than 1,000 kilograms per day, PEM Electrolysis is recommended due to its low capital cost, ease of maintenance, and proven portable plant design.

Steam reformation of natural gas is only recommendation for CONUS bases that have access to natural gas. Utilization of natural gas removes the possibility of an uninterruptable source and a key aspect of hydrogen's future, green hydrogen; therefore, it should be only utilized as a backup or as a need-based solution.

Recommendations for Future Research

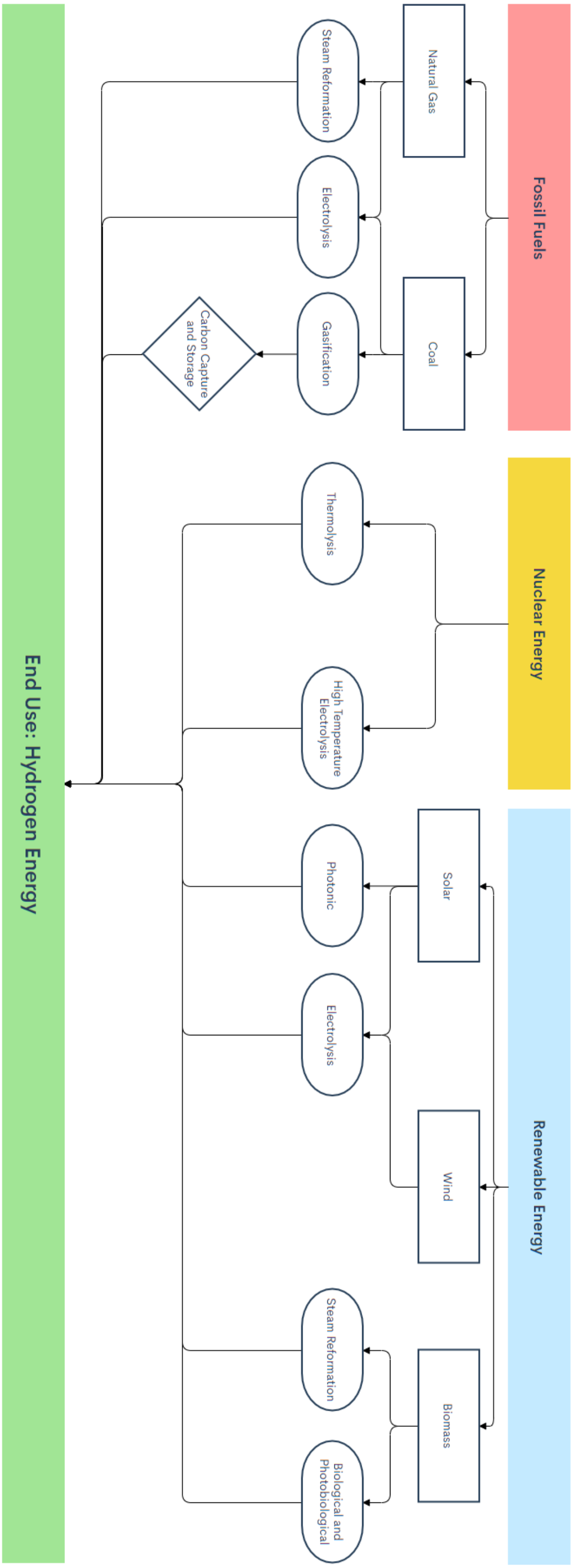
The main area of further research needed is determining whether the various factors of examination such as cost, efficiency, and environmental impacts are independent or dependent. If dependent, what is this relationship and how does it affect the overall scoring of each option. Additionally, there is no information on the reliability of the systems that have been only tested in laboratories, and limited reliability analysis on the systems built. Reliability analysis is necessary if these production methods are to be considered for military operations. Further research into small, portable PEM electrolysis plants would be beneficial for deployable military application. Additionally, portable options would allow for increased flexibility for small Stations or Bases to incorporate hydrogen into their vehicle fleet if demand or available space is small. These small, portable plants are a safe and reliable option with over 3,500 examples operating worldwide [51].

Overall, a switch to hydrogen vehicles takes into account a number of areas beyond simple production. Hydrogen storage, transportation, and vehicle pick are a few of the numerous areas where further research into the complete hydrogen energy cycle would be necessary before a switch or implementation of hydrogen fuel cell technology in USAF ground vehicles.

Hydrogen for Peace

In the 1953, President Eisenhower gave the famous *Atoms for Peace* speech at the United Nations general assembly leading the nuclear nations of the world to band together to utilize atoms not just for war, but for peace. Hydrogen, the ingredient for the deadliest weapon every created, the thermo-nuclear bomb, is one of these atoms that can be used for peace. Thermolysis, Steam Reformation of Landfill Gas, and PEM Electrolysis stand as solutions to providing uninterruptible production of fuel, a drop in source of energy, and decreased reliance on fossil fuels for the United States Air Force. In the words of Brigadier General Stan Osserman on hydrogen fuel cell technology after viewing a tow vehicle prototype: “This is the technology that can help the Air Force be more resilient…I have a feeling that that this will perform as well as our other prototypes, and the Air Force will want this kind of reliable, quiet, pollution free gear in its support equipment arsenal” [56].

Appendix A


Fossil Fuels
Natural Gas
Coal
Steam Reformation
Electrolysis
Gasification
Carbon Capture and Storage
Nuclear Energy
Thermolysis
High Temperature Electrolysis
Renewable Energy
Solar
Wind
Biomass
Photonic
Electrolysis
Steam Reformation
Biological and Photobiological
End Use: Hydrogen Energy

Appendix B

```
Function ValuePL(x, Xi, Vi)
   i = 2
   Do While x > Xi(i)
      i = i + 1
   Loop
   ValuePL = Vi(i - 1) _
      + (Vi(i) - Vi(i - 1)) * (x - Xi(i - 1)) / (Xi(i) - Xi(i - 1))
End Function

Function ValueE(x, Low, High, Monotonicity, Rho)
   Select Case UCase(Monotonicity)
      Case "INCREASING"
         Difference = x - Low
      Case "DECREASING"
         Difference = High - x
      End Select
   If UCase(Rho) = "INFINITY" Then
      ValueE = Difference / (High - Low)
   Else
      ValueE = (1 - Exp(-Difference / Rho)) / (1 - Exp(-(High - Low) / Rho))
   End If
End Function
Function ValueL(x, Low, High, Monotonicity)
   Select Case UCase(Monotonicity)
      Case "INCREASING"
         Difference = x - Low
      Case "DECREASING"
         Difference = High - x
      End Select
   ValueL = Difference / (High - Low)
End Function
Function Quad(x, Xi, Yi)
   Xnorm = (x - Xi(1)) / (Xi(3) - Xi(1))
   Xm = (Xi(2) - Xi(1)) / (Xi(3) - Xi(1))
   Ym = (Yi(2) - Yi(1)) / (Yi(3) - Yi(1))
   a = (Ym - Xm) / (Xm * Xm - Xm)
   b = 1 - a
   Ynorm = a * Xnorm * Xnorm + b * Xnorm
   Quad = Yi(1) + Ynorm * (Yi(3) - Yi(1))
End Function
```

Appendix C

Value Hierarchy Weights					
Decrease Cost	0.5	0.5			
Increase Efficiency	0.3	0.3			
Min Environmental Imp	0.2	0.2	**Min GWP**	0.6	0.12
			Min AP	0.3	0.06
Must Sum to 1:	1		**Min WC**	0.1	0.02
			Must SUM to 1:	1	

VALUE FUNCTIONS								
Cost		Efficiency		GWP		AP		
x	Value	x	Value	x	Value	x	Value	
Low	0	Low	0	Low	0	Low	0	Lo
High	10	High	100	High	10	High	10	Hi
Mono	Increasing	Mono	Increasing	Mono	Increasing	Mono	Increasing	M
Rho	Infinity	Rho	Infinity	Rho	Infinity	Rho	Infinity	Rh
Base Weights	0.50		0.30		0.12		0.06	
Weights for Cost	0.50		0.30		0.12		0.06	

SCORES (LEVELS)				
Alt 1	7.71	77	2.94	5.71
Alt 2	6.63	70	9.75	5.71
Alt 3	7.69	72	9.17	9.43
Alt 4	5.06	70	3.33	8.6
Alt 5	4.43	23	8.53	7.73
Alt 6	4.25	4	9.43	9.16
Alt 7	6.63	29	8.82	8.42
Alt 8	8.43	70	0	0

WEIGHTED SINGLE DIMENSIONAL VALUES				
Cost		Efficiency	GWP	AP
1	#NAME?	#NAME?	#NAME?	#NAME?
2	#NAME?	#NAME?	#NAME?	#NAME?
3	#NAME?	#NAME?	#NAME?	#NAME?
4	#NAME?	#NAME?	#NAME?	#NAME?
5	#NAME?	#NAME?	#NAME?	#NAME?
6	#NAME?	#NAME?	#NAME?	#NAME?
7	#NAME?	#NAME?	#NAME?	#NAME?
8	#NAME?	#NAME?	#NAME?	#NAME?

References

[1] United States Air Force, "United States Air Force Energy Flight Plan 2017-2036," United States Air Force, Washington, D.C., 2017.

[2] Wright-Patterson AFB, "How the Air Force got smarter about its aviation fuel use in 2018," U.S. Air Force, 12 December 2018. [Online]. Available: https://www.wpafb.af.mil/News/Article-Display/Article/1712437/how-the-air-force-got-smarter-about-its-aviation-fuel-use-in-2018/. [Accessed 16 July 2020].

[3] P. Murphy, "Why 'mond-boggling stupid' hydrogen-powered cars are not going away," S&P Global, 25 November 2019. [Online]. Available: https://www.spglobal.com/marketintelligence/en/news-insights/latest-news-headlines/why-mind-bogglingly-stupid-hydrogen-powered-cars-are-not-going-away-55328443. [Accessed 27 October 2020].

[4] J. Baronas and G. Achtelik, "Joint Agency Staff Report on Assembly Bill 8: 2020 Annual Assessment of Time and Cost Needed to Attain 100 Hydrogen Refueling Stations in California," California Energy Commission, Sacramento, 2020.

[5] OpenSecrets.org, "Oil and Gas: Money to Congress," Center for Responsive Politics, 2020. [Online]. Available: https://www.opensecrets.org/industries/summary.php?cycle=2020&ind=E01. [Accessed 16 July 2020].

[6] Nikola, "Hydrogen," 2020. [Online]. Available: https://nikolamotor.com/hydrogen. [Accessed 16 July 2020].

[7] J. O'Dell, "Nikola Detail Ambitious Plan for Hydrogen and Service Network," Trucks.com, 22 April 2019. [Online]. Available: https://www.trucks.com/2019/04/22/nikola-ambitious-plan-hydrogen-service-network/. [Accessed 16 July 2020].

[8] Navigant Research, "Advanced Energy Now 2019 Market Report," Advanced Energy Economy, San Francisco, 2019.

[9] Airbus, Twitter, 21 September 2020. [Online]. Available: https://twitter.com/Airbus/status/1308023305383936000/photo/1. [Accessed 21 September 2020].

[10] C. Ryan, "Airbus Unveils Hydrogen Designs for Zero-Emission Flight," Bloomberg, 21 September 2020. [Online]. Available: https://www.bloombergquint.com/technology/airbus-unveils-hydrogen-powered-designs-for-zero-emission-flight. [Accessed 21 September 2020].

[11] P. Sillers, "Why this space age airplane could change flying forever," CNN, 3 October 2020. [Online]. Available: https://www.cnn.com/travel/article/airbus-zero-emissions-concept-plane/index.html. [Accessed 29 October 2020].

[12] S. Rahman, M. Masdar, M. Rosli, E. Majlan, T. Husaini, S. Kamarudin and W. Daud, "Overview biohydrogen technologies and application in fuel cell technology," *Renewable and Sustainable Energy Reviews*, vol. 2016, no. 66, pp. 137-162, 2016.

[13] I. Dincer and C. Acar, "Review and evaluation of hydrogen production methods for better sustainability," *International Journal of Hydrogen Energy*, vol. 40, no. 34, pp. 11094-11111, 2015.

[14] C. Acar and I. Dincer, "Comparative assessment of hydrogen production methods from renewable and non-renewable sources," *International Journal of Hydrogen Energy*, vol. 220, pp. 1-12, 2014.

[15] M. Baksh and M. Ackley, "Pressure Swing Adsorption Process For The Production of Hydrogen". United States Patent 6503299, 7 January 2003.

[16] Environmental Protection Agency, "Basic Information on Landfill Gas," [Online]. Available: https://www.epa.gov/lmop/basic-information-about-landfill-gas. [Accessed 18 December 2019].

[17] R. Williams, K. Kornbluth, B. Jenkins and M. Gildart, "Estimates of Hydrogen Production Potential an Costs from California Landfill Gas," in *15th Europena Biomass Conference & Exhibition*, Berlin, 2007.

[18] A. Doyle, "Producing hydrogen from plastic waste," The Chemical Engineer Magazine, 17 October 2017. [Online]. Available: https://www.thechemicalengineer.com/news/producing-hydrogen-from-plastic-waste/. [Accessed 18 December 2019].

[19] B. Burcu, "Pyrolysis: A Sustainable Way from Waste to Energy," in *Forebiom: Potentials for Realizing Negative Carbon Emissions*.

[20] F. Reimert, H. J. Renner, W. Boll, E. Supp, M. Brejc, W. Liebner and G. Schaub, "Gas Production, 2 Processes," *Ullmanns Encyclopedia of Industrial Chemistry*, vol. 16, pp. 423-482, 2011.

[21] Y. Wang, T. Liu, L. Lei and F. Chen, "High temperature solid oxide H20/CO2 co-electrolysis for syngas production," *Fuel Processing Technology*, vol. 142, p. 2, 2016.

[22] O. F. Mehmet, I. Dincer and M. A. Rosen, "Energy and exergy assessments of the hydrogen production step of a copper-chlorine thermochemical water splitting cycle driven by nuclear-based heat," *Internation Journal of Hydrogen Energy*, vol. 33, pp. 6456-6466, 2008.

[23] A. Z. Ozbilen, "Life Cycle Assessment of Nuclear-Based Hydrogen Production Via Thermochemical Water Splitting Using A Copper-Chlorine (Cu-Cl) Cycle," Universtiy of Ontario Institute of Technology, Oshawa, 2010.

[24] D. B. Levin, L. Pitt and M. Love, "Biohydrogen production: prospects and limitations to practical application," *International Journal of Hydrogen Energy*, vol. 29, pp. 173-185, 2004.

[25] S. Kim, K. Choi, J. Chung and J. Kim, "Biological hydrogen by anaerobic digestion of food waste and sewage slude treated using various pretreatment technologies," *Biodegradation*, vol. 24, no. 6, pp. 753-764, 2013.

[26] I. Dincer and C. Acar, "Smart energy solutions with hydrogen options," *International Journal of Hydrogen Energy*, vol. 43, no. 18, pp. 8579-8599, 2018.

[27] B. Marepally, C. Ampelli, C. Genovese, E. A. Quadrelli, S. Perathoner and G. Centi, "Product of Solar Fuels Using CO2," *Horizons in Sustainable Industrial Chemistry and Catalysis*, vol. 178, pp. 11-13, 2019.

[28] C. Acar, I. Dincer and G. F. Naterer, "Review of photocatalytic water-splitting methods for sustainable hydrogen production," *International Journal of Energy Research*, vol. 40, no. 10, pp. 1449-1473, 2016.

[29] F. Zhang, P. Zhao, M. Niu and J. Maddy, "The Survey of Key Technologies in Hydrogen Energy Storage," University of South Wales, Pontypridd, 2016.

[30] I. Akkerman, M. Janssen, J. Rocha and R. Wijffels, "Photobiological Hydrogen Production: Photochemical Efficiency and Bioreactor Design," *International Journal of Hydrogen Energy*, vol. 27, no. 02, pp. 1195-1208, 2017.

[31] M. Huijbregts, Z. Steinmann, P. Elshout, G. Stam, F. Verones, M. Vieira, A. Hollander, M. Zijp and R. van Zelm, "ReCiPe 2016," National Institute for Public Health and the Environment, Bilthoven, 2016.

[32] C. Scheutz, P. Kjeldsen and E. Gentil, "Greenhouse gases, radiative forcing, global warming potential and waste management - an introduction," *The Journal of the International Solid Wastes and Public Cleansing Association*, vol. 27, no. 8, pp. 716-723, 2009.

[33] I. Dincer and A. Abu-Rayash, Energy Sustainability, Cambridge: Elsevier Inc., 2020.

[34] A. Mehmeti, A. Angelis-Dimakis, G. Arampatzis, S. J. McPhail and S. Ulgiati, "Life Cycle Assessment and Water Footprint of Hydrogen Production Methods: From Conventional to Emerging Technologies".

[35] I. Aleknaviciute, T. Karayiannis, M. Collins and C. Xanthos, "Towards clean and sustainable distributed energy system: the potenetial of integrated PEMFC-CHP," *International Journal of Low-Carbon Technologies*, pp. 296-304, 2016.

[36] United States Environmental Protection Agency, "Greenhouse Gas Emissions: Understanding Global Warming Potentials," [Online]. Available: https://www.epa.gov/ghgemissions/understanding-global-warming-potentials. [Accessed 17 April 2020].

[37] R. Williams, K. Kornbluth, P. Erickson, B. Jenkins and M. Gildart, "Estimates of Hydrogen Production Potential and Costs from California Landfills," 13 05 2013. [Online]. Available: https://biomass.ucdavis.edu/wp-content/uploads/09-20-2013-05-13-2013-2007-cbc-ca-lfg-h2-berlin-poster.pdf. [Accessed 17 April 2020].

[38] M. Kayfeci, A. Kecebas and M. Bayat, "Hydrogen production," in *Solar Hydrogen Production*, 2019, pp. 45-83.

[39] C. Ainscough, D. Peterson and E. Miller, "DOE Hydrogen and Fuel Cells Program Record," Department of Energy, Washington, D.C., 2014.

[40] S. T. Revankar, "Nuclear Hydrogen Production," in *Storage and Hybridization of Nuclear Energy*, London, Elsevier Inc., 2019, pp. 49-117.

[41] S. Czernik and R. J. French, "Production of Hydrogen from Plastics by Pyrolysis and Catalytic Steam Reform," *Energy & Fuels*, vol. 20, no. 2, pp. 754-758, 2006.

[42] Q. Ding, B. Song, P. Xu and S. Jin, "Efficient Electrocatalytic and Photoelectrochemical Hydrogen Generation Using MoS2 and Related Compounds," *Chem,* vol. 1, no. 5, pp. 699-726, 2016.

[43] Office of Energy Efficiency and Renewable Energy, "Hydrogen Production: Natural Gas Reforming," U.S. Department of Energy, [Online]. Available: https://www.energy.gov/eere/fuelcells/hydrogen-production-natural-gas-reforming. [Accessed 19 April 2020].

[44] R. Keller, "DOE Hydrogen and Fuel Cells Program Review Presentation," 14 June 20147. [Online]. Available: https://www.hydrogen.energy.gov/pdfs/review14/mt007_baxterclemmons_2014_o.pdf. [Accessed 20 January 2020].

[45] J. R. Rostrup-Nielsen and T. Rostrup-Nielsen, "Large Scale Hydrogen Production," *CATTECH: The Magazine of Catalysis Sciences Technology and Innovation,* vol. 6, no. 4, pp. 150-159, 2002.

[46] E. Ayapana, "Trash to Treasure: BMW to Convery Landfill Methane to Hydrogen," Motortrend, 26 July 2011. [Online]. Available: https://www.motortrend.com/news/trash-to-treasure-bmw-to-convert-landfill-methane-to-hydrogen-100645/. [Accessed 20 January 2020].

[47] V. Pachapur, S. Sarma, S. Brar, Y. Bihan, G. Buelna and M. Verma, "Biological Hydrogen Production Using Co-culture versus Mono0culture System," *Environmental Technology Reviews,* vol. 4, no. 1, pp. 55-70, 2015.

[48] S. S. Kumar and V. Himabindu, "Hydrogen Production by PEM water electrolysis - A review," *materials Science for Energy Technologies,* vol. 2, no. 3, pp. 442-454, 2019.

[49] National Renewable Energy Laboratory, "Champion Module Efficiencies," Alliance for Sustanable Energy LLC, Golden, CO, 2019.

[50] O. John, "Nikola Details Ambitious Plan for Hydrogen and Service Network," Trucks.com, 22 April 2019. [Online]. Available: https://www.trucks.com/2019/04/22/nikola-ambitious-plan-hydrogen-service-network/. [Accessed 4 August 2020].

[51] nel, "M Series Containerized Proton PEM Hydrogen generation systems," 2020. [Online]. Available: https://nelhydrogen.com/wp-content/uploads/2020/03/M-Series-Containerized-Spec-Sheet-Rev-B.pdf. [Accessed 6 January 2021].

[52] R. El-Emam and H. Ozcan, "Comprehensive review on the techno-economics of sustainable large-scale clean hydrogen production," *Journal of Cleaner Production*, vol. 22, pp. 593-609, 2019.

[53] G. Naterer, L. Stolberg, S. Suppiah, M. Lewis, Z. Wang, V. Daggupati, K. Gabriel, I. Dincer, M. Rosen, P. Spekkens, S. Lvov, M. Fowler, P. Tremaine, J. Mostaghimi, E. Easton, L. Trevani, G. Rizvi, B. Ikeda, M. Kaye, L. Lu, I. Pioro, W. Smith, E. Secnik, J. Jiang and J. Avsec, "Canada's program on nuclear hydrogen production and the thermochemical Cu-Cl cycle," *International Journal of Hydrogen Energy,* vol. 35, pp. 10905-10926, 2010.

[54] Q. Huang, L. Wang and C. Yang, "Design of Photobioreactors for Mass Cultivation of Photosynthetic Organisms," *Engineering,* vol. 3, no. 3, pp. 318-329, 2017.

[55] A. Wittenberg, "Air Force affirming role of renewables in energy security," Governors' Wing & Solar Energy Coalition, 15 April 2016. [Online]. Available: https://governorswindenergycoalition.org/air-force-affirming-role-of-renewables-in-energy-security/. [Accessed 4 November 2020].

[56] State of Hawaii, "Clean Energy Partnership Demonstrates 'Alternative' Way to Move Aircraft," 1 September 2019. [Online]. Available: http://dod.hawaii.gov/blog/in-the-news/clean-energy-partnership-demonstrates-alternative-way-to-move-aircraft/. [Accessed 4 November 2020].

[57] B. Kennedy and A. Tyson, "Two-Thirds of Americans Think Government Should Do More on Climate," Pew Research Center, 23 June 2020. [Online]. Available: https://www.pewresearch.org/science/2020/06/23/two-thirds-of-americans-think-government-should-do-more-on-climate/. [Accessed 6 November 2020].

[58] U.S. Energy Information Administration, "Nuclear explained U.S. nuclear industry," eia, 15 April 2020. [Online]. Available: https://www.eia.gov/energyexplained/nuclear/us-nuclear-industry.php. [Accessed 25 November 2020].

[59] M. Khzouz, E. I. Gkanas, J. Shao, F. Sher, D. Beherskyi, A. El-Kharouf and M. Al Qubeissi, "Life Cycle Costing Analysis) Tools and Applications for Determining Hydrogen Production Cost for Fuel Cell Vehicle Technology," MDPI, Basel, Switzerland, 2020.

[60] K.-Y. Show, Y.-G. Yan and D.-J. Lee, "Biohydrogen production from algae: Perspectives, challenges, and prospects," in *Biofuels from Algae,* Amsterdam, Elsevier Inc., 2019, pp. 324-343.

[61] C. Mittelsteadt, T. Norman and J. Willey, "PEM Electrolyzers and PEM Regenerative Fuel Cells Industrial View," in *Electrochemical Energy Storage for Renewable Sources and Grid Balancing,* Amsterdam, Elsevier B.V., 2015, pp. 159-181.

[62] B. D. James, G. N. Baum, J. Perez and K. N. Baum, "Technoeconomic Analysis of Photoelectrochemical (PEC) Hydrogen Production," Directed Technologies, Artlington, VA, 2019.

[63] V. Pachapur, S. Sarma, S. Brar, Y. Bihan, G. Buelna and M. Verma, "Biological hydrogen production using co-culture versus mono-culture system," *Environmental Technology Review,* vol. 4, no. 1, pp. 55-70, 2015.

[64] S. Patel and V. Kalia, "Integrative Biological Hydrogen Production: An Overview," *Indian Journal of Microbiology,* vol. 53, no. 1, pp. 3-10, 2013.

[65] Bhandari, Ramchandra, Trudewind, Clemens, Zapp and Petra, "Life Cycle Assessment of Hydrogen Production Methods - A Review," Forschungszentrum Jülich, Jülich, 2012.

[66] M. H. Goldberg, J. R. Marlon, X. Wang, S. v. d. Linden and A. Leiserowitz, "Oil and gas companies invest in legislators that vote against th environment," *National Academy of Sciences*, vol. 117, no. 10, pp. 5111-5112, 2020.

[67] Office of Energy Efficiency and Renewable Energy, "https://www.energy.gov/eere/fuelcells/fact-month-march-2019-there-are-more-6500-fuel-cell-vehicles-road-us," Department of Energy, March 2019. [Online]. Available: https://www.energy.gov/eere/fuelcells/fact-month-march-2019-there-are-more-6500-fuel-cell-vehicles-road-us. [Accessed 29 October 2020].

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)* 25-03-2021	**2. REPORT TYPE** Master's Thesis	**3. DATES COVERED** *(From - To)* August 2019 - March 2021

4. TITLE AND SUBTITLE An Analysis of Various Hydrogen Production Methods for Fleet Vehicle Fuel	**5a. CONTRACT NUMBER**
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) DeNezza II, Eugene, J, 2d Lt, USAF	**5d. PROJECT NUMBER**
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Air Force Institute of Technology Graduate School of Engineering and Management (AFIT/EN) 2950 Hobson Way Wright-Patterson AFB OH 45433-7765	**8. PERFORMING ORGANIZATION REPORT NUMBER** AFIT-ENV-MS-21-M-216
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) intentionally left blank	**10. SPONSOR/MONITOR'S ACRONYM(S)** N/A
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

Distribution Statement A. Approved for Public Release; Distribution Unlimited.

13. SUPPLEMENTARY NOTES

This work is declared a work of the U.S. Government and is not subject to copyright protection in the United States.

14. ABSTRACT

As conflict, the environment, and politics cause changes around the world, the United States Air Force is pursuing a diversification of drop-in and alternative fuel sources. Hydrogen fuel cells for vehicles are gaining popularity worldwide. Yet, how to best produce hydrogen gas still remains a question. This thesis will provide an overview of various hydrogen production methods and their respective environmental impacts, costs, efficiencies, and viability; and will perform sensitivity analysis to determine an optimal solution. The optimal production method is Thermolysis followed by Steam Reformation of Landfill or Natural Gas, Coal Gasification, and PEM Electrolysis. Based on varying requirements the recommended options for U.S. Air Force consideration are Thermolysis if nuclear power is available, Steam Reformation of Landfill Gas, and PEM Electrolysis. Steam Reformation of Natural Gas is only recommended for use in non-contested environments. PEM Electrolysis is extremely promising due to its portability and required inputs of only water and electricity.

15. SUBJECT TERMS

hydrogen production, fuel cell, methods, decision analysis

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON** Eugene John DeNezza II, AFIT/ENV
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			**19b. TELEPHONE NUMBER** *(Include area code)*
U	U	U	UU	100	(703) 967-7546 eugene.denezza@afit.edu

Reset

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

INSTRUCTIONS FOR COMPLETING SF 298

1. REPORT DATE. Full publication date, including day, month, if available. Must cite at least the year and be Year 2000 compliant, e.g. 30-06-1998; xx-06-1998; xx-xx-1998.

2. REPORT TYPE. State the type of report, such as final, technical, interim, memorandum, master's thesis, progress, quarterly, research, special, group study, etc.

3. DATES COVERED. Indicate the time during which the work was performed and the report was written, e.g., Jun 1997 - Jun 1998; 1-10 Jun 1996; May - Nov 1998; Nov 1998.

4. TITLE. Enter title and subtitle with volume number and part number, if applicable. On classified documents, enter the title classification in parentheses.

5a. CONTRACT NUMBER. Enter all contract numbers as they appear in the report, e.g. F33615-86-C-5169.

5b. GRANT NUMBER. Enter all grant numbers as they appear in the report, e.g. AFOSR-82-1234.

5c. PROGRAM ELEMENT NUMBER. Enter all program element numbers as they appear in the report, e.g. 61101A.

5d. PROJECT NUMBER. Enter all project numbers as they appear in the report, e.g. 1F665702D1257; ILIR.

5e. TASK NUMBER. Enter all task numbers as they appear in the report, e.g. 05; RF0330201; T4112.

5f. WORK UNIT NUMBER. Enter all work unit numbers as they appear in the report, e.g. 001; AFAPL30480105.

6. AUTHOR(S). Enter name(s) of person(s) responsible for writing the report, performing the research, or credited with the content of the report. The form of entry is the last name, first name, middle initial, and additional qualifiers separated by commas, e.g. Smith, Richard, J, Jr.

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES). Self-explanatory.

8. PERFORMING ORGANIZATION REPORT NUMBER. Enter all unique alphanumeric report numbers assigned by the performing organization, e.g. BRL-1234; AFWL-TR-85-4017-Vol-21-PT-2.

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES). Enter the name and address of the organization(s) financially responsible for and monitoring the work.

10. SPONSOR/MONITOR'S ACRONYM(S). Enter, if available, e.g. BRL, ARDEC, NADC.

11. SPONSOR/MONITOR'S REPORT NUMBER(S). Enter report number as assigned by the sponsoring/ monitoring agency, if available, e.g. BRL-TR-829; -215.

12. DISTRIBUTION/AVAILABILITY STATEMENT. Use agency-mandated availability statements to indicate the public availability or distribution limitations of the report. If additional limitations/ restrictions or special markings are indicated, follow agency authorization procedures, e.g. RD/FRD, PROPIN, ITAR, etc. Include copyright information.

13. SUPPLEMENTARY NOTES. Enter information not included elsewhere such as: prepared in cooperation with; translation of; report supersedes; old edition number, etc.

14. ABSTRACT. A brief (approximately 200 words) factual summary of the most significant information.

15. SUBJECT TERMS. Key words or phrases identifying major concepts in the report.

16. SECURITY CLASSIFICATION. Enter security classification in accordance with security classification regulations, e.g. U, C, S, etc. If this form contains classified information, stamp classification level on the top and bottom of this page.

17. LIMITATION OF ABSTRACT. This block must be completed to assign a distribution limitation to the abstract. Enter UU (Unclassified Unlimited) or SAR (Same as Report). An entry in this block is necessary if the abstract is to be limited.