

Product Design

Final Report

Fuel Cells for Vehicles

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Abstract

This is a CE404 Product Design final report about documenting our entire process of producing PEM fuel cells stack and our calculations on marketing strategies in California. The report was done to present what our decisions were and how they were carried throughout each phase. We presented the deficiencies and what we chose to focus on to improve our product along with important production processes. In the end, we decided to not proceed with this project due to the product's price and the production volume.

Fall 2020

AMENDMENT - Main modifications with respect to previous phases**1) Phase 1**

- Issue 1 - Added cost and durability in the deficiencies section
- Issue 2 - Added information about competitors
- Issue 3 - Added local incentives and regulations (Complimentary Fuel, Clean Vehicle Rebate, Executive Order)
- Issue 4 - Adjustment to the ideas of a novel product to include addition of Tungsten Oxide layer

2) Phase 2

- Issue 1 - Removal of two product concepts (GDL and Bipolar Plates) due to not being related to MEA production and lack of novelty
- Issue 2 - Customer needs along with product specifications
- Issue 3 - Reduction of Specification for Criterion Matrix
- Issue 4 - Change of Final Product Choice

3) Phase 3

- Issue 1 - Combination of Phase 3 and Phase 4 information for Manufacturing Process
- Issue 2 - Creation of SPFD and Explanation of Mass, Temperature and Pressure
- Issue 3 - Splitting Up Manufacturing Process Paragraphs and BFD and SPFD Paragraphs

4) Phase 4

- Issue 1 - Change of wording to clarify confusion of Equipment costs
- Issue 2 - Adjustment of the Fixed Operating Costs (loan interest and marketing costs)
- Issue 3 - Adjustment of the Sales cost to be determined from a Breakeven point at 900 units
- Issue 4 - Clarification of Breakeven Analysis (Fixed costs on y axis, not equipment cost)
- Issue 5 - Payback Analysis changed to include annual profits and not revenue
- Issue 6 - Determination of Loans based on Cash Flow Analysis of First Year
- Issue 7 - Complete Overhaul of Cash Flow Analysis
- Issue 8 - Corresponding Overhaul of Value of Project Analysis

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1. Introduction

The sustainability movement has swept across many industries, in particular the transportation industry. An interest in fuel cell vehicles (FCVs) increased research and development initiatives and government-industry cooperation to ensure the acceptance and success in the future. In 2018, the transportation sector was responsible for 28% of the U.S.'s annual greenhouse gas (GHG) emissions [1]. GHG emissions are a concern because it exacerbates the effects of climate change such as shifting wildlife populations, extreme weather conditions, loss of wildlife habitat and rising sea levels [2]. Another impact is the negative consequences it has on the air quality and inevitably the health issues that come along with poor air quality. Smog is a phenomenon caused by the accumulation of solid and liquid fog and chemical pollutants. Examples of chemical pollutants are carbon monoxide (CO), nitrogen oxides (NO_x), and lead (Pb). The adverse health effects of these pollutants include cancer, cardiovascular, and respiratory diseases [3].

Developing the proton-exchange membrane (PEM) FCV could help mitigate the mentioned effects since the only by-product of the process is water and heat. It is important to note that, hydrogen production is currently not sustainable since a majority of the fuel is produced through steam-methane reforming and the process emits GHG, this issue will be further discussed in the report.

The following sections will summarize the development process of our product, fuel cells for the transportation sector. To understand the current status of the product, the global context was established and a market analysis was done on the target market. For further improvements and added novelty, a customer/ stakeholder's approach strategy was utilized to outline the customer and technical needs and to generate new product concepts. A manufacturing process was then mapped out, along with a waste management plan and expected scaling-up challenges. To ensure that the product can be successful in the current market, a cost analysis and economic forecast was also performed. Lastly, a recommendation on whether or not the firm should continue with the project was discussed.

2. Global Context

2.1. Current Deficiencies of Existing Products

2.1.1. Cost

The cost of an FCV is much higher than the cost of a traditional internal combustion vehicle. A FCV from Toyota could cost up to \$58,550, while models from Hyundai and Honda could cost up to \$58,735 and \$58,490 respectively [4][5][6]. In comparison, the average price of a new IC vehicle is \$37,876 in 2020 [7]. According to a market report produced by Hyundai Motor Group,

more than 40% of the vehicle cost is from the fuel cell stack, drive mechanism, and hydrogen tank [8]. To increase the appeal in FCVs, a decrease in manufacturing cost for the fuel cell stack would alleviate much of the initial investment of purchasing one. The high manufacturing cost of a fuel cell stack is attributed to the high cost of the individual components. In low volume production, the membrane and bipolar plates dominate, while in high volume production, the cost of the platinum catalyst is the issue [9]. The overpowering cost of the catalyst can be seen in Figure 1 which describes the PEMFC stack cost breakdown [10]. Due to its rarity, platinum is not mined as frequently as other metals such as gold and is often a byproduct of other mining ventures. All of these factors contribute to the high and volatile price of platinum [11].

2.1.2. Durability

The durability of the fuel cell stack is a major obstacle to commercialization. The reliability of the fuel cell stack has to be optimal to justify the high initial cost. Many of the individual components are vulnerable to degradation due to the harsh working conditions the PEMFC experiences. Degradation of the platinum catalyst is induced by particle agglomeration and particle growth, this results in decreasing catalytic activity which reduces the stack performance. Another degradation issue comes from the structural integrity of the carbon support that the catalyst layer is manufactured with. Under prolonged operation, carbon degradation would weaken the attachment of the catalyst particles, eventually resulting in structural failure as well. The fuel cell performance would be affected because the catalyst active surface area would decrease as degradation persists. The membrane of the fuel cell can also degrade if exposed to hydrogen peroxide or other contaminants produced by the reaction or introduced through the manufacturing processes of other components. The degradation is caused by the attack on the perfluorosulfonic acid structure. Other factors that would worsen degradation are fuel starvation, flooding, membrane dehydration, and pressure imbalance [12].

2.1.3. Hydrogen Production

There are currently many setbacks that prevent fuel-cell-powered vehicles from becoming a mainstream option for the general population. Theoretically, hydrogen is a limitless fuel source with a large abundance of it available on the planet. It is often found in molecules such as water and natural gas. However, it is very costly and energy-intensive to extract hydrogen away from these molecules. 95% of the world's hydrogen is produced by steam methane reforming which is a process that blasts natural gas with high temperature and pressure steam. This process requires fossil fuels and also leaves a byproduct of carbon dioxide. Hydrogen can also be produced from water through electrolysis. Electrolysis is done by electrifying water, this causes the hydrogen to split from the oxygen. Electrolysis is an expensive process because hydrogen is very strongly

bonded to the oxygen in water [13]. The electrolysis process is also only 75% efficient. This process of storing and transporting hydrogen alone causes a 10% loss in efficiency. 5% more is lost from driving the vehicle motor. After all is done, the energy loss is 62%. A fuel cell vehicle gets 380W for each 1000W of electricity in comparison to a battery electric vehicle which generates 800W for each 1000W of electricity [14]. Hydrogen fuel produced through electrolysis is still not considered ‘green fuel’ if the electricity is produced by non-renewable sources. There are countries such as Australia who plan to produce hydrogen fuel with renewable energy due to their abundance of solar and wind energy and in anticipation of the hydrogen economy boom [15]. Once hydrogen fuel is produced this way, the PEMFC vehicle will be considered zero-emission.

2.1.4. Hydrogen Infrastructure

The infrastructure for fuel cell vehicles still needs to be developed. There are very few hydrogen refueling stations available globally because of its costly nature. Hydrogen is also very expensive to store and transport because it has to be converted into a liquid or compressed gas. Hydrogen storage tanks are currently very high in both weight and volume causing limited vehicle ranges. The energy efficiency, maintenance of the purity of the hydrogen, and leak prevention are all extra costs with transporting hydrogen. The cost of hydrogen storage systems is also high in comparison to petroleum fuels. H2USA was launched in 2013 as a group effort between the DOE, federal agencies, automakers, state governments, academic institutions, and additional stakeholders in order to expand the hydrogen infrastructure. By the end of 2015, the investment however only netted around 50 public stations for deploying hydrogen fuel, most of which are only located in California. While it was a good starting point, that is definitely not enough to allow a hydrogen-powered fuel cell vehicle to become a mainstream option [16]. There are also no set codes and standards for systems of hydrogen storage and transportation. Standardized hardware and operating procedures must also be set in place through codes for handling hydrogen fuel [17].

2.1.5. Hydrogen Storage

Fuel cells use the chemical energy of the combination of hydrogen gas and oxygen to power the engine using electrical energy. Many fuel cell vehicles also store and draw extra electrical energy from batteries. The battery can present danger to the electrical system and fuel system because of the presence of acids. Because of this, the possibility of electric shock is greater than it should be.

The hydrogen being stored inside the vehicle also remains a concern because of its flammability. Hydrogen is typically stored in a car compressed, as a liquid, in hydride form bound to metals or

on the surface of solid porous materials. Compressed hydrogen cannot be stored in steel tanks because the molecules can embrittle the metal. There are also issues in detecting hydrogen leaks and a high possibility of complication with the electrical circuitry being in close proximity with flammable gases in fueling sites. Hydrogen gas is odorless and colorless which means that leakages are hard to detect. Fuel leakage is a concern because hydrogen gas mixes well with oxygen, air, halogens, and strong oxidants which could cause combustion to occur. These can be further amplified with the presence of catalysts like platinum or nickel. The flames caused by burning hydrogen are visible but much less in comparison to other fuels [18]. Without guidelines and safety procedures, there is no guarantee of safety or accountability.

The proton exchange membrane (PEM) within the fuel cell can cause direct combustion between hydrogen and oxygen. Sometimes, hydrogen is also stored in liquid form but it boils very quickly because of its low boiling point of 20 Kelvins. The fuel as a result has to be stored at very low temperatures which can raise concerns about a possible cold burn. Low temperatures can wear down metal equipment and in normal temperatures, create gas pressures, and break apart vessels that lack safety valves. This extremely low temperature is also challenging to maintain without outside cooling, which is prohibited in passenger vehicles due to the energy cost. As a result, there is always an expected 1-3% hydrogen leakage in the typical LH2 tank per day which is not a safety concern unless a large scale rupture of the tank occurs [19].

Currently, the safest method of hydrogen storage within a vehicle is through binding with metal hybrids. This is done by binding hydrogen to different metal alloys in porous or loose forms by using moderate amounts of pressure and heat. The hydrogen gas is extracted from the metal by releasing the pressure. However, the weight of the metal hydrides required to hold enough fuel for a sustained vehicle operation is high. Some alloys can go up to 1250 kg to store 15 kg of hydrogen which greatly increases the weight of the vehicle and decreases the energy efficiency of the car [19]. Some of the metals within the alloys being used, such as the magnesium within MgNi alloy, is flammable which is a trade-off for better alloy weight to hydrogen weight ratio. Solid porous materials and carbon nanotubes are still currently in production but maintain similar issues with metal hydride storage like the increased weight.

2.2. Legislation, Regulation and Incentives

A legislation that would implore industries to change to the environment-friendly vehicle has been put forth by Governor Newsom. He demands to phase out gasoline-powered cars to fight against climate change. The executive order by Newsom directs the state to require that, by 2035, all new cars and passenger trucks sold in California be zero-emission vehicles [19]. Another proponent to adapt to a clean vehicle is the Clean Vehicle Rebate Project in California. The

project offers up to \$7,000 for electric and zero-emission vehicle user rebates [20]. Another incentive to buy FCVs is the complimentary fuel offered by car manufacturers. The top three FCV manufacturers, Hyundai, Toyota, and Honda, will offer up to \$15,000 worth of hydrogen fuel to their customers [21][22][23].

The federal government has recognized the promise of fuel cells. They have devoted billions of dollars in research and development to advance the technology in the past 50 years. Some corporations have expressed interest in the technology and have invested in the improvement of the technology. The Department of Energy has been the driving force for fuel cell development over the past two decades, spending \$2.4 billion on research and product development. Also, many governments have strengthened efforts to reduce emissions. But, many governments' plans still fall short on the necessary emission reductions [24]. They are trying to set up renewable energy targets and are trying to convert to 100% reliance on renewables by the mid-century. There is ample evidence that renewable energy can function at high levels. But, it is largely a matter of political decision to whether or not to deploy these technologies into the market. By doing so, fuel cell technology has the potential to thrive in these markets.

Recently in the US, the Democrats have regained the majority in the House, and climate change is one of their priorities [24]. They plan to create a market-based system for trading credits in greenhouse-gas emissions. This system will steer people away from internal combustion vehicles to a more environmentally sustainable vehicle that relies on renewable energy. Relying on fuel cells rather than mainstream vehicles helps reduce the carbon footprint by providing zero CO₂ emission.

The Chinese government has implemented an emissions trading system. This system permits a certain amount of carbon dioxide emitted, and the sectors that manage to undershoot their permitted emission by cleaning up and becoming more efficient will be able to sell excess permits to other generators. The trading system targets eight sectors, power, iron and steel, aluminum, chemicals, petrochemicals, paper, building materials, and civil aviation. This system is great because these sectors are encouraged to operate with greater efficiency as an alternative to paying for surpassing the permitted amount. China emits 3.3 billion tonnes of carbon annually. With this system, it will not resolve all the climate problems, but it provides regulations necessary for reducing carbon emissions. Implementing the trading system would incentivize alternative energy systems like fuel cells for public transportation [25].

In 2006, the German government devised a plan to make hydrogen fuel cells more viable for applications in the energy sector. With the ongoing advancement and commercialization of hydrogen fuel cell technology, Germany has become the forefront for encouraging other

companies to get involved in the hydrogen fuel cell technology [26]. As of today, there are 85 hydrogen stations for its consumers, and will likely increase. The Joint Initiative for Hydrogen Vehicles across Europe (JIVE) program receives EU funding and plans to deploy close to 300 fuel cell buses and accompanying infrastructure to 22 European cities by 2023. Shell has shown interest in the market venture, and it plans to construct a 10-megawatt hydrogen electrolysis plant in Germany and eventually scale up to 100 MW. Shell's involvement would be great for increasing hydrogen fuel cell vehicles [27].

3. Market Analysis

3.1. Size of Market and Target

As the hydrogen economy in the US expands, the fuel cell stack production has to increase as well. In the hopes of penetrating the market, our team is proposing a project to manufacture and sell fuel cell stacks for passenger vehicles. Our goal is to produce enough to satisfy the demand while making a profit, as well as increase the volume production to accommodate the projected sales. It is important to acknowledge that hydrogen fuel production is not always done sustainably, but through private and government incentives, research and development, production methods will progressively become environmentally sustainable. With the development of hydrogen production, hydrogen infrastructure, and the anticipated ban on combustion engines in California, the team has prepared a plan to increase volume production up to 1,000 units per year from the starting point of 400 units per year which accounts for approximately 24% of the FCV sales for the past few years (~1,700 FCVs sold and leased).

Currently, California is the driving force of the hydrogen economy in the US with 42 existing fueling stations, they aim to have 200 by 2025 and 1000 by 2030 [28][29]. There are approximately 10,000 hydrogen fuel cell vehicles registered [30]. The number of FCV sales and leases has increased from the year 2014, as can be seen in Table 1, except for the year 2019 when it decreased by 12% and 2020 where it decreased due to extraneous circumstances such as the Coronavirus pandemic. According to Technavio, the expected time for the market to normalize is towards the end of 2021 or the beginning of 2022 [31]. To specify the target market even more, San Francisco was chosen due to the high median household and individual incomes and established interest of FCVs in the area. The median household income is \$96,265 and the individual income is \$74,841, which is appropriate for our target market due to the high cost of our product [32]. As can be seen in Figure 2, the San Francisco bay area and Los Angeles has the most number of FCVs registered [33]. In 2019 the FCV was ranked as the number one trend among automotive executives, and in 2020, an executive order that 'require all new vehicles sold starting in 2035 to be zero-emissions' was signed in September, both of these factors contribute

to the projected increase in FCV sales [34]. The executive order will impact automotive manufacturing because it takes years to develop a new car model, if these companies want to release a model and be competitive in terms of cost, many will have to start developing electric vehicles. Since California is highly motivated to shift the electric vehicle industry towards FCVs, it will be reasonable to assume that more companies will start to develop them. To further reinforce the idea that more automotive companies will start developing FCVs, according to a report featuring leaders such as Hyundai, Toyota, and Honda, 25+ new models will be available by the year 2030 [35]. Not only will increasing options for FCVs increase potential buyers, but the declining initial investment for such FCVs will help gain traction as well. The DoE has been working alongside automakers and other government institutions to reduce the fuel cell stack cost to \$30/kW, many experts in the automotive industry believe that the target will be met by 2050 [36][37]. Other initiatives are also taken to help reduce the price such as developing manufacturing processes to increase volume production and increasing durability of the fuel cell stack. According to Ballard, a leading fuel cell stack manufacturer, FCVs will be cost-competitive by 2030 because of increased volume production scales [38]. Keeping in mind that in 2017, 2018, and 2019, the annual FCV sales and leases were above 2000 and it is projected to increase, the desired volume production after five years will be 1000 units.

3.2. End-Users and Customers

The manufacturing process was engineered to produce fuel cells made for light-duty vehicles, specifically, passenger vehicles. The end-users of the product would be the customers who buy FCVs. Companies that manufacture those FCVs are the customers of our product, they would be companies such as Toyota, Hyundai, Daimler, and so forth. If need be, other potential customers could be non-automotive companies who would need a back-up power system, the product could be adjusted for required power outputs by adding or removing fuel cells within the stack [39].

3.3. Benchmarking Analysis

Within any industrial sector, there will be competition. In our case, they would be Ballard, Hydrogenics, Elringklinger, Bosch, and Plug Power [40][41][42]. In 2015, the top three competitors were Ballard, Toshiba, and Plug Power. Their respective market shares were 17.36%, 16.68%, and 11.93% [43]. In 2015, Plug Power was shipping 10,600 fuel cells and by the end of 2020, that number increased to 40,000 units [44]. To compare, Toyota announced a plan to increase their production volume from 3,000 to 30,000 units per year after 2020 [45]. Scaling up production volume to be as competitive as the examples above is necessary since it will be the biggest driver of manufacturing cost reduction [46]. According to the DoE, the fuel cell stack cost, as of 2019, is \$181/kW from analyzing manufacturing cost at 'high production

volume with next-gen lab technology’ or \$210/kW from ‘bottom-up analysis of model system based on commercially available’ FCVs [36].

3.4. Marketing Strategies

To ensure the sales of our product, marketing the product is necessary. Since our product will not be at the end of the chain of derived demand, we will be doing business to business (B2B) marketing [47]. The marketing approach will be different compared to business to customer marketing. B2B marketing requires ‘interactions with the target’ customer, which requires a more knowledgeable marketer, therefore our team will produce a product specification brochure for our customers. The brochure will cost approximately \$20,000 for the whole production [48]. Since marketing is more targeted, a viable strategy is for sale representatives to reach out to those customers to expose and explain our product. This could be done through emails, phone calls, and in-person meetings. Another marketing strategy is to showcase our product at trade shows. According to the Business Marketing Association, trade shows are ‘the number one promotional tool’ for B2B companies. A mid-range budget to rent a booth at these trade shows will be approximately \$25k to \$50k [49]. Attending these trade shows will provide our product exposure and hopefully increase our customer base. Due to the B2B aspect of our company, a large part of our revenue will come from a small number of customers. The sales representatives will have to develop and maintain relationships with those customers. Not only will these relationships ensure that our customers remain with us, they will also serve as references for potential customers. Our product will benefit from this word of mouth type of marketing as well. Lastly, having a company website and social media platform like Instagram and Twitter could help gain our company some attention.

4. Ideas for a New Product

The catalyst is important for the reduction-oxidation (redox) process that occurs in the fuel cell. Much research and development have shown promising results to improve hydrogen fuel cell technology. One, in particular, platinum alloy, can combat the cost and the efficiency of current fuel cell technology. The issues of standard fuel cell technology comprise the cost of platinum used and the reduced electrochemical surface area when mass activities are high. Low ECSA leads to limitations on the reaction rate, not by kinetics. With recent research in platinum-cobalt oxide bone nanostructure, it led to promising results in high mass activity while sustaining large ECSA, and it is 5 to 10 factors of the cost to produce the standard platinum hydrogen fuel cell [50]. Pt-CoO shows promising results as opposed to other Pt catalysts in fuel-cell operation at high temperature, high current density, and low humidification [51]. Applying this property can solve some issues revolving current fuel cell technology and thus provide efficiency in the

targeted market. However, this idea is not novel and has already been applied to current products. The novelty in our product will be the added tungsten oxide layer between the Gas Diffusion Layer and Anode/Catalyst layer. This idea was first written about on March 4th, 2020 and has not yet been implemented to any current products. The Tungsten Oxide layer acts as an oxygen scavenger, sensor for power demand, and regulates the hydrogen-dissociation reaction [52]. This will be described in further detail in the Concepts section.

5. Customer/ Stakeholder Approach Strategies

5.1. List of Customer Needs

For the purpose of finding an effective way to introduce our product to our customers and stakeholder, a customer assessment was conducted to identify what customers want in a vehicle. Our team came up with a list of customer needs, which are separated into three categories: Customer preferences, Safety, and Technical Needs. Information regarding our customer preferences and technical needs were obtained through many types of research, such as Youtube videos, test drives, group discussion and analyzing different types of fuel cells vehicles that already existed on the market, including Hyundai Nexo and Toyota Mirai [53][54].

Furthermore, the list of technical needs were created from discussion between team members and individual research for the purpose of determining which needs are more important as well as possess the greater impact on the production of fuel cells and their performance.

5.2. Rank of Customer Needs

In order to prioritize certain needs, which customer needs we needed to eliminate and what we needed to concentrate on, along with further group discussion, the needs were then ranked from one to five being undesirable, not important, nice to have, highly desirable and essential respectively. Needs that directly affect those factors are given the highest rating while needs that have less of an effect are given the lower score of 4 or less. Due to the fact the concepts we were planning to improve on do not oppose any effects on the current safety features that are already implemented in fuel cell vehicles in current models, they are ranked lower than other needs. Trace metal contamination is also rated low in comparison to every technical need because it comes from manufacturing of the components which is difficult to control for. Our customer needs and how we ranked them are displayed in Table 2, 3 and 4.

6. Product Specifications and Metrics

Using the ranking that we made for our customer needs, we have created our specifications based on what were ranked a 4 or higher. Each of the specifications were given a metric name and unit. Further researches were needed to determine which specifications are related to the list of

needs. For example, in our technical needs list, mechanical strength was ranked a 4. In order to know what our improvement process needs to be focused on, we assume that it's specification is tensile strength/elongation. After determining the specifications that related to our needs, we then assign each of them a metric name and a unit. This facilitated the process in finding values for the marginal and ideal values table. Using information regarding to our competitors fuel cells vehicles, Toyota Mirai and Hyundai Nexo, marginal and ideal values were then set for the purpose of determine at what value we want our product to be, such as the marginal value of efficiency being 65%, we would want our fuel cells to have an efficiency of at least a 45%. Our product specifications along with their metrics and ideal values are shown in Table 5.

7. Product Concepts

Concept A: Tungsten Oxide Layer on Anode

Tungsten oxide (WO_3) has an hexagonal crystalline structure. The stability of the structure allows it to act as a proton-electron mixed conductor with capabilities of storing a high capacity of protons in a highly rapid and reversible fashion. In the design, a thin layer of hexagonal WO_3 is implemented on the anode between the two gas diffusion layers or GDLs and the Platinum/Carbon catalyst layer. The Hydrogen passes through the GDL and WO_3 layer which is converted to protons and electrons in the catalyst layer. The protons are transported through the PEM while the electrons are transported through the external circuitry. The protons and electrons react with WO_3 and stored as H_xWO_3 . If there is fuel starvation or a need for higher power demand, the H_xWO_3 is converted back to WO_3 and releases the electrons and protons to compensate. Afterwards, the WO_3 layer is recharged by reloading hydrogen and electrons for the next instance of fuel starvation[52].

The H_xWO_3 is also reacted with Oxygen from the anode, forming WO_3 and water. This reaction stabilizes the anode potential during transient operation, protects the cathode from degradation and increases the lifetime of a fuel cell. The discharge of the WO_3 layer in response to power demand will increase anode potential and promote the dissociation reaction which releases protons to prevent the power-output delay. The WO_3 layer in this case will function as a rapid-response hydrogen reservoir, oxygen scavenger and a regulator for the hydrogen-dissociation reaction by modulating the anode overvoltage and dissociation of hydrogen in accordance to the power demand. The durability of the PEM and the transient power performance is improved by adding a WO_3 layer in the anode. The structure of this hybrid PEMFC is displayed in Figure 3[52].

Most fuel cell devices should operate in low humidity or even dry conditions. A test on a hybrid cell with WO_3 performed significantly better in low humidity in comparison to a normal fuel cell. An extra average power output of 307 mW/cm^2 in the first 10 seconds was delivered by the WO_3 cell in comparison to the normal fuel cell. The reason for this is because the WO_3 layer improves the proton conductivity in non humid conditions. The presence of the WO_3 /CNT layer helps to retain water within the anode by slowing evaporation after it is transported from the cathode. During low humidity conditions, the protons within the H_xWO_3 are released rapidly which increases the charge-carrier concentration. The H_xWO_3 are proton conductive so the WO_3 particle facilitates transportation of protons in the WO_3 /CNT/Nafion layer. This lead to the increased proton conductivity within the hybrid cell which would initiate the cascade reactions that produces water and hydrates the membrane and WO_3 . This reaction would allow operation of the fuel cell even under non hydrated conditions[52].

A test was done on a normal fuel cell and compared to the WO_3 hybrid cell. The voltage for the normal fuel cell drops 1.0V in just 2 seconds after the hydrogen supply stops. The voltage reversal shows that anode potential actually ends up being more positive in comparison to the cathodic potential. A high anode voltage causes anode oxidation and catalyst aggregation which would reduce performance. On the other hand, the WO_3 fuel cell had much slower voltage decay and the voltage reversal happens roughly 6.5 seconds later [52].

The durability was also examined by testing the normal cell and WO_3 cell in an oscillating current output between 50 and 1000 mA/cm^2 . The normal cell displayed a steady decrease of -10% peak power after 1000 testing cycles. Meanwhile, the WO_3 cell did not display this trend and overall did not at all decrease in it's peak power across the cycles which shows it's increased durability under dynamic operating conditions[52].

This design reduces or eliminates the use of high cost energy storage systems and decreases the cost of the system. If a hybrid cell system with tungsten oxide using the model of fuel cell stack of the Toyota Mirai, it only uses 0.92 kg of tungsten oxide. It is currently being produced commercially for \$40/kg. This cost is negligible and the advantage would be providing an extra 27.6 kW of power for 10 seconds when the power output is increased from below 10% peak power to 100% peak power [52].

Concept B: BP 60 Membrane

The membrane Nafion, which is made of short side chain perfluorosulfonic acid (PFSA), is a very common membrane found in PEM fuel cells. An issue with the material is the need to humidify the reactant gasses to achieve high proton conductivity. Another issue is the

susceptibility to decomposition in the presence of metallic cations, degradation will lead to reduced proton conductivity and mechanical stability. Stress caused by cyclic swelling and shrinking can also result in reduced membrane efficiency [56]. A membrane with high or moderate IEC values and low WU would result in high stability and high conductivity.

Ion-exchange capacity (IEC) represents the total of active sites or functional groups responsible for ion exchange in polymer electrolyte membranes. The water uptake is a factor that impacts the performance of the fuel cell as well, although the membrane does need to be hydrated, excessive water uptake will result in limited mass transfer. The ‘GDL/CL flooding’ effect is due to the blockage of the CL, the decrease in performance can be explained through reduced catalytic sites. Another effect known as the ‘flow channel flooding’ is caused by the accumulation of water (from the reaction products)[56].

As a substitution to the Nafion membrane, SPAEs are a promising substitution. Some benefits to SPAEs are its competitive cost and thermal stability. For random morphology, a minimum ion exchange capacity (IEC) limit is needed for mass transport to occur but for a block copolymer, the block length is the important factor. Although random copolymers are preferred due to their high performance, the combination of random and block copolymer properties would optimize water uptake (WU), the IEC, and therefore proton conductivity. DFBP (decafluorobiphenyl) as linkage groups was used to increase the molecular weight. The molecular weight, if limited would cause issues with high WU and dimensional changes, leading to dimensional instability and mechanical failure. This is where fluorinated groups would be beneficial, it would increase thermal and oxidative stability. The WU value for the block copolymer with 60% DS, was calculated to be 77.8% at 80°C. The proton conductivity was found to be 0.25 S/cm, which is higher than the proton conductivity of Nafion, which is 0.0505 to 0.072 S/cm. Since dimensional change will affect the performance and durability, the swelling ratio was calculated for the polymer. It was calculated to be 43.1% which is relatively high compared to Nafion[56].

Concept C: SCN 5.7 Membrane

This membrane composition provides continuous proton transfer channels and reduces the weak proton conducting layer without nanofibers. Water-retention was improved by the addition of nanofibers containing CC3 and had a positive correlation with increasing CC3 content.

Increasing water retention helps with proton conduction by providing ‘broad direction of transmission.’ Although swelling ratios increased with increasing water-retention ability, the swelling ratio of SCN was still less than the cast Nafion membrane. This difference is caused by the ‘crimped nanofibers’ which functions as a structural frame to improve ‘dimensional stability.’ The IEC ended up being 0.89mmol/g and the proton conductivity was calculated to be 0.315 S/cm [57].

Concept D: Platinum Free Catalysts

A possible improvement to reducing the price of hydrogen FCVs is the catalyst used for FCVs. The common catalysts used for FCVs are platinum, platinum alloys with transition metals, platinum-ruthenium alloy, palladium, and other similar catalytic materials. RuP and RuP₂ used for hydrodesulfurization (HDS), hydrodeoxygenation (HDO), and Hydrodenitrogenation (HDN) exhibit similar reaction mechanisms to hydrogen evolution reaction (HER) with high catalytic activity and 4% of the cost of Pt. HER activity is strongly correlated with the Gibbs free energy of hydrogen adsorption on the catalyst surface. The optimal ΔG_H^* for electrocatalyst of HER is at 0 eV, and RuP₂ with a similar value -0.627 eV and with the incorporation of N, P dual-doped carbon (NPC) yield ΔG_H^* of 0.233 eV. When RuP₂ was used as an electrocatalyst for HER, it showed similar Pt-like activity and robust durability under the pH spectrum. The calculated free energy diagram of HER at equilibrium potential for RuP₂ is shown in Figure 4. For a comparison of electrocatalytic activity of RuP₂ and Pt/C in acidic solution (H₂SO₄ 0.5M), the results show excellent HER catalytic activities with a near-zero onset overpotential η . The current density from the Tafel plots is higher as well (Figure 5). The durability of RuP₂ performed better than the Pt/C in the Cyclic Voltammetry test for overpotential difference in cycles (Figure 6). The amount of hydrogen generated in the cathode compartment of the H-type electrolytic cell was collected and measured from the water drainage method. The results of the amount of H₂ agrees to the theoretical value, which suggests 100 % faradaic yields for RuP₂ (Figure 6,g) [58]. This comparison further supports that RuP₂ is a great alternative catalyst, and the application of this catalyst will have a profound impact on HER and the reaction of fuel cells technology [58].

Concept E: Platinum Cobalt Alloy

The current issue with the catalyst for FCV is the cost of platinum. Instead of the Pt/C catalyst in PEMFCs, platinum alloys can help reduce the cost of platinum in PEMFCs. The platinum-cobalt oxide bone nanostructure stands out as a potential solution to reduce the cost of platinum. The PtCoO provides many advantages with fuel-cell operation in which it can operate at higher temperatures, high current density, and low humidification. The traditional fuel cell system in vehicles operates at high current densities and relatively large overpotentials. This fact is crucial for the rate-determining step changes and mass transfer performance. With low overpotential and thus low current densities, the electrochemical surface area (ECSA) will reduce. The effect of reduced ECSA becomes increasingly limiting, especially with oxygen resistance in the fuel cell operation. The ECSA per mass is key to a specific activity (SA). SA helps sustain oxygen resistance in higher overpotential. The PtCoO got its inspiration from a carbon-free oxygen reduction reaction (ORR) catalyst capable of high SA with High ECSA. In addition to high SA and high ECSA, they circumvent the inherent carbon-corrosion problems of standard

carbon-supported catalysts. The electrochemical performance of PtCoO revealed outstanding ORR activity at 0.9 V_{RHE} (RHE) (reversible hydrogen electrode), with ORR current densities between 3.8 and 5.5 mAcm⁻²_{Pt}. The results correlated with an increase of ~ 8 factors compared to the Pt/C and serve as a benchmark for ORR. The stability measurement using the accelerated stress test between Pt/C, and Pt-CoO showed that Pt/C benchmark degraded rapidly, and 53% of the ECSA compared to 15% of the ECSA in Pt-CoO were lost after 800 cycles (Figure 7). The high SA and high ECSA lead to high mass activity (MA). High mass activity is a crucial performance of the PEMFC application. This process will require a new layout for the PEMFCs that require larger catalyst layers and enable extensive membrane electrode assembly. The temperature and humidified conditions of PtCoO catalysts analyzed resulted in superior performance compared to Pt/C in low temperature and dry conditions. However, PEMFCs operate at above 100 °C, and flooding in Pt/C causes corrosion to increase. PtCoO presents concepts that inspire the next generation of ORR Catalysts, and if positive outcomes prevail, the application of this catalyst provides a solution to reduce the cost of Pt/C catalyst [59].

8. Concept-Criteria Matrix: Own Products and Competitors

For our criterion matrix, we decided to discard the first stage because we only have 5 concepts so narrowing down the concept before Stage 2 was unnecessary. In that first Stage 2 Criterion Matrix, we listed all of our concepts across the 5 columns. We gave them values of -1, 0 or 1 for each customer need. A value of -1 means that it worsens that need. A value 0 means that it makes no difference in that need and a value of 1 means that it improves that need. The results of Stage 2 are displayed in Table 6. These were done through qualitative analysis based on the research and results that were done for each concept to see whether it improves or worsens a specification in comparison to current fuel cells in the market. Concept A, Tungsten Oxide layer had the highest number at 11 while Concept F, Platinum Alloy was 2nd.

We then combined Concepts A and F, the highest performing Concepts and compared it to some other combined concepts. The Stage 3 Criterion weights were determined from the importance values assigned to each customer in the technical needs. The r values were determined by adding the values from the Stage 2 results for each need. For example, concept A and F both improved the membrane ion conductivity so the r value is a 2 for that need. The r values and weight values are then multiplied to obtain the s values. The results from Stage 3 are displayed in Table 7. Based on the results of Stage 3, concept AF had a total score of 122 points, concept BF had a total score of 96 points and concept BD had a score of 96 points.

9. Final Product Choice

Our Final Product choice is the highest performing combined concept, concept AF which is combining the Tungsten Oxide Layer on the Anode side and replacing a pure platinum catalyst with a platinum-cobalt alloy catalyst. A figure displaying the changes to the classic Membrane Electrode Assembly in Figure 8.

9.1. Sustaining or Disruptive Change

Since our objective is to improve the hydrogen fuel cells' cost and durability using existing products, information, and technologies, we considered these concepts to be sustaining changes. The concepts are not disruptive because we are not trying to reinvent the fuel cell technology but research alternative ways to enhance the durability of hydrogen fuel cells but also reducing the cost for our customers. Due to the fact that our product won't be too different from what already exists in the market, the FCV consumers will interact with the product as normal.

9.2. Strategies to Protect the Final Product Choice

The strategy to protect our product would be to ensure that we limit the ways that Trade Secrets can be leaked. A Trade Secret is any information, pattern, method, technique or process that is necessary for the design of this product [60]. The most obvious way to limit the leak of trade secrets is by requiring every person working on this product to sign a Non-Disclosure Agreements or NDA. We will require employees to sign an Employee NDA, which makes it clear to employees that they are not allowed to disclose any trade secrets without permission. Independent contractors will be required to sign an Independent Contractor NDA. [61].

The purpose of NDAs is to prevent leaks of trade secrets during the period of before the patent application and during the patent application because a patent application requires the knowledge to not be public at the time of the application. We will be waiting longer before applying for a patent to get proper testing and experimentation of the product. A patent is used to claim a new product or a new process that will result in a new product. The patent application process will begin once the product has undergone a sufficient amount of testing to ensure it satisfies the specifications and customer needs.

10. Manufacturing Process

10.1. Recipe for Manufacturing Process: Components, Materials, Operations

10.1.1. Tungsten Oxide

Tungsten oxide can be synthesized through reaction of sodium tungstate and ammonium sulfate. However, Tungsten oxide is produced at Volta Materials Inc at Culver City, California at a price

of \$40/kg. Because of our relatively small production size for tungsten oxide, we will choose to purchase it to save the costs of the mixer, the power costs and the floor space for it. Carbon nanotubes are dispersed into the solution at a 1:4 weight ratio through sonication[52]. Sonication is a process that agitates particles in a solution through the use of soundwaves. Electrical signals are converted to physical vibrations in order to break substances apart which accelerates the uniform dispersion of carbon nanotubes throughout the solution. The energy from the sound waves produces friction within the solution and increases the temperature. To prevent the sample from overheating and degrading, the solution has to be cooled during and after sonication [52]. However, since the solution needs to be at 180 °C when it is transferred to the autoclave, the solution only has to be cooled within the reactor so the sonicator doesn't overheat. This process should take ~2-3 hours.

After the sonication process, the solution is transferred into a Teflon autoclave at 180 °C for 12 hours. The hydrothermal autoclave reactor is used for hydrothermal reactions at high pressure and high temperatures. It consists of the outer high quality stainless steel jacket and the inner Teflon chamber (3). After this process, the composite is cleaned with DI water through an Automatic DI water Washing Machine. This is used to wash away the unused ions and solvents that are left over from the reaction. This will take roughly 10 minutes to go through the length of the DI water washing machine. The composite is then processed through a dryer belt. This is used to evaporate the DI water and the ions that it dissolved. This process will take roughly ~20 minutes to pass through the length of the dryer belt[52].

The WO₃/CNTs composite electrodes are created by mixing the composite with 5 wt% Nafion solution produced by Dupont. The composite is mixed with the Nafion solution at a 9:1 weight ratio to form a slurry. This process can be done through a medium sized industrial mixer with an agitator. The process to form the composite slurry takes roughly 16-17 hours. The slurry is sprayed onto the PTFE-treated carbon paper to create the composite electrodes with the desired WO₃ loadings. The PTFE-treated carbon paper will be bought from a third-party company which produces them[52].

10.1.2. Pt/Co Catalyst

The Pt/CoPt was prepared by a plasma technique. The synthesis of PT/CoPt composite NPs, cobalt, and platinum was 1.00 mm as opposite electrodes immersed into deionized water. The gap between the two opposite electrodes was maintained at approximately 0.3-0.5 mm during discharge. The discharge was generated using a high voltage pulsed DC power supply without inert gas. The amount of metallic hybrid NPs was controlled by adjusting the discharge conditions, including voltage, pulse width, and time. The consumption of platinum and cobalt

wires was 10.1 mg and 2.9 mg. immediately after NPs were obtained in uniform suspension, it went to a mixer with dispersed aqueous MWCNT by ultrasonic treatment to prevent NP aggregation and improve their electrical conductivity. The composite catalysts were dried at 60 °C in air. Then, the catalyst was annealed at 700 °C for 2 hr under flowing N₂ to obtain Pt/CoPt-2/MWCNTs, which resulted in a high degree of alloying in the Pt-Co alloy. Then, the catalyst was added with deionized water, Nafion membrane, Vulcan XC-72, and methanol to the ball mill, which makes the catalyst ink[62].

10.1.3. Nafion/PTFE Blend Membrane

The two main materials needed for the membrane are 5wt% Nafion solution and 60wt% PTFE. For the sake of convenience, Nafion solution can be purchased from DuPont while PTFE alcohol dispersion at 60 volume % can be purchased from a third party company. In order for the production line to start, an appropriate amount of 810g of aqueous Nafion needed to become resin by leaving it to dry for approximately 10 hours at 60 Celsius on a teflon surface. N,N-dimethylformamide (DMF) was needed to dissolve the Nafion resin to make 10wt.% of Nafion/DMF solution. The DMF solution was also used to mix with 60wt.% PTFE dispersion to create 10wt.% PTFE/DMF. It would take roughly an hour for both of the mixing processes to be completed. The Nafion DMF and PTFE DMF solutions can both be formed through the use of a continuous flow stirred reactor. After the two mixtures of Nafion/DMF and PTFE/DMF are created, in another CSTR, they will be mixed with each other for an hour to create a Nafion/PTFE solution. The mixture then enters an ultrasonic bath for another hour in order for it to be well mixed. The product will be left at room condition for a certain time to remove trapped air bubbles without being stirred to achieve a homogenous and bubble free solution. In an oven set at a temperature of 80 Celsius, the final product will then be casted onto a clean glass plate and left in for approximately 4 hours to remove the majority of the solvent. A heating of 140 Celsius was being applied continuously for 12 hours in order for the membrane to be completely dried and enhanced the mechanical properties of the product. This is a process known as annealing which can be done in a gas fired conveyor furnaces. The dried membrane will be peeled off after being immersed in a 1mol/L H₂SO₄ aqueous solution for 24 hour. The procedure of the process is done under laboratory scale and is assumed to function the same way with industrial equipment[63].

10.2. Block Flow Diagram and Simplified Process Flow Diagram

10.2.1. Nafion/PTFE Membrane Production

The Block Flow Diagram for the production of the Nafion/polytetrafluoroethylene blended membrane was constructed with the manufacturing process described earlier. 5 wt% Nafion

solution is evaporated by being placed in a vacuum dryer to form Nafion resin and then processed into a stirred tank with Dimethylformamide to form a Nafion/DMF solution. A 60 wt% PTFE solution is also mixed with DMF to produce a PTFE/DMF solution. The PTFE/DMF and Nafion/DMF solution was then reacted in a stirred tank and an ultrasonic bath. The solution then enters a vacuum dryer for drying and then a gas fired conveyor furnace and then an immersion tank with Hydrosulfuric Acid, after which the membrane solution is ready. This process is displayed in Figure 9[63].

The Simplified Process Flow Diagram for the PTFE/Nafion blend membrane material was done for a basis of the amount needed for the production of one fuel cell stack. The mass of the Nafion membrane necessary per fuel cell is 1.35 g according to the DOE [9]. This means for our fuel cell stack, that is 1.35×400 or 540 g that is necessary per cell stack. Due to an absence of information, it will be assumed that the necessary ending solution of the PTFE/Nafion membrane is 50% PTFE and 50% Nafion in wt%. This means the mass of both the PTFE/DMF and PTFE/Nafion solution will be 270 g in total. According to the process described earlier in the manufacturing of the membrane, the PTFE/DMF and Nafion/DMF solutions are both 10%/90% in wt%. This means for both solutions, the amount of DMF necessary is 0.90×270 g or 243 g of DMF. For the PTFE/DMF solution, the PTFE dispersion is mixed directly with the DMF to produce the solution and so the amount of PTFE dispersion needed is 27 g to form a 10wt% solution with DMF. The amount of Nafion resin necessary is 27 g as well to form the same proportion as the PTFE/DMF solution. However, since the Nafion solution comes as a 5 wt% solution with a solvent of water, the water has to be evaporated in a vacuum dryer. In order to find the necessary amount of 5% Nafion solution then, the amount of Nafion resin (27g) is divided by the wt% (5%) to obtain 540 g of 5% Nafion solution. In the Vacuum Dryer, the water solvent is evaporated from the solution which is 95% of the Nafion solution or 513 g of water leaves the system. Finally, for the Immersion tank, the Sulfuric Acid solution is used to immerse membrane and so it can be assumed that 1000g is enough and that it leaves the immersion tank after the process is finished, producing 540 g of the PTFE/Nafion membrane. For all the temperatures of the reactants, it can be assumed that they come in at room temperature and pressure as they are just left at normal room conditions before they are reacted. The water leaving the vacuum dryer is assumed to be 100 °C and 1 atm because of the boiling point. According to the manufacturing process, the vacuum dryer had to operate at 60°C, the 2nd one at 80 °C and the furnace was operated at 140 °C. The temperature of the product is assumed to be room temperature because it is left in room conditions after the process is completed. The time for each process is also included based on the duration listed in the article [63]. The simplified process flow diagram of this process is shown in Figure 10.

10.2.2. Tungsten Oxide/Carbon Nanotube Composite Production

The production of the Tungsten Oxide/CNT composite is shown in the Block Flow Diagram in Figure 11. This Block Flow Diagram includes the manufacturing process that was described earlier. This includes Tungsten Oxide added to the Sonicator for 2-3 hours, being reacted in a Teflon Autoclave for 12 hours, being washed for 10 minutes with DI water, dried for 20 minutes and reacted in a stirred tank with Nafion solution to produce the Tungsten Oxide/CNT composite. The process flow diagram for the production of the Tungsten Oxide/CNT composite was done for the amount necessary to produce one fuel cell stack. The amount of the tungsten oxide/carbon nanotubes necessary for a fuel cell was determined using the dimensions of the Toyota Mirai fuel cell stack. It consists of 37L in total volume and has 370 cells with 1.34 mm in thickness for single line stacking. The total area of this fuel cell stack would be 746 cm^2 . Our fuel cell stack area is estimated to be 780 cm^2 which is roughly 1.05% larger than the Toyota Mirai fuel cell stack. The cell area is estimated to be $\sim 500 \text{ cm}^2$ accounting for the ancillary components which would provide a total anode area of $370 * 500 \text{ cm}^2 = 18.5 \text{ m}^2$. Since our fuel cell stack is 1.05% larger, it can be assumed that the total anode area is also 1.05% larger so 19.425 m^2 may be assumed to be the anode area. It takes roughly 0.92 kg of Tungsten Oxide loading for an anode area of 18.5 m^2 so it can be assumed that our fuel cell stack takes 0.966 kg of Tungsten Oxide instead. Carbon nanotubes are mixed into the composite at a 1:4 weight ratio. This amounts to $0.966/4 = 0.2415 \text{ kg}$ per stack (1). This solution is also mixed with Nafion 5 wt% at a 9:1 weight ratio. The weight of the Tungsten Oxide + Carbon Nanotube mixture together in a stack is $0.966 \text{ kg} + 0.2415 \text{ kg} = 1.2075 \text{ kg}$ so 1/9 of that is 0.111 kg of the Nafion solution per cell stack [52]. For the Washer, due to the lower scale production of this product, only 50kg of DI water is necessary and the DI water leaves the washer afterwards. The reactants are assumed to be at atmospheric pressure and room temperature as they are not treated in any way before the reaction. The product is also assumed to be so because it is left at room conditions after the manufacturing process. Adding all the masses necessary together results in 1.3185 kg. The simplified process flow diagram can be seen in Figure 12.

10.2.3. Platinum Cobalt Alloy Catalyst Production

The manufacturing process of the catalyst ink produced from the Platinum Cobalt Alloy is displayed in the Block Flow Diagram in Figure 13. As described earlier in the manufacturing process of the catalyst ink, the Platinum and Cobalt is first reacted in a High Voltage Generator as a Stirrer with Water flowing through to produce the Platinum Cobalt alloy for 8 hours. It is then dried for an hour. Afterwards, it is Annealed using Nitrogen gas for 2 hours to strengthen the alloy. It is then reacted with DI water, Nafion, Carbon nanotubes and methanol in a ball mill for 4 hours to produce the catalyst ink[62].

The simplified process flow diagram is done for the catalyst ink amount necessary for one fuel cell stack. In the cost analysis for manufacturing the catalyst ink, the number of cells was assumed to have a total of 400 cells, which were comparable to other companies with FCV like the Toyota Mirai. The platinum weight percentage of 6% and the catalyst weight of 5.3045 g/cell was assumed to be the same from the DOE document. These values were used as the basis for the calculated amount needed for the platinum cobalt alloy. The adjusted weight of 4.5% platinum and 1.5% cobalt was found to replace the original 6% weight of platinum. The weight of Nafion DE-521 was 72%, 9% for Vulcan XC-72, 6.5% for methanol, and 6.5% for DI water. The total weight of the catalyst was calculated by multiplying the catalyst weight 5.3045 g/cell and number of cells, which resulted in ~ 2.1 kg per stack. Multiplying the mass % of each part by the total mass of catalyst per stack will result in the total mass of each material needed for the fuel cell stack. This results in 95.48 g of Platinum, 31.82 g of Cobalt, 137.9 g of DI Water, 137.9 g of Methanol, 190.9 g of Carbon nanotubes and 1527.7 g of Nafion for one stack. For the Nitrogen air used in the drying process, it is assumed that 100 kg is necessary and that it can be recycled for use in the Annealing process as well. For the production of the Platinum Cobalt alloy, the water necessary will be assumed to be 200 kg and it is that it all leaves the system afterwards. For the reactants, it can be assumed that they are all at atmospheric temperature and pressure because they are not heated or cooled before the process. The Nitrogen however in particular has to be 60 °C and 1 atm. For the outlet for water and nitrogen, they will be allowed to be cooled to room temperature before being released and so they are assumed to be that temperature when released. For the catalyst ink, the product will be left in room conditions and so is 25 °C when completed. Adding all the masses together results in 2181.82 g of the ink[9]. The Simplified Process Flow Diagram for this process is shown in Figure 14.

10.2.4. MEA Assembly

For the process to assemble all the previous material together to produce the MEA, the catalyst ink must be taken from the ball mill through the use of the vacuum sieve. It is then distributed to two separate slot die coating machines. The slot die coating machine coats the catalyst ink onto the membrane material and transfer substrate. One is attached to the Nafion/PFTE membrane material while the other is attached to a Polyethylene Transfer Substrate, the former becomes the coated Anode and the latter becomes the Coated Anode. They are then attached to each other using a Decal Transfer. The Tungsten Oxide is then attached to the Gas Diffusion layer, purchased from an external source using another Slot Die Coating process. All these parts are then Hot Pressed together in the order from top to bottom, GDL, Tungsten Oxide layer, Anode layer, Membrane, Cathode and the GDL. It is then passed through a Die Cutting process to remove any excess grains on the edges and produces the Membrane Electrode Assembly. Due to

the relatively low amount of time it takes for each process since it is just combining materials, it is assumed each process takes 10 minutes. The Block Flow Diagram of this process is shown in Figure 15. The Simplified Process Flow Diagram for this process is done with the basis of one fuel cell instead of a fuel cell stack due to assembly process being typically done on a per cell basis. According to the DOE, the mass of each part necessary is 5.304 g of Catalyst ink, 1.35 g of the PTFE/Nafion membrane, 1.67 g of the Transfer Substrate, and 2.52 g for each Gas Diffusion layer [9]. As discussed earlier, the Tungsten Oxide/CNT mass necessary for the entire stack is 1.3185 kg so dividing by 400 gives us the amount necessary for each cell which is 3.3 g. Since all the materials used are first to room conditions, the temperature will be assumed as such. The hot press has to be operated at 130 °C and 0.1 MPa[9]. The result of the processes are operated in normal conditions. After the Die Cutting process, the MEA is left to chill in room conditions and so the temperature of the MEA product is assumed to be 25 °C. Since the Transfer Substrate is taken out during the Decal Transfer, the mass of the MEA mass was determined by adding the mass of all the materials besides the transfer substrate, resulting in 12.474 g. The Simplified Process Flow Diagram is displayed in Figure 16.

10.3. Main Equipment of the Manufacturing Process

The main equipment of the process to produce the Nafion/PTFE blended membrane are the vacuum dryer, reactor tank, ultrasonic bath, gas fired conveyor furnace, and an immersion tank. The equipment necessary for the production of the Tungsten Oxide/CNT mixture is the Teflon Lined Hydrothermal Autoclave, Ultrasonic Homogenizer Sonicator, Industrial Cleaning Station, Small Scaled Stirred Tank. The process to produce the Platinum/Cobalt alloy mixture is the High Voltage Tank, Stirrer and Annealing Machine. The process to produce the Catalyst ink requires the Ball Mill. The process to produce coat the catalyst ink on the membranes are the Vacuum Sieves, Tunnel Dryer, and Decal transfer. The process to coat the Tungsten oxide layer on the Gas Diffusion Layer uses the Slot Die Coating process equipment that is used for the catalyst ink. Lastly, a hot press is necessary for combining the previous components into the Membrane Electrode Assembly[9].

10.4. Waste Management in the Manufacturing Process

The waste that is primarily released from the processes are solvents such as water and hydrogen peroxide, which is typically dealt with through drying inside either vacuum dryers or belt dryers depending on the process. Other waste products are typically unused ions from reactions and acidic solutions that were used to create a low pH environment for reactions. These waste products were dealt with by washing them with DI water for the case of the tungsten oxide/CNT composites or with distilled water for the case of creating the 5% Nafion solution. In both of

these situations, the washer will use an excess of DI water and distilled water while the mixtures flow through the equipment. Since these will be polluted by the solutions, the DI water and distilled water is given to a third party to discard it. The dryer used to remove the water with the dissolved ions and acids will have to have an outlet to ensure no build up of steam with those solutes occur. This is given to a 3rd party company. For the case of the catalyst formation, the N₂ and water are excess in the feed which does not react with the Pt/Co alloy. The water is released into the environment and N₂ is reused for the process of catalyst ink.

An issue with the MEA formation process is the catalyst ink is often scrapped. This happens in both the ink mixing process and also the delivery process. This happens most often during start-up and shut-down of the equipment. Unused ink is often left in feed lines, the mixing vessels and transfer hoppers within the reactor. Keeping used polyethylene would be a fire hazard. The unused polyethylene will be recycled in a third party recycling facility to reduce waste and hazard. The unused ink in the reactor is known as skins. This problem can be alleviated by either increasing individual batch sizes but often requiring higher equipment downtime and increased labor needed to run the equipment. The most efficient way to reduce the skin loss is to use a continuous mixing process. Another way to minimize the waste is to reduce the surface area within the mixing vessel, holding container and the equipment used to coat the membrane. Reducing the frequency of it being cleaned is also important because the catalyst is actually scrapped during this process [64].

10.5. Challenges Expected for Scaling Up the Manufacturing Process

The manufacturing processes proposed in the prior sections were linearly translated from lab-scale conditions to industrial applications. However, in reality, such compositions, operating conditions, and manufacturing methods have to be specifically tailored to the desired process at hand. Due to the differing mechanical, chemical, and electrochemical properties that each component has to satisfy, each process needs to be engineered to those specifications. The following paragraphs will discuss the components individually and how the manufacturing process could cater to and affect their respective specifications.

A scaling-up challenge that applies to every manufacturing process is the equipment used in the lab versus in industrial settings. To overcome this, a conversation with the company that produces industrial machines would be beneficial in terms of having the specifications of the appropriate equipment. With those specifications, a theoretical or empirical model could help conclude whether or not the industrial equipment would produce the desired product or a similar one. If it does not, other equipment could be chosen to carry out that process. Also, in lab-scale productions, the process is usually done in batches while the goal of the processes proposed

above would be done continuously. Since reactions were done in reactors, start-up and shut-up procedures have to be determined along with turnaround times to determine the net rate of production. To account for production increase, the operations that take the longest time need to be modified. This modification would mean an increase in the number of batches and an increase in the production line. Safety guidelines will also have to be procured for the safety of the workers and legal reasons. Lastly, quality control is an issue that needs to be addressed when scaling up to ensure that the processes are appropriate for the desired quality level and cost-effective. Testing methods could be done in-house or through a third-party company. The catalyst layer is a paramount component in the MEA because it is where the redox reaction needed to create electricity occurs. Three factors that would affect the quality of the catalyst layer are the composition of the catalyst ink, the deposition method, and the solidification rate of the layer [65]. Firstly, the quality of the ingredients in the ink bought in bulk could be less compared to the quality if it was bought in small quantities. This issue would affect the composition since contaminants could be introduced through lesser quality products. As for the deposition method, the equipment and process used will affect the performance of the fuel cell. The rate at which the ink is sprayed on or coated on would determine the final dimensions of the electrode and distribution of the catalyst loading on it, which would also affect the solidification rate. An optimal solidification rate is wanted because a high rate could cause the ‘surface of the electrode film to boil and peel’ [65]. It is going to impact the microstructure of electrodes, the main idea is to avoid the ‘agglomeration of the catalyst particle’. Two factors that would be investigated for the solidification rate is the amount of solvent added and the heat output of the dryer used.

As for the membrane component, the final thickness and uniformity of the polymer film are very important. The challenge for scaling up the casting process is the controlling of the spreading and stretching of the polymer solution while it is being layered onto a surface. Also, since a Nafion membrane was chosen, the catalyst deposition step could damage it. Since it absorbs water and other solvents well, the membrane could ‘wrinkle up’ and reduce the overall performance of the fuel cell since intimate contact is desired for optimal mass transfer [65].

Again, the microstructure of the layer would also affect the performance of the final product, so the drying process has to be engineered so that defects are minimized. Another factor to consider is the cost of this process since the carbon cloth that the layer is sprayed onto is bought from an outside company, improving the cost-effectiveness of this process could benefit the overall cost of the final product.

11. Cost Analysis

11.1. Expenses and Costs

The production of the platinum cobalt catalyst was inspired by the article, "Facile Fabrication of Platinum-Cobalt Alloy Nanoparticles with Enhanced Electrocatalytic Activity for a Methanol Oxidation Reaction [62]." The types of equipment used to produce the catalyst ink were bipolar pulsed HV power generator with a stirrer, annealing equipment, a ball milling, a coating machine, and a vacuum sieve. The price of all the equipment was found using the store website and Alibaba eCommerce. The cost of a bipolar pulsed HV power generator was found to be \$10,999 [66]. The stirrer was found to be \$10,000 [67]. The bipolar pulsed HV power and the stirrer created the platinum cobalt alloy. The cost of the annealing treatment equipment was found to be \$28,000 [68]. The annealing equipment strengthens the alloy before going into the ball mill to create the ink. The cost of the ball mill was found to be \$29,347 [69].

The cost to produce the catalyst ink per stack was obtained from using the Department of Energy document, "Manufacturing Cost Analysis of 100 and 250 kW Fuel Cell Systems for Primary Power and Combined Heat and Power Application." Additional cost for manufacturing the catalyst ink was the inclusion of the cobalt platinum catalyst instead of the original catalyst used from the document. The bill of the material for the catalyst ink was calculated from the DOE document and other websites for an updated cost for current materials. The catalyst cost per kg was found to be \$34354 per kg for platinum and \$79.49 per kg for cobalt [70,71]. The Nafion DE-521 price of \$219.84 came from the DOE, the carbon support Vulcan XC-72 cost was \$0.99 per kg. The methanol cost was found to be \$0.38 per kg [72]. The price of deionized water costs \$0.10 per kg. Using these costs and multiplying it by the mass of each material per fuel cell stack results in \$3280.18 of platinum, \$2.53 of cobalt, \$335.85 of Nafion, \$0.19 of Vulcan XC-72, \$0.05 of Methanol, \$0.01 of Water per stack. The catalyst material cost per stack with all the material needed resulting in \$3,618.82 in total per stack.

As determined earlier, the amount of Tungsten Oxide needed for the composite is 0.966 kg per stack. The cost of Tungsten Oxide is \$40/kg [52]. This means it will cost \$38.64 per stack. . The price of the Vulcan XC-72, the carbon nanotube material is assumed at \$0.990/kg when bulk purchased according to a learning curve analysis by the DOE. This means it would cost \$0.239/stack . The adjusted price for bulk purchase is assumed to be \$219.84/kg for Nafion which amounts to \$24.43/fuel cell stack [9].

The machinery necessary for this process is the Sonicator, teflon autoclave, washer, dryer and mixer. Since the total mixture is mostly tungsten oxide, the density will be assumed to be equivalent to that, which is 7160 kg/m³[73]. The teflon autoclave is used to mix the CNT and

Tungsten oxide mixture. The total annual amount of that mixture produced is 1207.5 kg assuming 1000 fuel cells which is equivalent to 0.169 m³ or 169,000 mL. This process cannot be processed on a monthly basis or weekly basis because there are no industrial scale Teflon Lined Hydrothermal Autoclave reactors in the market. Assuming 250 work days, only 1352 mL need to be processed every other day so a Teflon Lined Hydrothermal Autoclave-02000mL capacity will be enough to support the production scale. This cost is \$1899 [74]. The BAOSHISHAN Ultrasonic Homogenizer Sonicator Handling Capacity 100-2000ml is enough to support this production scale. The cost of this equipment is \$1889 [75]. This process can use the oven dryer of another process such as the MEA assembly process. An industrial cleaning station is roughly \$1000 dollars[75]. For the stirred tank, a small scale reactor is enough for this process. This is roughly \$700[76]. The Tungsten oxide mixture has to be sprayed onto the Gas Diffusion layer. This is done through the use of the Slot Die Coating from the Cathode/Anode catalyst deposition process line. For both the dryer and slot die coating, it can be assumed that there will be no contamination from the processes.

Due to an absence of information, the energy usage calculation for this process is not possible . However,because of how little of the mixture is processed annually in comparison to the rest of the fuel cell, it can be assumed that the energy consumption costs for this process is negligible in comparison to the rest of the processes.

For the final decision on manufacturing our MEA, we decided to not produce the polymeric membrane material in house due to the cost of obtaining required equipment for the process, such as gas fired conveyor furnace and an ultrasonic bath. Another factor that impacted our decision is the time it takes for the process to be completed. The production line for this process is also very long and will take a large amount of space within the factory. The amount of the PTFE 60 wt% which is needed for the production of one fuel cell stack is also not clear so determining the manufacturing costs for this process is difficult. This will also increase the amount of employees we need by at least 2 because of the amount of equipment this process needs. Lastly, the last part of the process, placing the mixture inside the immersion tank with Sulfuric Acid solution takes around 24 hours. The process altogether would take roughly 40 hours as well [63]. Because of all these reasons, we have decided to not produce the membrane material.

The membrane material will be PFSA, 0.2 mm in thickness and PTFE reinforced. According to the USDOE Office of Energy Efficiency and Renewable Energy (EERE)'s report on Fuel Cell Manufacturing for Automobile application , production of the membrane is \$3167 per stack assuming a 1000 annual production rate. It will be assumed that the amount of membrane material needed increases linearly with the amount of fuel cells in a stack. For our stack, we will

have 400 cells while the EERE's stats are for 379 stacks. To obtain the cost, we multiplied \$3167 by $(400/379)$ and then by 1.3 for the 30% price increase to purchase the material instead of producing it. This will then cost \$4345.22 per stack [77]. Our transfer substrate will be made of polyethylene which costs \$0.03 per cell. This cost will be \$12 per fuel cell stack which was determined by multiplying that cost by the number of cells.

The catalyst ink has to be coated onto the membrane and the transfer substrate. This will require the SM950 Sievmaster Vacu-siev which costs roughly \$7720[78]. This machinery is used to remove and separate the catalyst ink from the ball mill and then transport it to the coater reservoir. The coating process will use the Slot Die Coater which costs \$55,000 [79]. Since the catalyst ink has to be coated on both the Membrane and the Transfer Substrate, two Slot Die Coaters will be necessary for this process. After the deposition of the catalyst ink, the anode and cathode parts will be brought into a Tunnel Dryer. The length of the tunnel dryer has to be over 7.07 meters to dry the cathode. This will cost approximately \$50,000.

The Catalyst Layer Decal Transfer process occurs immediately after the drying and will consist of loading the anode and cathode into calendering rollers so they align. According to Batelle, the baseline cost of the entire Decal Transfer process is roughly \$58,400 [9]. The baseline cost of a process line is calculated taking into account the number of units in one line, the capital cost of each unit and the expected life of each unit. The total capital cost for said equipment is calculated assuming a 20 year production life to determine if the equipment has to be replaced in that time span (3).

The rest of the parts of the fuel cell stack will be purchased instead of made in house. These parts include the End Plates, Gas Diffusion Layers, Bipolar Plates, MEA Sub-Gaskets, Coolant Gaskets, Current Collectors, Compression Bands . The production prices which includes Material, Labor, Machine, Scrap and Tooling costs for each part are listed by Batelle and the EERE. However, since we are not producing these parts inhouse, it will be assumed for each part listed that the price to bulk purchase each part will be 30% higher than the cost of production to account for the markup. The end plates cost \$73.08 per stack to produce. Since the number of end plates does not change regardless of how big the fuel cell stack is, it will be assumed that it will cost $\$73.08 \times 1.3 = \95 per stack [9].

The cost of production for the Gas Diffusion layers is \$2602 per fuel cell stack. As done before, it can be assumed that the amount of Gas Diffusion layers increase linearly with the amount of fuel cells. This means our cost will be $\$2602 \times (400/379) \times 1.3$ to account for the markup price and the increased amount of fuel cells in our system. This equals \$3570.03 per fuel cell stack [77].

The cost of the Bipolar Plate is \$1985/stack according to ECE. As before, we can assume that this cost increases linearly with the amount of fuel cells necessary so this will cost will be $1985 \times (400/379) \times 1.3$ to account for the part not being made in house. This cost will be \$2723.48 per cell stack [77].

The cost of the MEA Sub-Gasket, Coolant Gasket and End Gaskets are \$917, \$410 and \$1 respectively. For the Coolant Gasket and MEA Sub-Gaskets the amount can be assumed to increase linearly with the cell stack. This would cost \$1258.15 and \$562.53 respectively per fuel cell stack. For the End Gasket, since there are only two regardless of production size, it will be assumed that the End Gasket price per stack is \$1.30. For the Current Collector and Compression Bands, the cost to produce is \$8 and \$10 respectively. Assuming the previously listed assumptions, these costs will be \$10.98 and \$13.72 respectively per fuel cell stack [77].

The baseline cost for both the MEA Hot Pressing and Die Cutting Process is \$289,000 and \$125,000 respectively. These values take into account the typical cost of a unit, the amount of units per line and the expected life expectancy for each equipment to see if the equipment needs to be replaced in the next 20 years. The process consists of attaching the top Gas Diffusion layer attached to the tungsten oxide layer to the catalyze membrane on the anode side to the Gas diffusion layer. After this process, the MEA then goes through the Die Cutting process with a Press Energy of 37.95KW. Both of these processes can be assumed to be able to handle a production of 1000 stacks per year. The MEA is then assembled by applying pressure to the completed stack using a hydraulic press. The tie rods and gas fittings are then installed to complete The hydraulic press is estimated to cost \$1310. The testing of the PEM Stack requires \$39.61 worth of materials. Since Batelle obtained this material cost value through calculation of bulk purchasing of Air, Hydrogen and Nitrogen to test the stack, it will be assumed that this cost already accounts for the markup price. The baseline cost for the Testing and Conditioning Line is \$300,000[9].

For producing the Platinum + Cobalt alloy, the power output is 105 kW for the Annealing Machine, 100 kW for the stirrer and 4 kW for the AC Power source(1)(2)(3). The Annealing equipment is run for 2 hours, stirrer for 8 hours and high voltage tank for 2 hours. This equals $105 \times 2 + 100 \times 8 + 2 \times 4$ or 1018 kWh per batch. This amounts to 12216 kWh for 11 batches. This is \$855.12/year and dividing that by 1000 stacks would give a cost of \$0.86/cell stack. According to Batelle, the power costs for the entire production of the MEA from the catalyst material to the hydraulic press including machinery costs and tooling costs is \$0.97 per fuel cell which is \$388/stack for our 400 cell stack [9]. The Tungsten oxide mixture production line is a very small fraction of the fuel cell stack in comparison to the rest of the stack. It can be assumed that this cost is 10% of the overall cost which is \$38.80/stack. For the Stack Testing and Condition costs,

the machinery costs \$91.58/stack. The machinery costs are calculated taking into account the power output according to the DOE and how often the production line is used through the utilization. Adding all these prices would equal \$520.21 per fuel cell stack produced. These energy costs were calculated under the assumption that the cost is \$0.07/kWh.

During the process of finding an industrial building to rent, there are several assumptions that need to be made. These assumptions including data of the utilization of machines, operators per line (Table %), and the floor space for our production stations (Table ft²) to be the same as what was provided by the Department of Energy[9]. Because the Tungsten Oxide production is needed more frequently than the Catalyst, we also assume the utilization rate of the Tungsten Oxide production to be double the rate of the Catalyst production. Before obtaining the number of operators per shift, we also assume that each skilled labor is capable of controlling any type of equipment. The number of operators was obtained by using the same calculations as the DOE, multiplication between production stations' number, utilization rate, and operators per line to determine the number of operators per shift, then finding the total of those values. We found the result of 4 operators for one shift, and 2 supervisors will be assigned to every 4 operators. Two quality people along with 2 engineers will also be needed for the production process. For our marketing department, there will be three employees at entry-level, including 1 marketing manager, and 1 sales representative. The total number of employees in the facility will be 12 and using the measurements from the Texas Office advisors, we would need 12 offices total with a floor space of 100ft² each, 1 common room (110ft²x3) for every 7 employees, and 1 restroom for every 4 employees (75ft²x4). This leads to the facility floor space being 4829 ft² after totaling the floor space measurement accordingly to their quantities[80].

Since Tungsten Oxide is being produced under a lab-scale production, we are assuming the floor space of this station would be too small to impact the overall building size. The building we would need to rent should have a total size of 4827ft². A listing of an industrial building with a size of 4843ft² in Missouri City, Texas at a rental rate of \$5252.4 monthly and \$63,028.8 yearly. The facility also comes with parking spots for employees [81].

The equipment costs were determined by adding all the equipment costs of producing the catalyst ink, producing the tungsten oxide solution and the production lines necessary for assembling the rest of the fuel cell stack. The equipment costs also included a cost for a crane and a forklift. The cost of the equipment and production lines is shown in Table 8. The total equipment cost ends up being \$1,006,290.00 for our production.

The maintenance cost of the machinery is assumed to be 5% of the total cost of all the machinery. The depreciation cost of the machinery was found to be 5% of the equipment

consistently across all of our equipment under Asset Class 28.0 for Manufacture of Chemicals and Allied Products. The transport cost was assumed to be roughly \$200,000 per year. From our previous analysis, we determined that we needed 4 skilled laborers, 2 supervisors, 2 engineers, 2 quality personnel, 1 marketing manager and 1 sales representatives. Assuming the annual salary is \$75,000, \$80,000, \$110,000, \$90,000, \$57,750, \$26,970 respectively[82]. The personnel overhead cost was determined assuming that the cost is 20% of the cost of every employee. The loan interests are also included assuming that the interest on the loan is consistently 4% of the total loan annually [83]. How the desired loan amount was determined is described later. The cost was determined to be \$114,307 per year. The annual fixed operating costs come out to \$1,692,321.80 per year. The table of Fixed Operating Costs are shown in Table 9. Note that the equipment costs are not included in the Fixed Operating Costs.

The costs per stack of each material and part purchased was determined through the analysis earlier. The cost of Nafion and Vulcan XC was determined by adding the necessary amounts from the Tungsten/Oxide production process and the catalyst ink production process. The overhead cost was assumed to be 20% of the cost of every material that was produced. This amounted to \$783.63/stack. The energy costs were determined to be \$520.21 per fuel cell stack. No extra personnel is necessary under the assumption that our scale up of the production is not enough to require more personnel. Adding all these costs together equals \$17,573.05 per fuel cell stack produced. The variable costs per fuel cell stack is shown in Table 10.

11.2. Sales

The sales cost was determined through a Breakeven Analysis that will be discussed later. As discussed earlier, the annual fixed operating costs are \$1,692,321.80 per year. The variable operating costs are \$17,533.05/stack produced. The desired breakeven point is 900 units sold annually and so the total costs of production to breakeven is $\$17,533.05/\text{stack} \times 900 \text{ stacks} + \$1,692,321.80$ or \$17,472,066.80 per year. Dividing this value by 900 stacks will determine the sales price which is \$19,453.41/stack. This sales cost will allow the company to breakeven at 900 units. Assuming a production scale of 1000 cell stacks annually, the total operating costs is $\$1,692,321.80 + \$17,533.05 \times 1000 = \$19,265,374.60$. Assuming all the cell stacks are sold, this is an annual revenue of $\$19,453.41 \times 1000 = \$19,453,410.36$. This cost is not competitive with the market due to other companies producing stacks at a larger scale and so has reduced costs per stack. Even for production scales of 1000 stacks, typically a stack is sold at \$181/kW. For our stack, this is $\$181 \times 80$ or \$14480/stack which is considerably lower than our sales price of \$19,453.41/stack[10].

11.3. Break-Even Point

The Breakeven point was used to determine the sales cost of \$19,453.41/stack as discussed earlier. The analysis was done by graphing the revenue generated per fuel cell stack as the slope of the Revenue line. The total operating costs line was generated by using the annual fixed operating costs of \$1,692,321.80/year as the y intercept. The annual operating costs as discussed earlier includes the depreciation and maintenance of equipment, interest of the loan, the marketing costs along with the personnel costs. It does not include the costs of the equipment. The slope of the operating costs line is the variable operating cost of \$17,533.05/stack. As discussed earlier, the break-even Analysis was used to determine the sales cost to breakeven at 900 units. Therefore, the breakeven point is 900 units. The break-even analysis is shown in Figure 17.

11.4. Payback

The payback analysis was done assuming 1000 units produced and sold per year. The Capital investment which is only the equipment costs is the y intercept of the line (\$1,006,290.00). The slope of the graph is the annual net profit. This is determined by subtracting the annual revenue (\$19,453,410.36) from the annual fixed operating costs (\$1,692,321.80) and the variable operating costs (\$17,573,052.80) to obtain an annual net profit of \$188,032.76. Dividing the Capital Investment by the annual net profit will give us a Payback at 5.35 years. The Payback Analysis is shown in Figure 18.

11.5. Initial Investment

The loans were determined through a cash flow analysis of the first year. The capital expenses were calculated by taking into account the total equipment cost plus a 20% installation cost (11). These installation costs were not added to the forklift or the crane. The development phase was assumed to take half a year, which equates to two quarters. This developmental cost also includes the rent costs but not the Fixed Operating Costs due to no production. The calculation is shown in Table 11. The other half of the first year was dedicated to build inventory, based on a desired starting inventory of 100 units. The fixed operating costs for the second half of the first year was found by dividing the annual fixed cost by 2 and subtracting the transportation costs due to no sales occurring that first year. This was found to be a total of \$373,080 per quarter for the last 2 quarters. The quarterly variable operating costs was found by multiplying the variable costs per stack by 200 and dividing by 4 for the last two quarters. Assuming that \$700,000 will come from grants and private investments, the total negative cash flow for the first year without a loan ends up being \$2,997,348.58. This cash flow analysis shown in Table 12 . Based on this

analysis, we will take out a loan of \$3,000,000 and assuming an interest rate of 4%, a consistent \$120,000/year for the interest rate is included in the fixed operating costs.

12. Economic Forecast

12.1. Cash Flow

For the first year, the development costs are divided into the first 2 quarters of the year as described earlier. The DOE grant is divided into 4 quarters and there is no revenue due to no sales occurring the first year. The Variable Costs and Fixed Costs are the same as described earlier for the loan determination. The 3 million dollar loan is split in a manner that ensures that there is never a negative cash flow. For the first two quarters, the development cost is \$596,941.20 and the DOE grant is \$175,000. To ensure that we do not go into negative cash flow, we only need $\$596,941.20 - \$175,000$ or \$421,941.20 for the first two quarters. In the next two quarters of inventory buildup, the variable costs and fixed costs combined is higher than the development costs so the left over amount of the loan (\$2,156,117.6) is split into the last 2 quarters to ensure no negative cash flow. This would give a cash flow out of \$2651.42 for the first year. Note that there is no loan payment for the first year besides the interest which is a part of the fixed costs.

For the second year, the production was scaled up to 400 units and so the variable costs were changed accordingly to \$7,029,221.12/year. The production costs per stack for 400 including both variable and fixed costs is \$21,803.86/stack. The sales cost per stack was decided to be 11% higher than the production cost/stack for every year besides the last year which is \$24,202.28. The revenue accounts for both the 400 units generated the second year and the 100 units surplus of the first year. Lastly, the loan is paid quarterly and will be completely paid by the 5th year. To accomplish this, the 3 million dollar loan is divided by the 16 quarters of the next 4 years to get a quarterly payment of \$187,500. This amounts to a total profit of \$2,629,597.88 for the 2nd year.

For the third year, the production was scaled up to 500 units and the variable costs were adjusted accordingly to \$8,786,526.40. The production costs per stack for 500 units including both variable and fixed costs is \$20,957.70/stack and so the sales cost is determined to be \$23,263.04. Using the same methodology, the annual profits are \$402,673 for the third year. For the fourth year, the production is scaled up to 800 units and the production cost per stack becomes \$19,688.46/stack and so the sales cost is adjusted to be \$21,854.19. This amounts to a total profit of \$982,584.04 for the 4th year.

For the last year, the production is scaled to 1000 units and the variable costs are adjusted accordingly. For the last year, the sales cost was considered to set at \$19,453.41/stack, which is

the cost found earlier through the Breakeven Analysis to breakeven at 900 units. However, this leads to a negative cash flow for the last year and so the sales costs were set to be \$21,384.57, the same method as for the other 3 years. This amounts to a total profit of \$1,369,191.21 for the 5th year. The \$3mil loan is also completely paid by this time. The quarterly cash flow tables are shown in Table 13. The quarterly cash flow is graphed on Figure 19. The massive drop in money flow after the 2nd year is due to the reduction in sales cost alongside the variable costs for the extra 100 units not being included for year 2.

12.2. Value of the Project

The value of the project is determined by adding the accumulation of the Net Profits for each quarter. The net profits for each was determined in the previous section. Using this method, the Value of Project is graphed in Figure 20. As can be seen in the Figure, the Value of Project never goes negative, proving the \$3mil loan is perfect. The value of the project by the end of the 5th year which is when the initial loan is completely paid is \$5,386,697.85.

13. Recommendations to your Firm

The market and economic analysis was conducted to determine whether or not this proposal should be realized. The break-even point was calculated to be 833.73 units per year on a volume production of 1,000 units per year basis, and the payback period ended up being 3.13 years (approximately 4 years). The value of this project after five years, considering loan payments as well, was \$7,942,591. For a volume production of 1,000 units, the final selling price of our product was 11% higher than the manufacturing cost. At a price of \$19,509.09 per fuel cell stack, with a net power output of 80kW, the cost per kW is approximately \$244. The \$243 per kW was calculated by taking the selling price divided by the net power output. Due to this high selling price and low volume production, although the break-even point and payback period is optimal, the project should not be continued.

14. Summary

Our goal was to develop and improve the performance of the PEM fuel cell stack. In order for our team to be able to have a better picture of what we need to do, we first picked our marketing location which was California since it already has the basic knowledge of FCV. The marketing strategies were to attend trade shows, using social media, and telemarketing, with drivers as our end-users, and Toyota, Hyundai to be our customers. After determining our basics, we then proceeded with gathering information about the customer needs, which included customer preferences, safety, and technical needs. For the sake of our improvement concepts, we proceed with a criterion metric to find which concept(s) should be concentrated on. After we obtained our

priority concepts, production processes were needed to be determined. With that being researched, we as a group created our process flow diagrams that corresponded with our production processes. Our last step was to conduct an economic analysis to plan out our selling plan. We wanted to be able to sell about 1,000 stacks by the end of our first year. Since our products need to be sold at a much higher price than our competitors and our production volume is not enough to make an appropriate profit, our team has recommended not to proceed with the project.

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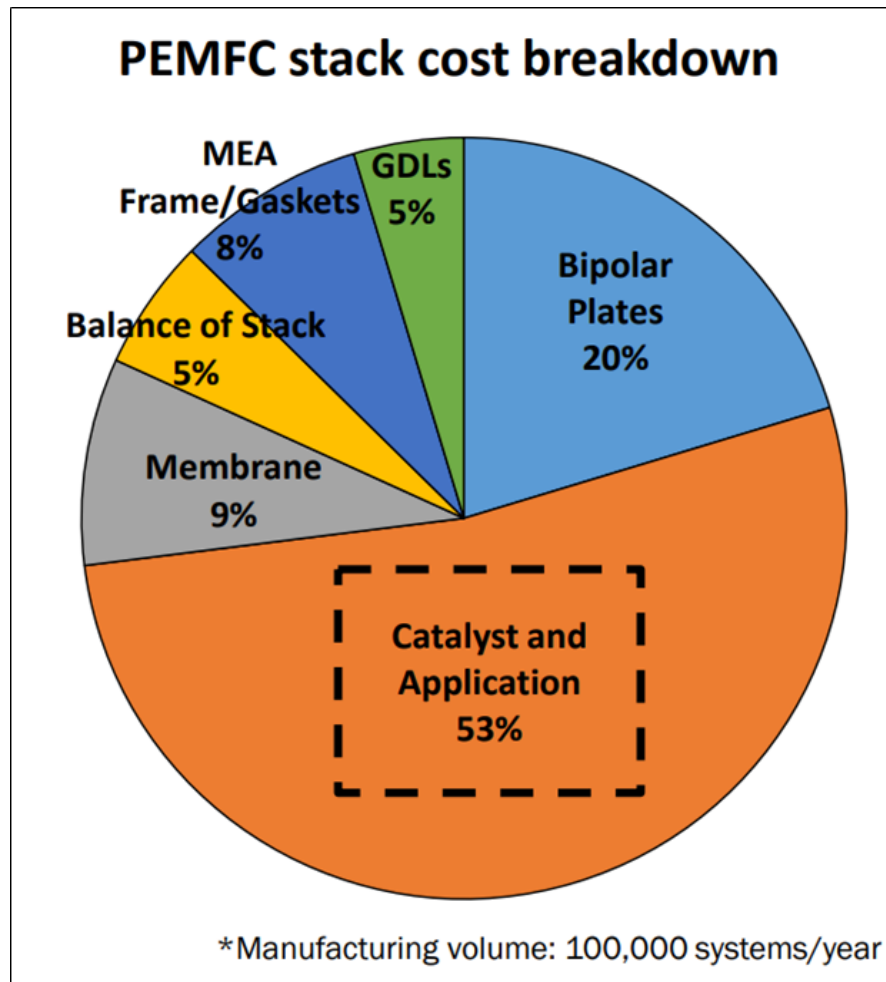
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APPENDIX I – FIGURES**Figure 1:** PEMFC Stack Cost Breakdown [10]

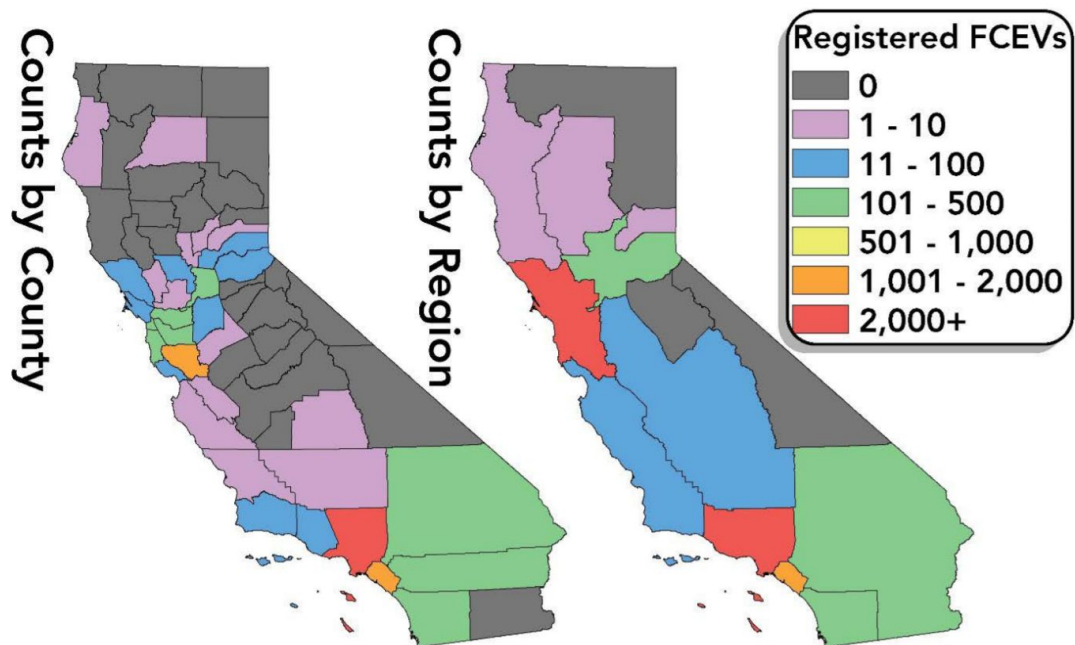


Figure 2: Distribution of Current FCV Registrations as of April 1, 2020, [17] Market Ana

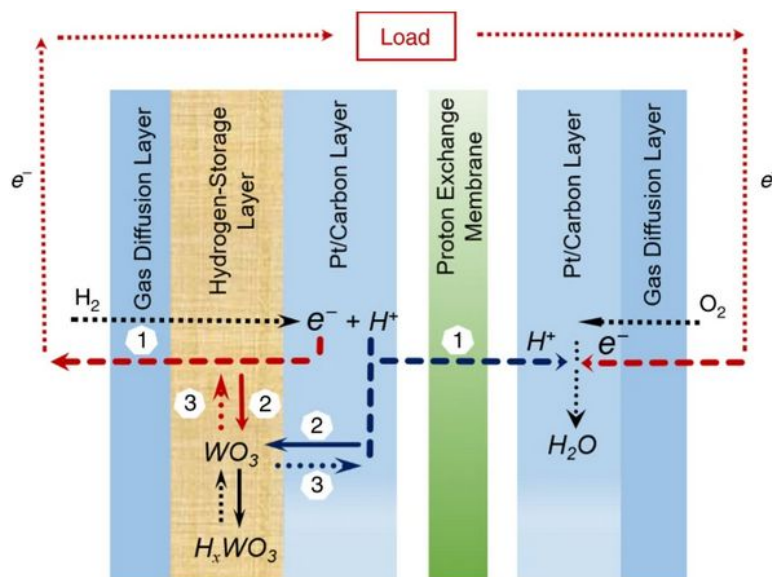


Figure 3: Addition of Tungsten Oxide Layer

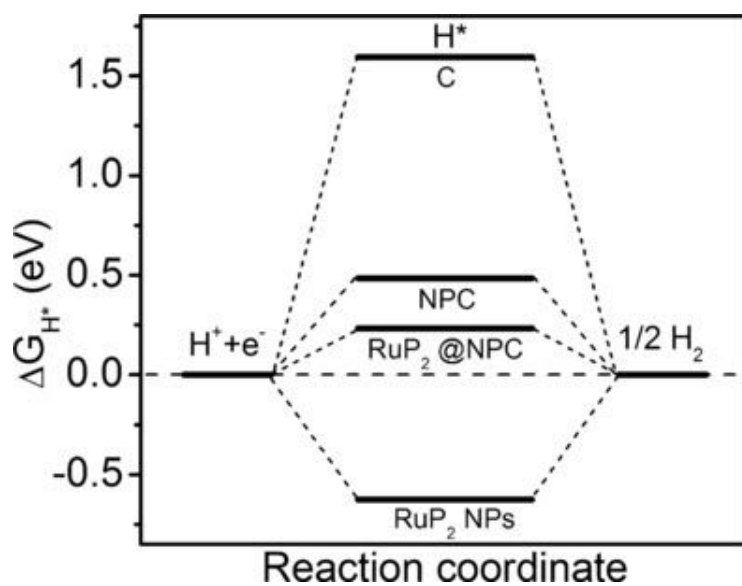


Figure 4: The calculated free-energy diagram of HER at Equilibrium potential for RuP_2

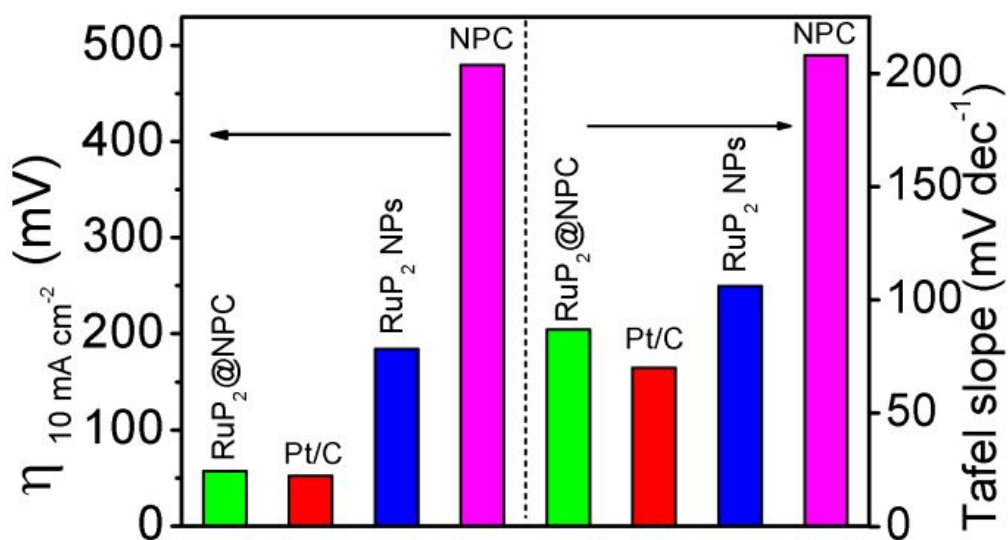


Figure 5: Tafel plot for the RuP_2 and Pt/C catalysts.

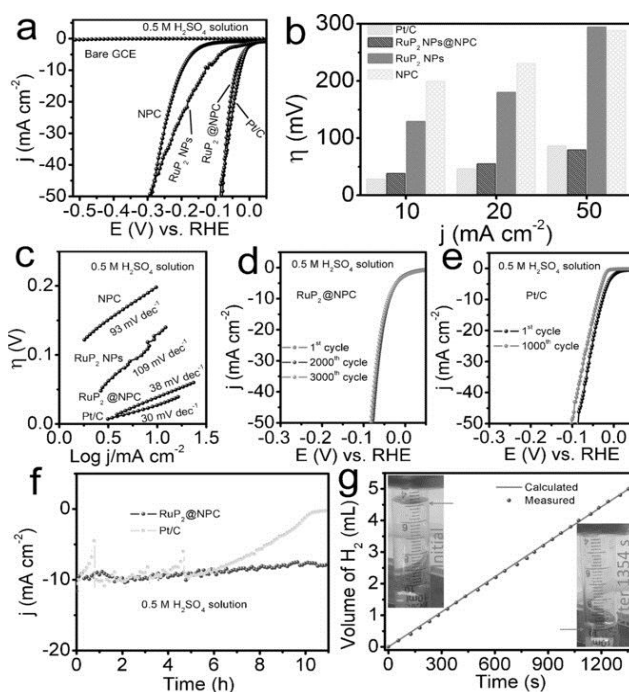


Figure 6: a) polarization of RuP₂ and Pt/C in 0.5M H₂SO₄ at scan rate 5 mV/s. b) overpotential at j (mA/cm²) of Pt/C and RuP₂. c) Tafel plots of Pt/C and RuP₂. d and e) Cyclic Voltammetry test in cycles between Pt/C and RuP₂. f) time-dependent current density for RuP₂ and Pt/C. g) the amount of H₂ collected and measured

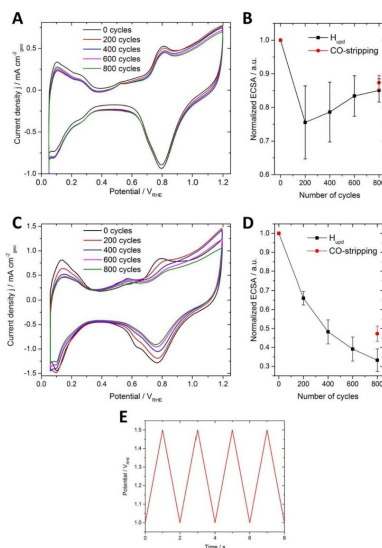


Figure 7: Cyclic voltammograms of np Pt-CoO catalyst in air 0.1 M HClO₄ AST Pt lost

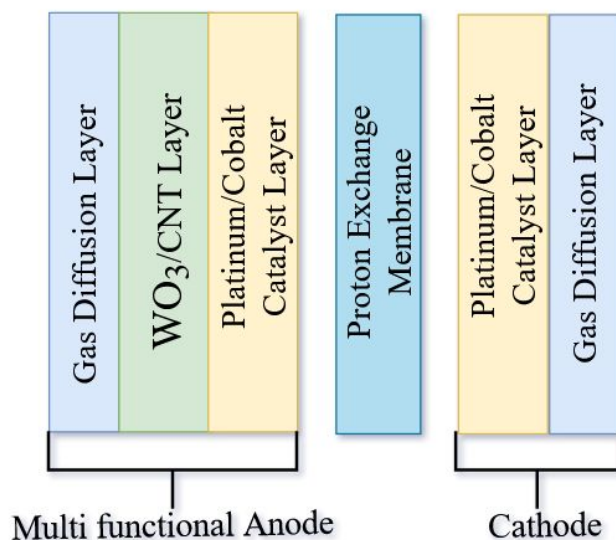


Figure 8: Final Concept with Tungsten Oxide Layer and Platinum Cobalt Catalyst

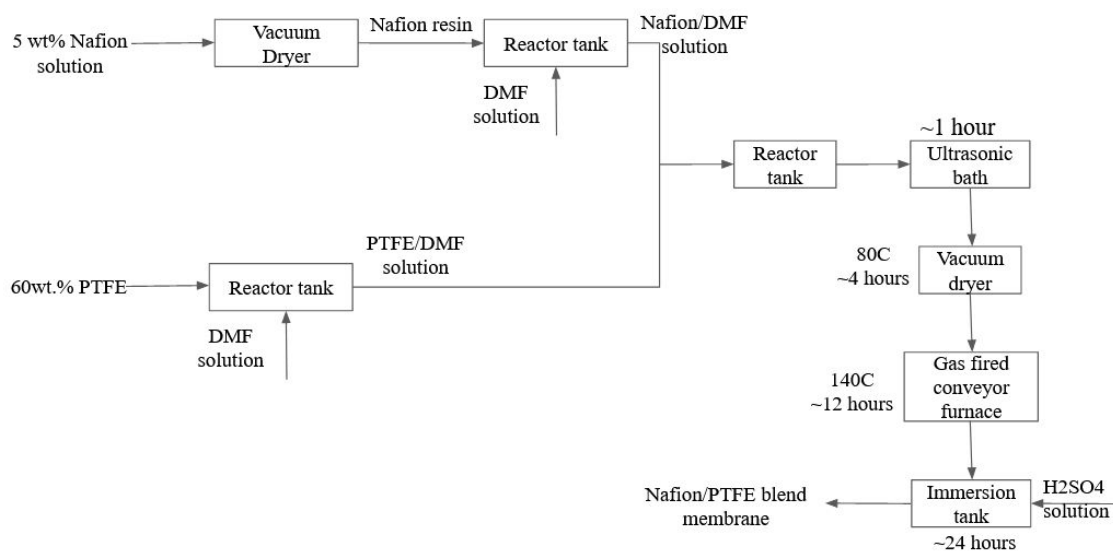


Figure 9: Block Flow Diagram: Production of Nafion/PTFE Membrane Material

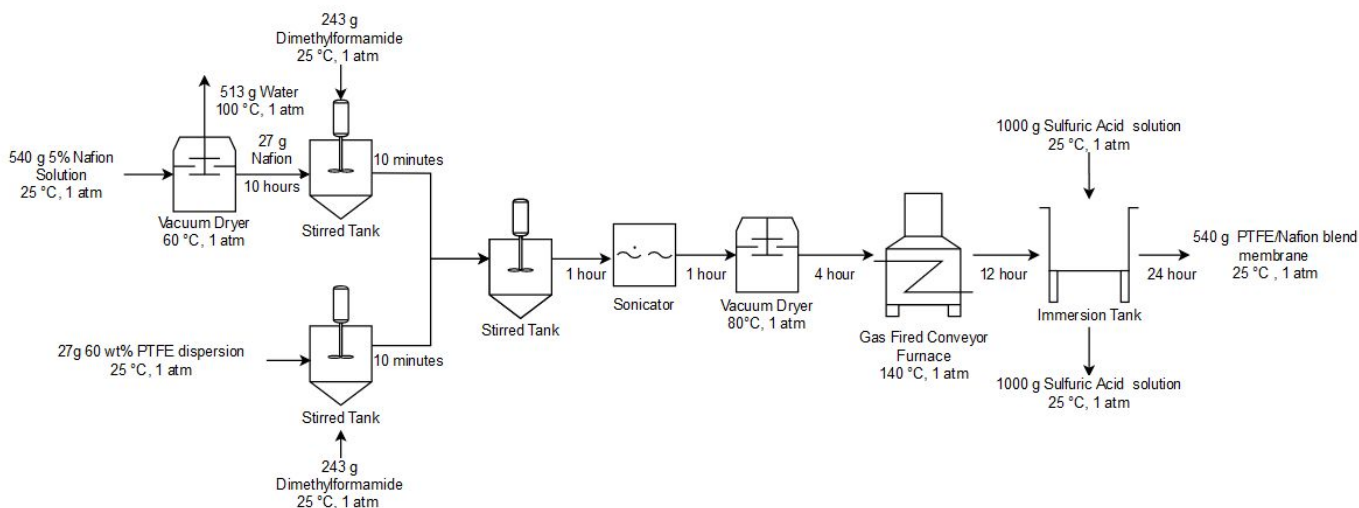


Figure 10: Simplified Process Flow Diagram: Production of Nafion/PTFE Membrane Material

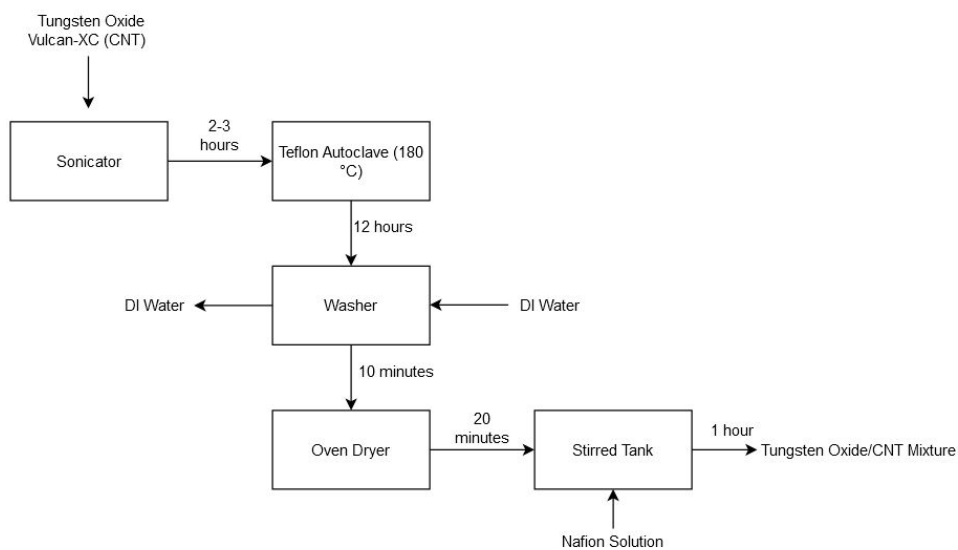


Figure 11: Block Flow Diagram: Production of Tungsten Oxide/CNT Mixture

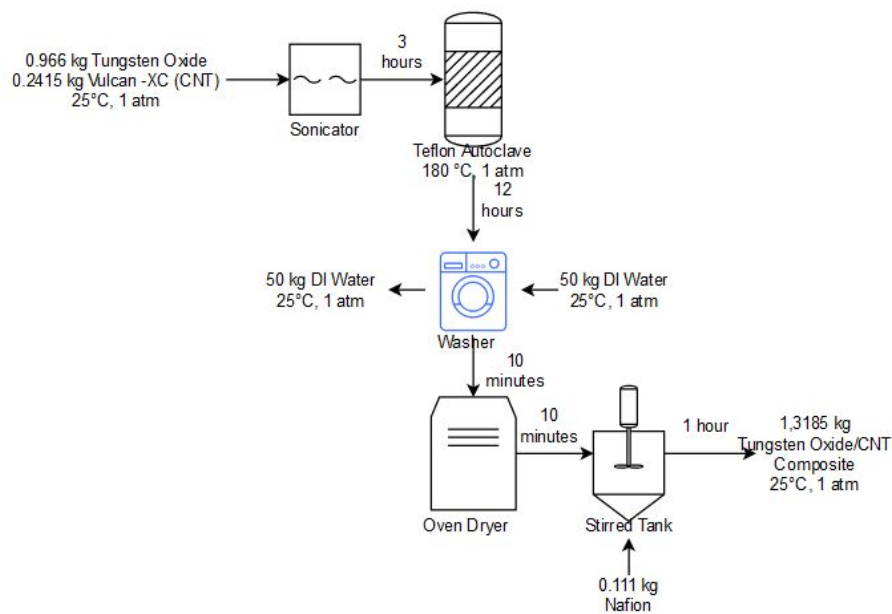


Figure 12: Simplified Process Flow Diagram: Production of Tungsten Oxide/CNT Mixture

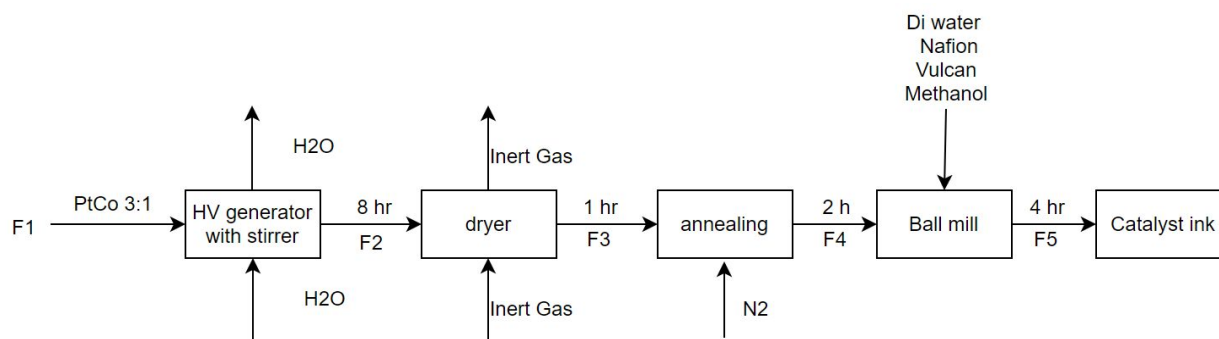


Figure 13: Block Flow Diagram: Production of Catalyst Ink

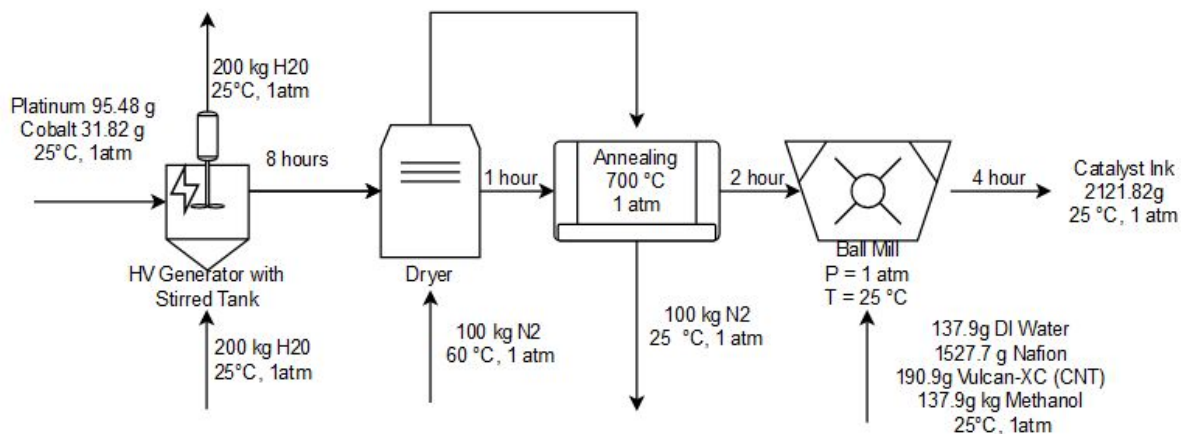


Figure 14: Simplified Process Flow Diagram: Production of Catalyst Ink

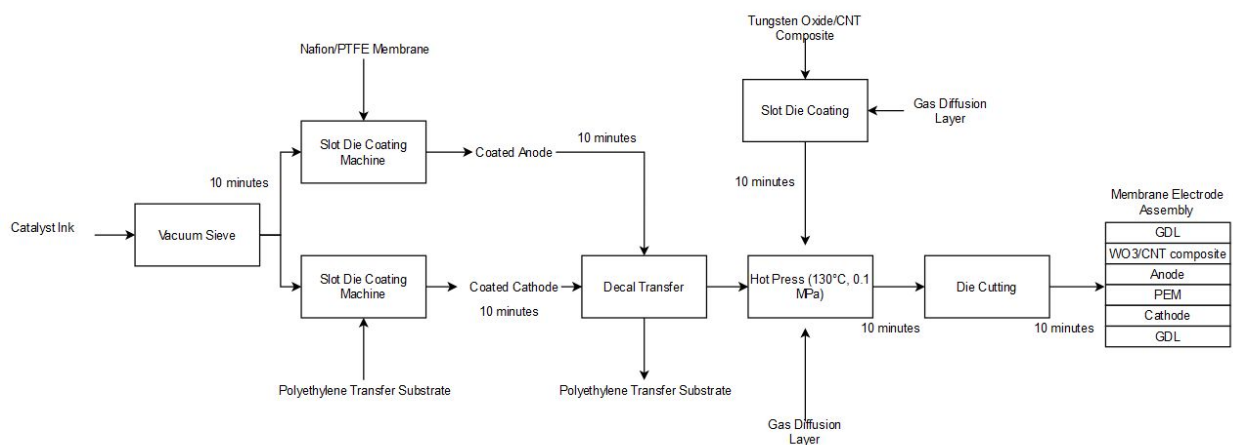


Figure 15: Block Flow Diagram : MEA Assembly

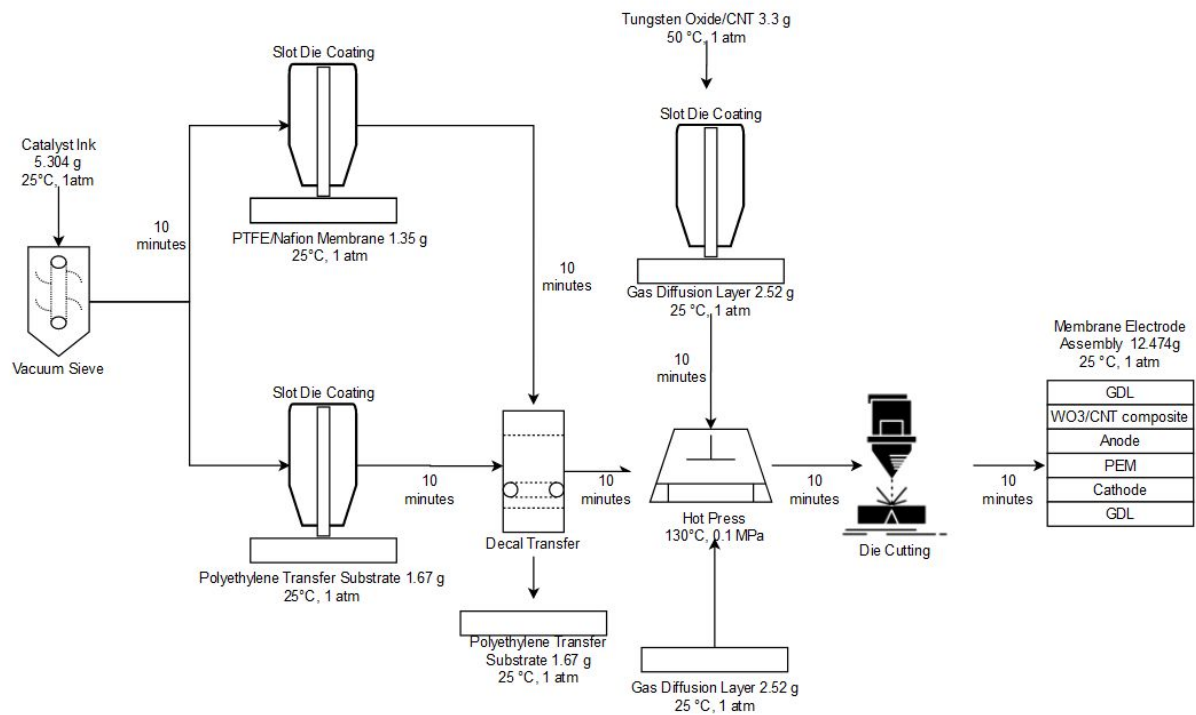


Figure 16: Simplified Process Flow Diagram : MEA Assembly

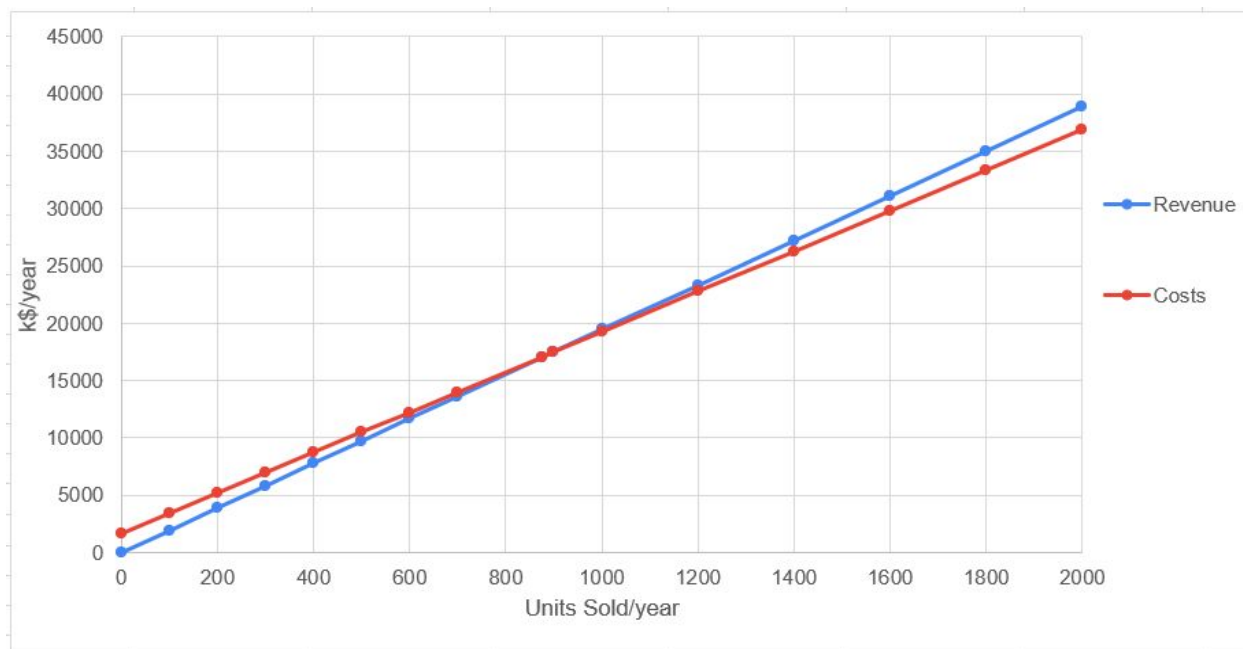
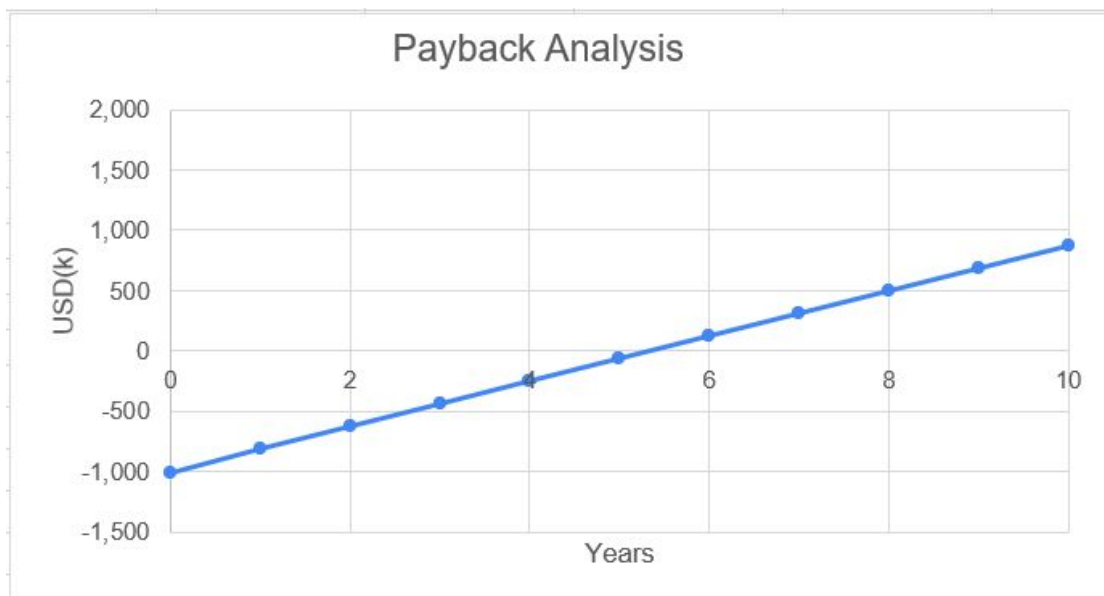
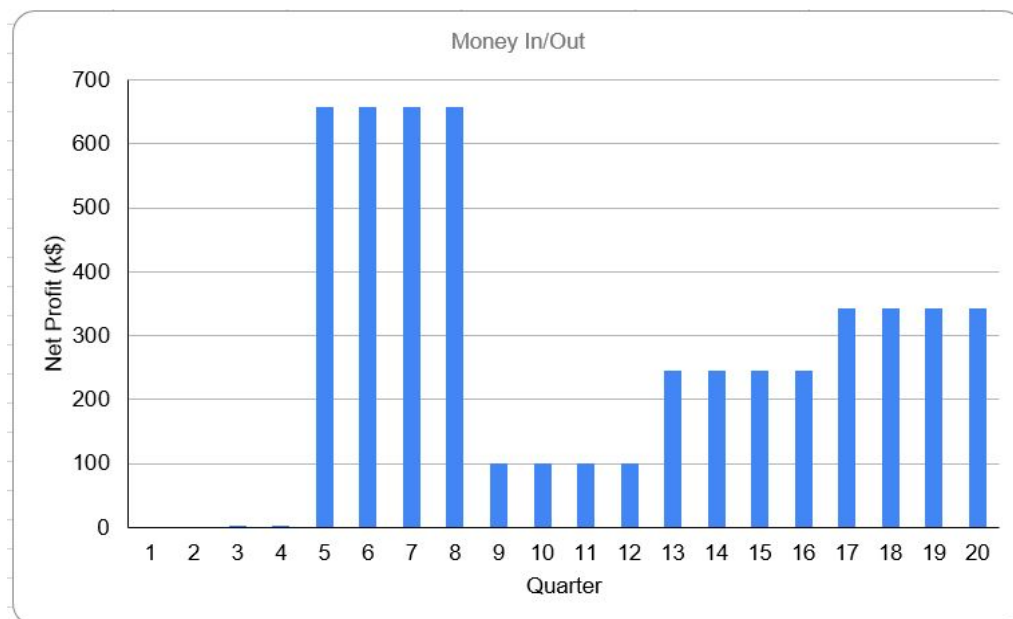


Figure 17: Breakeven Analysis

**Figure 18: Payback Analysis****Figure 19: Quarterly Money Flow Analysis**

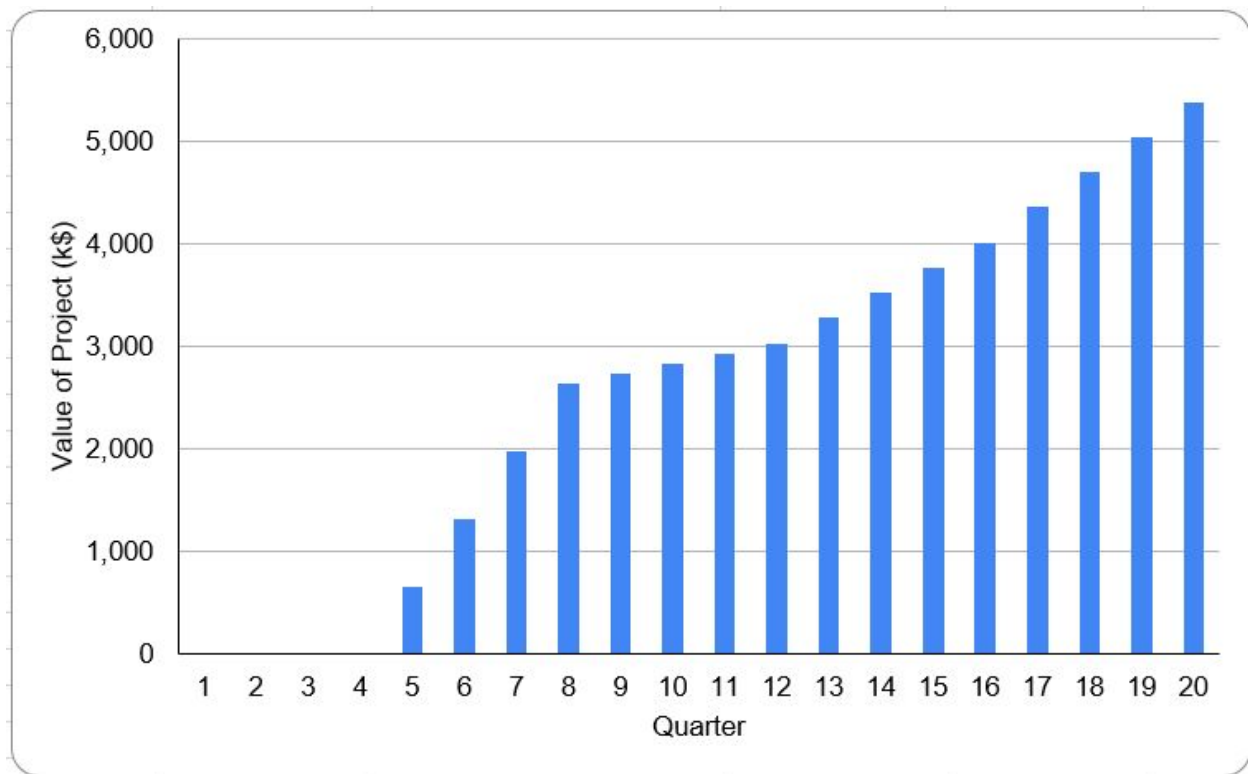


Figure 20: Quarterly Value of Project

APPENDIX II – TABLES

Year	2012	2013	2014	2015	2016	2017	2018	2019	2020
Annual Sales	4	10	31	112	1083	2298	2368	2089	896

Table 1: Table of Annual FCV Sales, Reference [1]

Rank of customer needs

Metrics Number	Customer Preferences	
	Need	Score
1	Cost	5
2	Lifetime	5
3	Mileage	2
4	Refueling Time	3
5	Driving Range	3

Table 2: Customer Preferences

Metrics Number	Safety Needs	
6	Max Hydrogen Leak	3
7	Max Voltage	3
8	Flammability	3

Table 3: Safety Needs

Metrics Number	Technical Needs	
9	Membrane Ion Conductivity	4
10	Electrical Conductivity	5
11	Robustness (T)	4
12	Robustness (H)	4
13	Corrosion	4
14	Mechanical Strength	4
15	Mechanical Durability	4
16	Chemical Durability	4
17	Catalyst Activity	5
18	Catalyst Activity	5
19	Surface Area	3
20	Manufacturing Cost	5
21	Trace Contamination	2
22	Bipolar Plate Surface roughness	3
23	Bipolar Plate Geometry	3
24	Performance	5
25	System Durability	5
26	System Power Density	5

Table 4: Technical Needs

List of Metrics					Benchmark Metrics	
Metric Number	Need	Metric Name	Unit	Importance	Marginal Value	Ideal Value
1	Cost	Dollars/Kilowatt	\$/kW	5	62185 [55]	5800 [55]
2	Lifetime	Years	yrs/unit	5	8 [55]	10 [55]
7	Max Voltage	Volts	V	4	>50 [55]	42 [55]
9	Membrane Ion Conductivity	Proton Conductivity	S/cm	4	0.1 [55]	0.3 [55]
10	Electrical Conductivity	Electrical conductivity	S/cm	3	>100 [55]	4400 [55]
11	Robustness (T)	Temperature	degC	3	90 [55]	-40 to 120 [55]
12	Robustness (H)	Relative Humidity	RH%	3		0 - 100 [55]
13	Corrosion of Electrodes	Corrosion rate	microA/cm ²	4	<0.1 and no active peak [55]	<1 and no active peak [55]
14	Mechanical Strength	Tensile Strength/ Elongation	MPa/ %	4	23 - 45 / 90 - 95 [55]	50 [55]
16	Chemical Durability	Hours w/ <5mA	hours	4	614 [55]	500 [55]
17	Catalyst Activity	Electrochemical Specific Activity (ECSA)	m ² /g	5	129 [55]	152 [55]
18	Catalyst Activity	Specific Activity (SA)	mA/cm ²	5	1.1 [55]	5.01 [55]
20	Manufacturing Cost	Dollars	\$	5	72 [55]	60 [55]
22	Bipolar Plate Surface roughness	Surface roughness	epsilon	4	0.8656 [55]	1-2[55]
24	Performance	Efficiency	%	5	45 - 65 [55]	65% [55]
25	System Durability	Hours	hrs	5	5000 [55]	8000 [55]
26	System Power Density	Watts/Liter	W/L	5	3.1 - 3.12 [55]	3.2 [55]

Table 5: List of Metrics and Benchmark metrics

	A (Tungsten)	B (BP-60 Membrane)	C (SCN-5.7 Membrane)	E (PMG-free Catalyst)	F (Platinum Alloy)
Cost	0	1	0	1	1
Lifetime	1	0	1	1	1
Max Voltage	0	0	0	0	0
Membrane Ion Conductivity	1	1	1	0	0
Electrical Conductivity	1	0	0	0	0
Robustness (T)	1	0	0	1	0
Robustness (H)	1	0	0	0	1
Corrosion of Electrode	1	0	0	1	1
Mechanical Strength	0	1	1	0	0
Chemical Durability	1	1	1	1	1
Catalyst Activity (ECSA)	1	0	0	1	1
Catalyst Activity (SA)	0	0	0	0	1
Manufacturing Cost	0	0	0	0	0
Performance	1	0	0	1	1
System Durability	1	1	1	0	1
System Power Density	1	1	1	0	1
Total	11	6	6	7	10
Rank	1	4	4	3	2

Table 6: Phase 2 Criterion Matrix

Concept combinations		AF		BF		CF	
	W	r	s	r	s	r	s
Cost	10	1	10	2	20	1	10
Lifetime	10	2	20	1	10	2	20
Max Voltage	8	0	0	0	0	0	0
Membrane Ion Conductivity	6	1	6	1	6	1	6
Electrical Conductivity	5	1	5	0	0	0	0
Robustness (T)	5	1	5	0	0	0	0
Robustness (H)	5	2	10	1	5	1	5
Corrosion of Electrode	4	2	8	1	4	1	4
Mechanical Strength	5	0	0	1	5	1	5
Chemical Durability	4	2	8	2	8	2	8
Catalyst Activity (ECSA)	6	2	12	1	6	1	6
Catalyst Activity (SA)	6	1	6	1	6	1	6
Manufacturing Cost	10	0	0	0	0	0	0
Performance	6	2	12	1	6	1	6
System Durability	5	2	10	2	10	2	10
System Power Density	5	2	10	2	10	2	10
Total Score		122		96		96	
Rank		1		3		2	

Table 7: Phase 3 Criterion Matrix

Equipment	Price
Teflon Lined Hydrothermal Autoclave	\$1,899.00
Ultrasonic Homogenizer Sonicator	\$1,889.00
Industrial Cleaning Station	\$1,000.00
Small Scaled Stirred Tank	\$700.00
High Voltage Tank	\$11,000.00
Stirrer	\$10,000.00
Annealing Machinery	\$28,000.00
Ball Mill	\$29,347.00
Slot Die Coating (Anode)	\$55,000.00
Vacuum Sieve	\$7,720.00
Tunnel Dryer	\$30,000.00
Decal Transfer	\$58,400.00
Hot Pressing Production Line	\$289,000.00
Die Cutting Production Line	\$125,000.00
Stack Assembly Production Line	\$1,310.00
Testing and Condition	\$300,000.00
Forklift	\$45,000.00
Crane	\$11,025.00
	\$1,006,290.00

Table 8: Equipment Costs

Fixed Costs	
Equipment	\$1,006,290.00
Maintenance	\$50,314.50
Depreciation	\$50,314.50
Renting	\$63,028.80
Transport	\$200,000.00
Skilled Labor	\$300,000.00
Supervisor	\$160,000.00
Engineer	\$220,000.00
Quality person	\$180,000.00
Marketing manager	\$57,750.00
Sales representative	\$26,970.00
Personnel Overhead	\$188,944.00
Loan Interest	\$120,000.00
Marketing	\$ 75,000.00
Total FV	\$1,692,321.80

Table 9 : Fixed Operating Costs

Variable Costs	
Material	Cost/Stack
Tungsten/Oxide	\$38.64
Platinum	\$3,280.18
Cobalt	\$2.53
Nafion	\$360.28
Vulcan-XC (CNT)	\$0.43
Methanol	\$0.13
Membrane	\$4,345.22
Transfer Substrate	\$12.00
Gas Diffusion Layer	\$3,570.03
Bipolar Plates	\$2,723.48
MEA Sub-Gaskets	\$1,258.15
Coolant Gaskets	\$562.53
End Gasket	\$1.30
End Plate	\$95.00
Current Collectors	\$10.98
Compression Bands	\$13.72
Overhead Cost	\$738.63
Energy	\$520.21
Testing	\$39.61
hired personnel (extra)	None
Total VC	\$17,573.05

Table 10: Variable Operating Costs

Teflon Lined Hydrothermal Autoclave	\$1,899.00
Ultrasonic Homogenizer Sonicator	\$1,889.00
Industrial Cleaning Station	\$1,000.00
Small Scaled Stirred Tank	\$700.00
High Voltage Tank	\$11,000.00
Stirrer	\$10,000.00
Annealing Machinery	\$28,000.00
Ball Mill	\$29,347.00
Slot Die Coating	\$55,000.00
Vacuum Sieve	\$7,720.00
Tunnel Dryer	\$30,000.00
Decal Transfer	\$58,400.00
Hot Pressing Production Line	\$289,000.00
Die Cutting Production Line	\$125,000.00
Stack Assembly Production Line	\$1,310.00
Testing and Condition	\$300,000.00
TOTAL	\$950,265.00
TOTAL + INSTALLATION	\$1,162,368
RENT	\$31,514
DEVELOPMENT	\$1,193,882

Table 11: Development Costs Calculations

	Year 1 (100 units for Inventory)			
	Q1	Q2	Q3	Q4
Development	-\$596,941	-\$596,941		
Loan				
Variable Cost			-\$878,653	-\$878,653
Fixed Cost			-\$373,080	-\$373,080
DOE Grant	\$175,000	\$175,000	\$175,000	\$175,000
Revenue				
Total Recieved	-\$421,941.20	-\$421,941.20	-\$1,076,733.09	-\$1,076,733.09
Necessary Loan	-\$2,997,348.58			

Table 12: Estimation of Loan Amount

	Year 1 (100 units for Inventory)			
	Q1	Q2	Q3	Q4
Development	-\$596,941	-\$596,941		
Loan	\$421,941	\$421,941	\$1,078,059	\$1,078,059
Variable Cost			-\$878,653	-\$878,653
Fixed Cost			-\$373,080	-\$373,080
DOE Grant	\$175,000	\$175,000	\$175,000	\$175,000
Revenue				
Total Recieved	\$0.00	\$0.00	\$1,325.71	\$1,325.71
Total Profit	\$2,651.42			

	Year 2 (400 units/yr)			
	Q1	Q2	Q3	Q4
Development				
Variable Costs	-\$1,757,305	-\$1,757,305	-\$1,757,305	-\$1,757,305
Fixed Costs	-\$423,080	-\$423,080	-\$423,080	-\$423,080
Revenue	\$3,025,285	\$3,025,285	\$3,025,285	\$3,025,285
Loan Payment	-\$187,500.00	-\$187,500.00	-\$187,500.00	-\$187,500.00
Total Received	\$657,399	\$657,399	\$657,399	\$657,399
Total Profit	\$2,629,597.88			

	Year 3 (500 units/yr)			
	Q1	Q2	Q3	Q4
Development				
Variable Costs	-\$2,196,632	-\$2,196,632	-\$2,196,632	-\$2,196,632
Fixed Costs	-\$423,080	-\$423,080	-\$423,080	-\$423,080
Revenue	\$2,907,880	\$2,907,880	\$2,907,880	\$2,907,880
Loan Payment	-\$187,500	-\$187,500	-\$187,500	-\$187,500
Total Received	\$100,668.33	\$100,668.33	\$100,668.33	\$100,668.33
Total Profit	\$402,673.30			

	Year 4 (800 units/yr)			
	Q1	Q2	Q3	Q4
Development				
Variable Costs	-\$3,514,611	-\$3,514,611	-\$3,514,611	-\$3,514,611
Fixed Costs	-\$423,080	-\$423,080	-\$423,080	-\$423,080
Revenue	\$4,370,837	\$4,370,837	\$4,370,837	\$4,370,837
Loan Payment	-\$187,500	-\$187,500	-\$187,500	-\$187,500
Total Received	\$245,646.01	\$245,646.01	\$245,646.01	\$245,646.01
Total Profit	\$982,584.04			

	Year 5 (1000 units/yr)			
	Q1	Q2	Q3	Q4
Development				
Variable Costs	-\$4,393,263	-\$4,393,263	-\$4,393,263	-\$4,393,263
Fixed Costs	-\$423,080	-\$423,080	-\$423,080	-\$423,080
Revenue	\$5,346,141	\$5,346,141	\$5,346,141	\$5,346,141
Loan Payment	-\$187,500	-\$187,500	-\$187,500	-\$187,500
Total Received	\$342,297.80	\$342,297.80	\$342,297.80	\$342,297.80
Total Profit	\$1,369,191.21			

Table 13 : Cash Flow Analysis for the first 5 year