# KATHMANDU UNIVERSITY SCHOOL OF ENGINEERING DEPARTMENT OF MECHANICAL ENGINEERING

### PROJECT REPORT ON



Development of Hydrogen Production and Storage System for the Demonstrative use in the Transportation Sector of Nepal

> Submitted by: Himanshu Giri (024230-18) Rohit Joshi (024232-18) Vikram G.C. (021229-18)

# **Project Evaluation**

# Development of Hydrogen Production and Storage System for the Demonstrative use in the Transportation Sector of Nepal

By

HIMANSHU GIRI (024230-18) ROHIT JOSHI (024232-18) VIKRAM G.C. (024229-18)

This is to certify that I have examined the above Project report and have found that it is complete and satisfactory in all respects, and that any revisions required by the thesis examination the committee has been made.

> Assoc. Prof. Dr. Biraj Singh Thapa Project Supervisor

Asst. Prof. Dr Surendra Sujakhu Project Coordinator

# Acknowledgment

We are much pleased to conduct the project on the **Development of Hydrogen Production and Storage Systems for the Demonstrative use in the Transportation Sector of Nepal**. We would like to thank the Department of Mechanical Engineering, Kathmandu University for providing us with an opportunity to work on this project. We would like to thank our Project Supervisor Assoc. Prof. Dr. Biraj Singh Thapa, Advisor Abhishek Subedi, Project Coordinator Asst. Prof. Dr. Surendra Sujakhu, and other associated Green Hydrogen Lab researchers for assisting us in various ways for carrying out this project. They have been helping us in many ways from the day we started this project.

# **Table of Contents**

Chapter 1	INTRODUCTION	7
1.1	Background	7
1.2	Objective	10
1.2.1	Objectives with their associated activities Error! Bookmark not defin	ned.
1.3	Scope	10
1.4	Limitation	10
Chapter 2	METHODOLOGY	11
2.1	Flowchart	11
2.2	Literature review	11
2.2.1	Source of hydrogen production	11
2.2.2	Hydrogen Production Method	12
2.2.3	The working principles of electrolyzers	16
2.2.4	The working Principle of the alkaline electrolyzer	17
2.2.5	The working Principle of the PEM electrolyzer	18
2.2.6	Process flow of electrolytic hydrogen production system	20
2.2.7	Hydrogen Storage	22
2.3	Balance of Plant (BOP) / Schematic	28
2.4	Mathematical Modeling	29
2.4.1	Hydrogen Production System	29
2.4.2	Hydrogen Storage	31
2.4.3	Pressure in the storage tank	31
2.4.4	Hydrogen Energy Demand	32
2.4.5	Work done by Compressor	33
2.5	Hydrogen Hazards	34
2.5.1	Physiological Hazards	34
2.5.2	Physical Hazards: Embrittlement	34
2.5.3	Chemical Hazards: Ignition and Explosion	35
2.5.4	Safety planning	36
Chapter 3	CALCULATION AND COMPONENT SELECTION	42
3.1	Calculation	42
3.2	Component Selection Error! Bookmark not defin	ned.
3.3	Auxiliary Component	50
Chapter 4	Work Schedule	53
4.1	Gantt Chart	53
Chapter 5	Budget Expenditure	54
Chapter 6	Conclusion	55
Chapter 7	REFERENCE	56

# List of Tables

Table 1: Different hydrogen Production methods	. 15
Table 2: Specifications of Alkaline Electrolysis Cells (AEC), Phosphoric Acid and Sulfuric Acid	d
Electrolysis Cells (Acid), Polymer Electrolyte Membrane Electrolysis Cell (PEMEC), Solid Oxi	ide
Electrolysis Cells (SOEC), and Solid Proton Conducting Electrolysis Cells [13]	16
Table 3: Comparison of Characteristics of Alkaline and PEM electrolyzers [14]	19

# List of Figures

Figure 1: CO2 emission per capita in Nepal [3]	. 8
Figure 2: Pie chart showing the distribution of the contribution of hydrogen production method	
[28]	12
Figure 3: Hydrogen feedstock and production route [29]	12
Figure 4: Alkaline electrolyzer reaction Schematic	17
Figure 5: PEM electrolyzer reaction Schematic	17
Figure 6: Allkaline Electrolyzer process flow diagram	21
Figure 7: PEM Electrolyzer process flow diagram	22
Figure 8: Sunburst Pie chart to show different ways of hydrogen storage	23
Figure 9: Cm and Cv as a function of the pressure [17](Type III and IV)	25
Figure 10: Gaseous storage Vessel's type [15]	26
Figure 11: Alakaline Electrolyzer BOP	28
Figure 12:Compressibility (Z) for Hydrogen	31
Figure 13: Asphyxiation Symbol	34
Figure 14: Hydrogen Cylinder bursts, Intergranular crack [24]	35
Figure 15: Minimum ignition energy of different gases [23]	36
Figure 16: Polarization Curve	43
Figure 17: Faraday Efficiency Chart	44
Figure 18: Hydrogen Production Flowrate	44
Figure 19: Hydrogen consumption Vs Output Current	46
Figure 20: Volume Vs No. of moles	47
Figure 21 Production and Storage equipment at Green Hydrogen Lab, KU	49
Figure 21: 2D drawing of the Hydrogen Cylinder stand	50
Figure 22: 3D Views of the Hydrogen cylinder stand	50
Figure 23: 2D drawing of Electrolyzer trolley	51
Figure 24: 3D Views of the Electrolyzer trolley	52

#### Abstract

The global energy demand is increasing as the population grows. The extensive research is going on to assess diverse energy sources to fulfill the energy needs. Today major sources of energy for transportation purposes are fossil fuels yet these are non-renewable sources of energy and henceforth they are limited. The fossil fuels are the major contributor to greenhouse gas emissions. The wideranging research is being carried out to introduce innovative renewable technology yet the greater part of them fails in delivering energy that fulfills the demand of the masses. The renewable energy has the limitations of fluctuating production and storage. With the advancement in technologies. Green Hydrogen can be a possible alternative for energy carrier to channel large amount of renewable energy in the industry and transportation. Soon this technology will be established in Nepal and it will need rigorous research for the technological acceptance. This study presents a review of hydrogen production and storage technologies for the demonstrative purposes in the transportation sector. The hydrogen value chain has an integrated technological system with several parameters. A case of 5 kW Load demand to drive a fuel cell is taken as an reference. Component sizing of compressed storage tank, compressor, buffer tank and electrolyzer is done. Different parameterbased scenario models are developed for analyzing storage systems and alkaline electrolyzer. Mathematical models for the parameters like energy demand, volume, pressure, cell voltage, no. of cells, temperature, etc has been identified. Based on these models the operation constrains of the electrolyzer is developed. A parameter-based model is further analyzed for optimum storage sizing for the same power demand in end-use. The result of the models is discussed. An optimized mathematical model is proposed that lays the foundation for system sizing of the production and storage systems for the application in transportation sector.

# Appendix

Ι	Current, A	m <sub>tank</sub>	Mass flow rate in tank
V <sub>cell</sub>	Voltage of cell (V)	$\dot{m}_{H_2c}$	Mass flow rate through compressor
V <sub>rev</sub>	Reversible Voltage(1.23 V)	m <sub>tank</sub>	Mass flow rate in tank
$\eta_{cat}$	Cathode activation overpotential (V)	m <sub>tank</sub>	Mass of hydrogen in tank after filling
$\eta_{an}$	Anode activation overpotential (V)	Т	Temperature of hydrogen in tank, °C
$\eta_{ohm}$	Ohmic overpotential (V)	Р	Pressure, bar
$\eta_{\text{con}}$	Concentration overpotential	V	Volume, m <sup>3</sup>
T <sub>elec</sub>	Operating temperature electrolyzer (°C)	R	Universal gas constant (8.314 * 10 <sup>-5</sup> ), m <sup>3</sup> bar K <sup>-1</sup> mol <sup>-1</sup>
p <sub>elec</sub>	Operating pressure of electrolyzer (bar)	m <sub>initial</sub>	Mass of hydrogen in tank initially
i	Current density (A/m <sup>2</sup> )	P <sub>fe</sub>	Power of fuel cell, Watt
V <sub>stack</sub>	Stack Voltage (V)	$\eta_{fc}$	Efficiency of fuel cell
N <sub>cell</sub>	Number of cell	n <sub>H2</sub> cons	Hydrogen consumption rate (mol/s)
$A_{cell}$	Area of electrode (m <sup>2</sup> )	$W_{el}$	Electricity produced from fuel cell (Watt)
$\dot{n}_{\rm H_2}$	Hydrogen production rate (mol/s)	$W_{H_2}$	Hydrogen consumed by fuel cell (Watt)
z <sub>e</sub>	Number of free electrons, e <sup>-</sup>	I <sub>fc</sub>	Current output of fuel cell (A)
F	Faraday's Constant (96485.332 coulomb/mol)	ΔH	Higher heating value of Hydrogen (286 KJ/mol)
$\eta_{\rm f}$	Faraday efficiency	$T_{\rm H2}$	Temperature of Hydrogen <80°C
$N_{o}$	Initial storage level of the buffer tank, mol	$V_{\text{max}}$	Maximum Volume of buffer tank (L)
$N_{H_2}$	Final hydrogen stored in the buffer tank, mol	$\mathbf{R}_{\mathrm{g}}$	Gas constant of Hydrogen
Nout	Hydrogen exiting buffer tank, mol	$\mathbf{P}_{\mathrm{bf}}$	Pressure inside buffer tank, bar
$n_{H_2}$	Hydrogen entering buffer tank, mol	Po	Initial pressure buffer tank, bar
$MW_{H2}$	Molecular weight of Hydrogen, Kg/mol		

# **Chapter 1 INTRODUCTION**

#### 1.1 Background

Every mechanical object that operates or functions requires energy. Energy is the most basic thingto establish any industry. Global population is driving up global energy demand, which has led to greater consumption of fossil fuels. So, energy is the main topic of discussion to achieve it through the sustainable way. As fossil fuel consumption increases, greenhouse gas emissions in nature increase, resulting in adverse environmental effects such as global warming, melting ice from mountains, ozone layer depletion, acid rain, etc. Renewable energy sources, such as solar energy, wind energy, waves, and tidal energy are considered eco-friendly. Renewable Hydrogen technology is the consistent source that helps in decarbonizing the environment [1]. Transitioning to hydrogen technology will be possible only if it is as efficient as other existing technologies. The fuel sector has undergone two kinds of transition; one is based on efficient use of energy to produce the product and another is toward fuel consumption, which has a lower ratio of carbon to hydrogen. Soon, if hydrogen technology progresses along that path, considering those two factors, hydrogen will be the primary source of energy consumption [2]. The main aspect of developing hydrogen technology is to reduce carbon dioxide emissions by achieving a transition towards a green transport system.



Figure 1: CO2 emission per capita in Nepal [3]

Figure 1 shows the carbon dioxide emission trend in Nepal for the last 70 years. A large proportion of GHG emissions are from the extraction, processing, and utilization of fossil fuels for energy requirements. In Nepal, fossil fuel is imported from other countries to meet the demand of people. Hydrogen is proclaimed future energy source, ideally for transportation where energy content is utilized in the hydrogen fuel cell.

Hydrogen can be produced from renewable and non-renewable resources which can be converted to electrical power and water by using fuel cells. If hydrogen is produced from a renewable form of energy and does not harm the environment by emitting GHG during the process of extraction of hydrogen, then the hydrogen is called green hydrogen.

Hydrogen is the lightest element and has the highest energy density per unit mass (between 120 and 142 MJ kg-1) [4]. Hydrogen's fuel is the high specific energy (Lower heating value per unit mass). Hydrogen is lighter than gasoline or diesel for the same amount of energy. Hydrogen has 1.2 times more energy by weight than that of gasoline, also it is nontoxic. It was reported that hydrogen is 39% more efficient than fossil fuels [5]. It can either be produced from water or natural gas for

commercial purposes. The sustainable source is water and hydrogen can be achieved through the water electrolysis process. The end-use application of hydrogen is stationary like power plant, fuel cell, automobiles and backup generators [6]. Also, hydrogen can be produced from different raw materials and then stored both as compressed, liquefied, and via solid-state reactions to be used in all types of applications.

A hydrogen value chain can be selected based on the end-use and initial production process. On small scale, it is an integrated set of power sources, production units, compressors, cooling systems, storage and fuel cell including safety devices, sensors, and flow metering devices [7]. The modeling for the above mention system should be done to optimize the laboratory setup. This paper deals with the parameter obtained from the production system, storage system, and end-use application i.e. fuel cell. The result of the mathematical model is used to understand the fuel consumption rate by the fuel cell, storage system sizing, and the impact of current on electrolyzer to produce hydrogen. Finally, hydrogen is a stable non-corrosive element, however, safety aspects need to be considered.

# 1.2 Objective

- Study production and storage processes in relation to Hydrogen Technology and identifya suitable option for the transportation sector.
- Component selection, system design, and analysis to produce and store hydrogen withsafety considerations for demonstrative use in the transportation sector of Nepal.
- Setup and operate the laboratory scale facilities to analyze the production and storage of hydrogen for demonstrative use in the transportation sector.

# 1.3 Scope

- The project incorporates the review of the production and storage system of hydrogen for demonstrative use in the transportation sector.
- The system design obtained from the project is independent of economic factors

# 1.4 Limitation

- The research analysis doesn't incorporate the distribution of hydrogen for differentend-use applications.
- The review and analysis of the storage system will be done for the gaseous medium only.

# Chapter 2 METHODOLOGY

### 2.1 Flowchart

The flowchart describes the overall approach of the study and activity for the project. The literature review on hydrogen production, storage and safety is used to develop the foundation for the analysis and calculation. Based on the literature review, parameters are identified. These parameters are used to identify mathematical model for electrolyzer and storage system. The mathematical model for end-use of hydrogen is also investigated. The mathematical model is used for analysis of production and storage system. Based on the analysis optimized model is proposed.



## 2.2 Literature review

#### 2.2.1 Source of hydrogen production

Globally 70 million metric ton of hydrogen is produced yearly [8]. Out of which, hydrogen is mostly used in industry to produce ammonia, hydrogenation of fats, and pharmaceutical manufacture. Hydrogen is produced from a different pathway. Each production pathway has unique benefits and disadvantages, such as the cost of production and the purity of hydrogen produced. As a result of new sustainable methods of producing hydrogen more research is required in the optimization and commercialization. Of current hydrogen production, 96% comes from fossil fuel sources. The feedstock to these processes are finite and produce GHGs which is unsustainable and undesirable

for the vision of a long-term hydrogen economy [9]. Renewable hydrogen does not yet contribute to the hydrogen market as the cost of renewable power is still uncompetitive. Currently, many studies are going to improve the technology which requires renewable procedures to produce hydrogen.



Figure 2: Pie chart showing the distribution of the contribution of hydrogen production method [28]

# 2.2.2 Hydrogen Production Method

Here, in the figure hydrogen energy feedstock and production route are explained. The main three routes for hydrogen production are; reforming from hydrocarbons, electrolysis, and thermal decomposition or cracking.



Some major hydrogen production technologies are explained below:

#### 2.2.2.1 Steam Reforming

In this process, the natural gas or methane stream is reacted with steam in presence of a catalyst at approximately 900°C, and high pressure (3-4 MPa) to produce hydrogen and carbon dioxide. When starting with natural gas, SMR is approximately 72% efficient in producing hydrogen on alower heating value basis. The efficiency can be somewhat lower with sources of methane that include sulfur or other impurities that require a pre-treatment cleanup step to remove the impuritiesupstream of the SMR process. This method is widely explored, cheap, and can easily be handled [10]. The reaction to this process is shown below:

$$CH_4 + H_2O \rightarrow CO + 3H_2$$

Hydrogen production is accomplished in several steps: steam reforming, water gas shift reaction, and hydrogen purification. The hydrogen exiting from the water gas shift reactor is 70-80% pure [11]. So, the produced hydrogen gas has to go through purification to make it 99% pure for vehicular application.

#### 2.2.2.2 Partial Oxidation

In the partial oxidation (POX) process, hydrocarbon fuel is reacted with oxygen to produce hydrogen. Hydrogen is produced from a range of hydrocarbon fuels, including coal, heavy residual oils, and other low-value refinery products. The hydrocarbon fuel is reacted with oxygen in a less than the stoichiometric ratio, yielding a mixture of carbon monoxide and hydrogen at 1200° to 1350°C. Hydrogen can be produced from coal gasification at delivered costs of about \$2.00-2.50 per kilogram at present at a large scale, with delivered costs as low as about \$1.50 per kilogram believed to be possible in the future [10].

$$2CaHb + aO_2 \rightarrow 2aCO + bH_2$$

This method also depends on fossil fuel which is not a renewable source of energy and also a major by-product of this method is CO<sub>2</sub>. So, in long term for the vehicular purpose, this method is not appropriate.

#### 2.2.2.3 Biomass

Biomass conversion technologies can be divided into thermo-chemical and biochemical processes.

Thermo-chemical processes tend to be less expensive because they can be operated at higher temperatures and therefore obtain higher reaction rates. They involve either gasification orpyrolysis (heating biomass in the absence of oxygen) to produce a hydrogen-rich stream of gas known as "syngas" (a blend of hydrogen and carbon monoxide). They can utilize a broad range ofbiomass types. In contrast, enzyme-based biochemical "digester" type processes are at present mainly limited to wet, sugar-based feedstocks but could include cellulosic feedstocks in the future with continued improvements in process techniques and systems.

The most significant challenges for hydrogen production by biological technologies are these:

- The low thermodynamic efficiency of biomass-to-hydrogen conversion, the high costs of bioenergy crop production and biomass gasification, and the significant demand for and impact on land use and natural resources for bioenergy crop farming; and
- The engineering of (micro)organisms and processes for direct photo biological hydrogen production without biomass as an intermediate at high thermodynamic efficiency and highkinetic rates [12].

#### 2.2.2.4 Electrolysis

It is the process by which deionized water is split into hydrogen and oxygen using electricity. The overall electrolysis reaction is:

$$2H_2O + e^- \rightarrow 2H_2 + O_2$$

Water splitting occurs when a direct current is passed between an anode and a cathode submergedin water separated by a solid electrolyte or an aqueous electrolyte to transport ions and complete the electrical circuit. The purity of hydrogen produced from electrolysis is almost 98-99%. If the renewable source is used as a form of electricity, we can produce green hydrogen at the commercial level. So robust research and development works are going on this technology to optimize it to make it cost-effective. Currently, small-scale electrolyzers are used to produce hydrogen; however, hydrogen produced via this method is strongly affected by high electricity prices. The main aim for water electrolysis is to use the surplus electricity generated from renewable resources such as wind, solar, hydropower, geothermal so it can be used in all different applications when stored inhydrogen. Renewable electrical generators need to be further developed to achieve energy sustainability. Water electrolysis can be used to produce hydrogen over a wide range of scales from a few kilowatts to

hundreds of megawatts. The capital cost depends on the size of an electrolyzer. The capital cost of alkaline systems varies with size, although there is little scale economy above sizes of perhaps a few hundred kilowatts. Hydrogen plant costs for commerciallyavailable largescale alkaline electrolysis systems are currently ~\$500-\$600/kW, with projected costs as low as \$300/kW (5). Thomas and Kuhn have estimated recently that mass-produced small small-PEM electrolyzers might cost <\$300/kW of H2 out (HHV), even at sizes of only a few kilowatts. So, from the economic point of view for lab-scale set up of electrolyzer alkaline electrolyzer is better as it cost less than that of PEM for a small Kilowatt system.

Drocoss	Feedstock	Efficiency	Moturity	Renewable and
F10CESS	required	Efficiency	Wiaturity	non-renewable
Steam reforming	Hydrocarbons	60–75%	Commercial	Non-renewable
Partial oxidation	Hydrocarbons	60–75%	Commercial	Non-renewable
Electrolysis	Water and	70%	Commercial,	Renewable as
	electricity		R&D	well as non-
				renewable
Photo- electrolysis	Water and solar	12.4%	R&D	Renewable
ofwater				
Solar steam	Hydrocarbon	60–75%	R&D	Renewable
Reforming				
Thermo-water	Water and heat	30%	R&D	Non-renewable
splitting				
Photolysis	Water and solar	0.5%	R&D	Renewable

Table 1: Different hydrogen Production methods

The electrolysis method is the leading technology in the world for producing hydrogen for transportation purposes. Also, this method has been practiced at the commercial level, unlike biomass which is still under the research phase. The main attraction toward the electrolysis method over low-cost steam reforming and partial oxidation method is it has no bi-product like CO<sub>2</sub> and also produced hydrogen gas that is 99.99% pure whereas for SMR and POX method it is 70-80% only. From the above comparison table, we can see that electrolysis is more efficient than other technology. So, for hydrogen lab electrolysis method is best-suited for producing hydrogen.

Table 2: Specifications of Alkaline Electrolysis Cells (AEC), Phosphoric Acid and Sulfuric Acid Electrolysis Cells (Acid), Polymer Electrolyte Membrane Electrolysis Cell (PEMEC), Solid Oxide Electrolysis Cells (SOEC), and Solid Proton Conducting Electrolysis Cells [13]

	AEC	PEMEC	SOEC	acid	SPCEC
Reactant	H <sub>2</sub> O	H <sub>2</sub> O	H <sub>2</sub> O	H <sub>2</sub> O	H <sub>2</sub> O(CO <sub>2</sub> )
			$CO_2$		
Overall Reaction	$H_2O \rightarrow H_2 + \frac{1}{2}O_2$	$H_2O \rightarrow H_2 + \frac{1}{2}O_2$	$H_2O \rightarrow H_2 + \frac{1}{2}O_2$	$H_2O \rightarrow H_2 + \frac{1}{2}O_2$	$H_2O \rightarrow H_2 + \frac{1}{2}O_2$
Cathode	$2H_2O + 2e^- \rightarrow H_2 +$	2H <sup>+</sup> + 2e <sup>-</sup> → H <sub>2</sub>	$CO_2 \rightarrow CO + \frac{1}{2}O_2$	2H <sup>+</sup> + 2e <sup>-</sup> → H <sub>2</sub>	$CO_2 + 2H_2O \rightarrow 2O_2$
Reaction	20H-		$H_2O + 2e^- \rightarrow H_2 + O^{2-}$		$+ CH_4$
Anode reaction	20H <sup>-</sup> → ½ O <sub>2</sub> +	$H_2O \rightarrow H_2 + \frac{1}{2}O_2 +$	$CO_2 + 2e^- \rightarrow CO +$	$H_2O \rightarrow H_2 + \frac{1}{2}O_2 +$	CO <sub>2</sub> +8H <sup>+</sup> +8e <sup>-</sup>
	$H_2O + 2e^-$	2H+ + 2e-	$O^2$	2H <sup>+</sup> + 2e <sup>-</sup>	$\rightarrow$ CH <sub>4</sub> + 2H <sub>2</sub> O
			$O^{2-} \rightarrow \frac{1}{2} O_2 + 2e^{-}$		$H_2O \rightarrow \frac{1}{2}O_2 + 2H^+$
					+ 2e-
Charge Carrier	OH-	H <sup>+</sup>	O <sup>2-</sup>	H <sup>+</sup>	H <sup>+</sup>
Electrolyte	NaOH	Polymer	Ceramic	$H_2SO_4$	Ceramic
	KOH			$H_2PO_3$	
Electrode	Nickel	Pt/C/IrO <sub>2</sub>	Nickel, Ceramic	Pt/C/IrO <sub>2</sub>	Nickel, Ceramic
Temperature	80°C	80°C	750-900°C	150°C	400-600°C
Advantage	Commercially	Commercially available	Expensive electrode	Expensive electrode	High efficiency and
	available	High efficiency and the	material	material	the possibility to
	Cheap cell	possibility to produce			produce synthesis
	materials	Cheap cell material			gas
					Pure H <sub>2</sub> produced to
					H <sub>2</sub>
Disadvantage	Low efficiency	Low electrode and	Not commercially	Low electrode	Not commercially
		electrolyte durability	available	durability	available
		Expensive platinum		Expensive platinum	
		electrode		electrode	
		Increased hydrogen			
		crossover at elevated			
		temperature			

Table 2 suggests the maturity of different electrolyzers. Two of the electrolysis technologies (i.e., Phosphoric Acid and Sulfuric Acid Electrolysis Cells (Acid) and Solid Proton Conducting Electrolysis Cells (SPCEC)) are still not yet commercialized. The temperature at which hydrogen has to be handled for Solid Oxide Electrolysis Cells (SOEC) is too high. So, therewill be always safety issues with this electrolyzer. The safety code and standards for SOEC are still under the phase of research. So, it brings down to differentiate among PEM and alkaline electrolyzer whose maturity is at commercial level. If we compare the cost of both electrolyzers at a small level (few KW), alkaline electrolyzer.

# 2.2.3 The working principles of electrolyzers

For the electrolysis water hydrogen production technology, hydrogen production electrolier is the main/core component, which not only directly affects the hydrogen production but also accounts for a large proportion of equipment manufacturing costs.



Figure 4: Alkaline electrolyzer reaction Schematic



Figure 5: PEM electrolyzer reaction Schematic

### 2.2.4 The working Principle of the alkaline electrolyzer

Alkaline electrolyzer uses 30% wt KOH solution or 25% wt NaOH solution as electrolyte. The DC current is  $2000A/m^2 \sim 4000A/m^2$ , the working temperature is generally maintained at 80°C~90°C, and the working pressure is within 3.2MPa. It also needs to ensure equal pressure operation. Structurally,

the electrolytic cell uses a permeable membrane, such as asbestos, and polyphenylene sulfide. The electrode uses a porous nickel-based electrode, and there is also an endplate, gasket, plate, fasteners, and other components [14].

The principle of single-chamber electrolysis reaction is shown in Figure 4. The alkaline electrolyte enters the anode and cathode regions on both sides of the membrane, and water molecules can permeate through the membrane to the other side. After the electric current, the water molecules in the electrolyte in the cathode region combine with electrons to form hydrogen and hydroxide ions, and in the anode region, the hydroxide ions lose electrons to generate oxygen and water. Due to the hindrance of the permeable membrane, the gas generated by the electrolysis cannot pass through the membrane to the other side in a large amount, and the generated gas and the electrolyteare discharged from the chamber together for treatment.

#### 2.2.5 The working Principle of the PEM electrolyzer

The PEM electrolyzer is a kind of solid oxide hydrogen production cell. The electrolyzed raw material is deionized water. The DC current density is 10000A/m<sup>2</sup>~20000A/m<sup>2</sup>, which is about 5 times that of the alkaline water hydrogen electrolyzer. The PEM electrolyzer, with its working temperature of 50°C~80°C, pressure less than 5 MPa, and volume smaller than the alkaline electrolyzer, can be operated under different pressure [14].

The structure of the PEM electrolyzer is similar to that of the alkaline electrolyzer. The main difference is the use of a thin film-electrode assembly (also known as a membrane electrode) to form a zero-pole spacing. The separator is a Nafion membrane, which is strongly acidic after beingsoaked in water, and the anode catalyst and the cathode catalyst are attached to both sides of the separator by electroless plating or hot pressing [14].

The reaction principle of the PEM electrolyzer is shown in Figure 4. Unlike the alkaline electrolyzer, the deionized water only needs to enter the anode side of the electrolyzer. After energization, oxygen and hydrogen ions are generated on the anode side of the membrane electrode, and hydrogen ions reach the cathode side in a hydrated state (H +  $XH_2O$ ) to generate hydrogen gas. The membrane separates hydrogen from oxygen. Because of the separation of the Nafion membrane and the absence of solution voltage drop, this method has a high energy efficiency for hydrogen production. However, since the catalyst uses a noble metal, the manufacturing cost of the electrolyzer is high.

	Alkaline Electrolyzer	PEM Electrolyzer
Electrolyte	30% wt KOH or 25% wt	Solid polymer
-	NaOH	
Current density (A/m <sup>2</sup> )	2000~4000	10000~20000
Work pressure (MPa)	<= 3.2	<= 5
Operating Temperature (°C)	80-90	50-80
Hydrogen Purity (%)	>=99.8	>=99.99
Raw materials	Deionized water and alkali	Deionized water
Corrosion	Alkaline corrosion	No
Operating characteristics	Isobaric operation	Differential pressure
		operation
Structural features	Endplate, gasket, permeable	A similar structure, but using
	membrane, plate, fasteners, etc.	membrane electrode, zero
		pole spacing
Volume and weight	Big	Small, about $1/3$ of the
		alkaline electrolyzer
Manufacturing cost	Low	High
Lifetime	10 years	3-4 years

Table 3: Comparison of Characteristics of Alkaline and PEM electrolyzers [14]

#### 2.2.6 Process flow of electrolytic hydrogen production system

#### 2.2.6.1 Process of producing hydrogen by alkaline electrolyzer system

The alkaline water hydrogen production device mainly comprises three parts: an alkaline water hydrogen production system, a control cabinet, and a rectifier cabinet. The alkaline water hydrogen generator includes an alkaline electrolyzer, a hydrogen separator, an oxygen separator, a gas cooler, lye circulating pump, a lye cooler, a water storage tank, an alkali tank, control valves, and some other components.

The alkaline hydrogen production process is shown in Figure 6. When the equipment is started, the electrolyte is evenly mixed in the alkali tank, and then pressurized into the electrolytic tank through the pump to enter the entire hydrogen production system. After the liquid in the separator reaches the specified liquid level, the lye inlet valve is closed and the power is turned on. After the alkali solution is electrolyzed in the alkaline electrolyzer, the hydrogen separator and the oxygen separator are respectively introduced from the hydrogen side of the electrolyzer and the oxygen side outlet in a gas-liquid mixed state. The gas is cooled from the upper part of the separator and discharged. The liquid merges into the bottom of the separator at the bottom of the separator and circulates. At the time of electrolysis, since the water is reduced due to electrolysis, it is necessary to periodically replenish water in the hydrogen separator. At the same time, it is necessary to regularly check the specific gravity of the alkali solution and replenish the alkali solution. Since the alkaline electrolyzer can only be operated at the same pressure, the hydrogen generator needs to be gradually pressurized to the set pressure by the regulating valve at the start, which causes the start-up time to be about 1 hour [14].



Figure 6: Allkaline Electrolyzer process flow diagram

#### 2.2.6.2 Process of producing hydrogen by PEM electrolyzer system

The PEM hydrogen production unit includes a PEM hydrogen production system, a control system, and a DC power supply. Compared with the alkaline water hydrogen production system, the PEM hydrogen production system is relatively simple: the gas after-treatment device is relatively small, no special alkali tank is needed, and the water tank can also be used as an oxygen separator.

The PEM hydrogen production process is shown in Figure 7. When the equipment is started, the water in the water tank is replenished to the set liquid level, and the circulation pump is turned on to circulate, and the water level of the hydrogen separator is observed to reach the designated position. After the liquid level in the water tank and the hydrogen separator is stabilized, the DC power source is energized and the PEM electrolytic cell starts to electrolyze. Oxygen and water are separated into the water tank and separated, and the oxygen is filtered through a molecular sieve to be discharged. Hydrogen and a small amount of water enter the hydrogen separator, and the hydrogen gas passes through the molecular sieve for further treatment. After the water in the hydrogen separator reaches a certain liquid level, part of the water flows into the water tank. During operation, electrolysis causes a decrease in moisture, so it is necessary to control the amount of water replenishment. In addition, the PEM electrolyzer can be operated under differential pressure. It does not need to be gradually regulated like hydrogen by alkaline water when starting up. The pressure of the regulating valve can be directly set to the specified pressure, and the equipment can

be stabilized in 15 minutes [14].



Figure 7: PEM Electrolyzer process flow diagram

### 2.2.7 Hydrogen Storage

Hydrogen production from the electrolyzer is first placed into buffer storage and later produced gas is compressed at desired pressure and is then transport to the storage facility at the refueling station. The requirements from a hydrogen store are different for stationary and vehicular applications. For the transportation sector, the weight and size should be low, refueling should be fast and the hydrogen storage system should have most of the characteristics that current fossil fuel vehicles have like range, passenger space, cost, acceleration/deceleration, start and stop, refueling time, life and cost, etc. For the stationary purpose, there are not many issues with the weight and size, so from the economic point of view storage facility can be chosen by compromising features like weight and size. Hydrogen is stored in all three different states: gaseous, liquid and solid [15].



Figure 8: Sunburst Pie chart to show different ways of hydrogen storage

### 2.2.7.1 Solid Storage

Hydrogen is stored in the solid-state form where either the molecular hydrogen gets adsorbed on the high surface area materials or absorbed to form a hydride. This method of storage has several advantages as against the compressed and liquid state storage methods i.e., it is safe, volumetrically efficient and operating conditions involved like temperature and pressure are optimum, unlike the other two methods. Solid-state storage refers to the storage of hydrogen in metal hydrides, chemical storage materials, and nanostructured materials. This method of hydrogen storage offers the best opportunities for meeting the requirements for onboard storage. In these materials, hydrogen can be stored both reversibly and irreversibly. Reversible storage means that hydrogen is released by raising the temperature, for example, of a metal hydride at a suitable pressure; hydrogen is subsequently replaced (stored) through the control of temperature and hydrogen pressure. Although temperature and pressure are the two typically controlled thermodynamic parameters, other types of energy (e.g., mechanical and acoustical) can be employed to control both the release and uptake of hydrogen. Metal hydrides may represent ideal storage systems. Although a database published at Sandia National Laboratory6 lists more than 2,000 elements, compounds, and alloys that form hydrides, no material has yet been demonstrated to meet all the Freedom CAR targets. Conventional metal hydrides, which are well characterized and have wellestablished values for interstitial hydrogen storage, include intermetallic of the types AB, AB2,

AB5, A2B, and body-centered cubic metals. These materials typically store between 1.4 and 3.6 wt % hydrogen. Examples of these intermetallic compounds are TiFe, ZrMn2, LaNi5, and Mg2Ni. Generally, the hydrogen storage capabilities are a factor of three lower than the Freedom CAR requirements.

#### 2.2.7.2 Liquid Storage

This type of storage system is mainly used for the delivery of hydrogen from one place to another rather than onboard supply. It is also mature technology and also widely used for space and industrial applications. The liquefaction of hydrogen is much more energy-intensive than compression, roughly requires 0.33 kWhH2. Liquid hydrogen temperature is 20K (density is 70.8 kg/m3), as such the container design should involve super insulation to protect any heat inflow into the vessel, but these are not meant to bear high pressures. A major drawback of liquid storage is the large quantity of energy required for liquefaction. The loss of hydrogen through evaporation is also an issue, especially with small tanks. High-pressure cryogenic tanks are also being explored to alleviate the requirement for very low-temperature storage.

#### 2.2.7.3 Compressed Gaseous Storage

Compressed gaseous storage technology is a widely explored technology and is more mature. Gaseous hydrogen can be stored in 4 types of pressure vessels according to their use. Hydrogen storage is chosen based on its final application. Cost and technical performance are the basis of compromise. Since the density of hydrogen is very low  $0.089 \text{ kg/m}^3$ , such storing in gaseous form requires compression to high pressures. The commercially available Type III and Type IV tank can store hydrogen at 350 bar or 700 bars. As we go from Type I to Type IV tanks the weight of the tank reduces but the cost increase. The major drawback of gaseous storage for transportation applications is the small amount of hydrogen that may be stored in a reasonable volume [16]. The performances which are generally used to compare the pressure vessels are C<sub>m</sub> and C<sub>v</sub> defined as:

- C<sub>m</sub>: weight performance: mass of H2 stored divided by the mass of the vessel (% wt)
- C<sub>v</sub>: volume performance: mass of H2 stored divided by the external volume of the vessel(g/l)

• cost

The safety requirements are of course the same for all of them. The figure below shows the technical performances as a function of service pressure for today's technology of type III and type

IV vessels. The performances are given with 10% of incertitude. Note that the  $C_m$  for type I and type II vessels are respectively 1 and 1,5 % at 200 bars (the weight is ~60-70kg to store 10 Nm<sup>3</sup> of hydrogen).



### Pressure (bar)

Figure 9: C<sub>m</sub> and C<sub>v</sub> as a function of the pressure [17](Type III and IV)

The general features for type I vessels and that they are heavy ( $C_m \sim 1\%$  max) and pressure limited. Indeed, to have high service pressures of type I tanks, the thickness of the wall shall be increased. But, heat treatment during the manufacturing cannot be as efficient as on thinner walls: the very high-pressure walls will have strong material properties heterogeneity through the thickness. It generally reaches the point where steels are very sensitive to hydrogen embrittlement and thus defects growth is unpredictable. As a consequence, for higher-pressure applications (700 bar refueling pressure) type I technology, shall be avoided to reach an appropriate safety level. For onboard storage in vehicles, both the weight and the pressure limit will restrict their use. On the other hand, they are the cheapest high-pressure vessels. Thus, when no space or weight savings are required, they are the more competitive and technological sufficient supply mode [17].

- Type 1: A traditional all-metal bottle made of steel used for storing liquid and gases for industrial processes. Cheap to produce, but heavy.
- Type 2: An additional layer of carbon fiber reinforcement is added around a steel inner

tank and shares the load with the metal. This gives it added strength and reduces weight, but makes it more expensive than Type 1

- Type 3: A carbon-fiber composite vessel, with a steel or aluminum vessel inside. The carbon fiber outer vessel takes the load. With more carbon fiber involved, costs are higher than type 2, but higher pressures can be achieved
- Type 4: A vessel made of all carbon fiber, with an inner liner of polyamide or polyethylene plastic. Characteristics are much lower weight and very high strength. Comparatively expensive, because of the volume of carbon fiber [15]



Figure 10: Gaseous storage Vessel's type [15]

Compressed gas is simple to implement, refilling is as rapid as that for gasoline (a few minutes or less), dormancy is good, and the energy requirements for compression are modest. (Electrical requirements for compression to high pressure are typically 5%–7% of the energy content of the hydrogen and can be lower if hydrogen is produced at high pressure.) Although the energy density per unit weight and volume are low with conventional steel pressure cylinders, advanced composite, high-pressure cylinders hold the promise of acceptable weight (>10% hydrogen by weight) and large, but probably acceptable, volume. Conceptual designs have been developed by Ford Motor Co. for lightweight, potentially low-cost (\$500–\$1000/tank in mass production), high-pressure (5000 psi) hydrogen tanks holding >10% hydrogen by weight, which can be refilled in  $\leq 3 \min (60)$ . By contrast, current onboard metal hydride systems store only 1%–1.5% hydrogen by weight, are costly, and require a relatively long recharge time (10–20 min). Heat must be applied to the vehicle to release hydrogen, which involves the use of an onboard burner and heat exchanger. For liquid storage, boil-off of the cryogenic liquid from storage and refueling losses

isa major issue. Also, the large amount of energy required for the liquefaction of hydrogen makes the total energy cycle efficiency of liquid storage significantly less than that of compressed gaseous storage. Hence, hydrogen could be stored in advanced compressed-gas cylinders at an acceptable cost, weight, and volume for vehicle applications. This is true in part because hydrogen can be used so efficiently in fuel cells that relatively little fuel is needed on board to travel a long distance [11].



# 2.3 Balance of Plant (BOP) / Schematic

Figure 11: BOP of Hydrogen Electrolyzer

#### 2.4 Mathematical Modeling

The Parametric modeling for hydrogen production, storage and compression system is identified and used for sizing electrolyzer system and storage system. The mathematical description is based on the Physical correlation (fluid dynamic model, thermodynamic model electrochemical model, and thermal model) and empirical relation obtained from experimental data. In developing relation

- Pressure drop and pressure effects are neglected, and no high-pressure electrolyzer has been considered, where problems such as cross-permeation phenomena and corrosion take place more frequently
- Operating temperature for electrolyzer is considered constant
- Each cell has the same thermal behavior
- Each cell has identical electrical behavior and is connected in series



#### 2.4.1 Hydrogen Production System

The electrochemical model helps to predict electrochemical behavior of alkaline electrolysis stack under different condition temperature and pressure. The proposed equation determines the polarization curve, Faraday efficiency, hydrogen production rate under given condition of current and current density. The polarization curve helps to determine ( $V_{cell}$ ) according to current density. For electrolysis to occur the minimum voltage must be supplied which is called reversible voltage ( $V_{rev}$ ), which is determined as 1.23 V at standard conditions (1 bar and 25°C). The voltage of the cell is more than the theoretical value because of over potential due to kinetic and resistive effects. The output voltage of the cell of electrolyzer is given in Eq. (1)

$$V_{cell} = V_{rev} + \eta_{cathode} + \eta_{anode} + \eta_{ohm} + \eta_{con}$$
(1)

The concentration over potential occur at very high current density and it can be neglected for the usual range of operation for electrolyzer. The empirical relation in terms of temperature, pressure, and current density has been developed for cell voltage which is given in Eq. (2)

$$V_{cell} = V_{rev} + (r_1 + d_1) + (r_2 \cdot T_{elec} + d_2 \cdot p_{elec})i + s \cdot \log[(t_1 + \frac{t_2}{T_{elec}} + \frac{t_3}{T_{elec}^2}) \cdot i + 1]$$
(2)

The equation (2) gives polarization curve which determine cell voltage at different current density.

Where,

$$\begin{split} r_1 &= 4.4513 * 10^{-5} \ \Omega \ m^2 \\ r_2 &= 6.88874 * 10^{-9} \ \Omega \ m^{2} ^{\circ} \text{C} \\ d_1 &= -3.12996 * 10^{-6} \ \Omega \ m^2 \\ d_2 &= 4.47137 * 10^{-7} \ \Omega \ m^2 \text{bar}^{-1} \\ s &= 0.33824 \ \text{V} \\ t_1 &= -0.01539 \ m^2 \ \text{A}^{-1} \\ t_2 &= 2.00181 \ m^{2} ^{\circ} \text{C} \ \text{A}^{-1} \\ t_3 &= 15.24178 \ m^{2} ^{\circ} \text{C}^2 \ \text{A}^{-1} \end{split}$$

### 2.4.1.1 Power of stack

It can be found out by using ohm equation,

$$P_{\text{stack}} = V_{\text{stack}} \cdot I = (N_{\text{cell}} \cdot V_{\text{cell}}) \cdot (i \cdot A_{\text{cell}})$$
(3)

#### 2.4.1.2 Hydrogen production rate

Hydrogen production rate at the cathode depends on the electrochemical behavior of the cells and can be determined by using faraday efficiency by equation (4):

$$N_{\text{cell}} \cdot I = \dot{n}_{\text{H}_2} \cdot \frac{z_{\text{e}} \cdot F}{\eta_{\text{f}}}$$
(4)

Faraday efficiency is the measure of the effectiveness of the process. It is the ratio of mole produced  $(n_{H2}, prod)$  and theoretical moles  $(n_{H2, th})$  that should be produced during the same time.

i.e 
$$\eta_f = \left(\frac{nH2, prod}{nH2, th}\right)$$

Faraday efficiency at a given temperature is obtained through empirical relation. The 2-coefficient empirical relation has been used to obtain faraday efficiency.

$$\eta_{f} = \left(\frac{(i)^{2}}{(f_{1} + (i)^{2})}\right).(f_{2})$$
(5)

Where,

$$f_1 = 2.5 T_{elec} + 50$$
  
$$f_2 = -0.00075 T_{elec} +$$

1

Faradaic efficiency vs current density helps to understand behavior of electrolyzer under different condition of current density at given operating temperature and pressure. Similarly, from equation (4) and (5) we can optimize stack voltage according to given power input and current.

#### 2.4.2 Hydrogen Storage

#### 2.4.2.1 Buffer storage

The produced hydrogen gas is initially stored in a buffer tank and the quantity of hydrogen stored in the vessel is calculated as:

$$N_{H_2} = N_0 + n_{H_2} - N_{out}$$
(6)

The pressure inside the buffer tank can be calculated using equation proposed by Gorgon [18].

$$p_{bf} = p_0 + \frac{z.(N_{H_2}.R.T_{H_2})}{MW_{H_2}.V_{max}}$$
(7)

Here, z is the compressibility factor [18].

The figure below shows the compressibility graph in relation to pressure



Figure 12:Compressibility (Z) for Hydrogen

The figure 12 gives the value of compressibility factor at different pressure and temperature condition. From figure, the value of compressibility factor below 30 bar and temperature above 200K the compressibility factor can be considering 1.

#### 2.4.3 Pressure in the storage tank

Hydrogen from the buffer storage tank is then going into the compressor for compression at multiple stages and during the process temperature of hydrogen rises which is then cooled through the heat exchanger. The dynamic of hydrogen at these processes has not been considered in the model. The desired pressure is obtained through the compressor process and temperature is considered to be maintained at room temperature while filling process in the storage tank. Mass conservation law has been used to model the dynamics of the pressure inside the hydrogen storage tank during its filling operation [19].

$$\dot{m}_{tank} = \dot{m}_{H_2 compressor} \tag{8}$$

$$m_{\text{initial}} = \frac{p_{\text{tank,initial}}.V_{\text{tank}}}{\left(\alpha.\frac{p_{\text{tank,}}}{T}+1\right).R_{\text{g}}.T}$$
(9)

Where,

$$\alpha = 1.9155 * 10^{-6} \frac{K}{Pa}$$

$$R_g = 4124.3 \frac{J}{Kg.K}$$

$$m_{tank} = m_{initial} + \int \dot{m}_{tank} dT \qquad (10)$$

The sizing of the gaseous storage system can be modeled by using a real gas law equation which is given as:

#### **Real gas law equation**

Vander Waals Real gas model equation can be used to size the storage tank as it gives the relation between pressure, volume, and the number of moles of the gas.

$$\left(P + \frac{a n^2}{V^2}\right)(nV - b) = RT$$
(11)

Where a and b are van der wall's constant.

 $a = 0.2453 \text{ atm} \cdot l^2 \cdot \text{mol}^{-2}$ 

 $b = 0.02651 l. mol^{-1}$ 

 $R = 0.080257338 l. atm. K^{-1}mol^{-1}$ 

### 2.4.4 End use of hydrogen fuel and its demand

Fuel cell power can be determined by the given equation

Power = efficiency of fuel cell \* Hydrogen consumption

$$P_{fc} = \eta_{fc} * n_{H_2 \text{ consumed}} * \Delta H$$
(12)

. . .

The efficiency of fuel cell:

Fuel cell efficiency is the ratio between the amount of electricity generated and the amount of energy consumed. These musts both be in the same unit of measurement as Watts or kilowatts.

$$\eta_{\rm fc} = \frac{W_{\rm el}}{W_{\rm H_2}} \tag{13}$$

Through mathematical analysis equation (13) can be written in terms of voltage which is given by:

$$\eta_{\rm fc} = \frac{\rm V}{1.482} \,\eta_{\rm fu} \tag{14}$$

Where,  $\eta_{fu}$  is fuel utilization which is equal to  $1/S_{H_2}$  and  $S_{H_2}$  refers to Hydrogen stoichiometric ratio i.e. the ratio between the amount of hydrogen actually supplied to the fuel cell and that is consumed in the electrochemical reaction:

$$S_{H_2} = \frac{N_{H_{2,act}}}{N_{H_{2,theor}}} = \frac{nF}{I} \cdot N_{H_{2,act}}$$
(15)

Well-designed fuel cell may operate with 83% to 85% fuel cell utilization with reformate and 90% when operated with pure hydrogen [20].

From equation 13 and 15, we get relation between current output and fuel consumption.

 $P_{fc} = \frac{V_{fc}}{1.482} \eta_{fu} * n_{H_2 consumed} * \Delta H$   $N_{fc} * I_{fc} = \frac{1}{1.482} \eta_{fu} * n_{H_2 consumed} * \Delta H$   $n_{H_2 consumed} = \frac{1.482 * N_{fc} * I_{fc}}{\eta_{fu} * \Delta H}$ (16)

#### 2.4.5 Work done by Compressor

Mass flow rate out of the compressor is determined by displacement volume in the compressor's cavity(V), the frequency of compression(N) in cycles per unit time, and the density of supplying the compressor( $\rho$ ) or suction pressure [21].

$$\dot{m}_{\rm H_2 comp} = V_{\rm d} * f * P_{\rm suc} / (zRT_{\rm s})$$
(17)

$$\dot{m}_{H_2 \text{comp}} \propto P_{\text{suc}}$$
 (18)

Where,

V<sub>d</sub>=volume displacement of compression piston

f = frequency of compression

R = real gas constant

 $P_{suc} = Suction pressure$ 

 $T_s =$ Suction Temperature

 $\dot{m}_{H_2comp}$  = Compressor flow rate

The equation (9) gives the relation between suction pressure and mass flow rate. By equation (10), we can get different value of mass flow rate at different suction pressure. The equation (10) can further be made by using experimental data and manipulate it to give empirical relation.

Similarly, work done by compressor in each stage for polytropic compression is given by [22],

$$W_{\text{comp}} = \dot{m}_{\text{H}_2\text{comp}} \left[ \left( \frac{nRT_s}{\eta_{\text{comp}}(n-1)} \right) \left( \left( \frac{P_{\text{suc}}}{P_{\text{dis}}} \right)^{\frac{n-1}{n}} - 1 \right) \right]$$
(19)

Where,

 $P_{dis} = Discharge pressure$ 

 $\eta_{comp}$  = Compressor efficiency (usually range between 0.7-0.9)

n = polytrophic coefficient of hydrogen (1.609 for hydrogen)

# 2.5 Review of Hydrogen Hazards

The identification and control of possible hazardous consequences is an ethical requirement in any case. Hydrogen is colorless, odorless, and tasteless making impossible its detection by human sense. It is nontoxic but there is the risk of asphyxiation if its presence in air leads to an oxygen- deficient atmosphere. Leakages from the valve, flanges, storage containers, gaskets, seals, fittings, and distributions pipelines constitute a risk more serious than in the case of natural gas or liquid hydrocarbon fuels [23].

The hazards associated with hydrogen are usually classified into three main categories:

### 2.5.1 Physiological Hazards

This category includes asphyxiation, thermal, hypothermia, and injury by blast waves.

• Asphyxiation will exist whenever hydrogen gas displaces the air in an area. Several stages of asphyxiation have been established depending concentration of oxygen.



Figure 13: Asphyxiation Symbol

• Thermal burns are produced through the absorption by the organism of radiation produced by a flame or fire. Harm provoked by IR radiation is higher than that of the UV one.

# 2.5.2 Physical Hazards: Embrittlement

Physical Hydrogen hazards arise as a consequence of its interaction with the multitude of materials used to build the hydrogen systems consisting of pipelines, storage containers, valve bodies, gaskets, etc.

Hydrogen can provoke an important deterioration in the mechanical properties of metals; this effect is referred to as hydrogen embrittlement. It occurs in one or a combination of the following terms:

- Environmental embrittlement observed in metals and alloys plastically deformed in contact with gaseous hydrogen. The deformations produced lead to increased cracks that start at the surface, loss in ductility, and a decrease in fracture stress.
- Internal embrittlement is produced by absorbed hydrogen. Small amounts of hydrogen may cause premature failures with little or no warning. In this case, cracks start internally.



Figure 14: Hydrogen Cylinder bursts, Intergranular crack [24]

- Reaction embrittlement takes place when absorbed hydrogen reacts with metallic elements to form a brittle hybrid. In the case of carbon steels, the formation of methane has been reported.
- It is recognized that (HE) increases when the partial pressure of hydrogen increases. Nevertheless, studies have shown that in general a maximum embrittlement effect of hydrogen is attained for a certain pressure. This maximum effect is reached at moderate hydrogen partial pressures. In actual practice, this critical value can vary between 20 and 100 bars, but in the case of steels very sensitive to HE, even at very low pressure (a few bars), the embrittling effect can be very pronounced

# 2.5.3 Chemical Hazards: Ignition and Explosion

Chemical hydrogen hazards are principally associated with the deflagration and detonation phenomena that can be produced when a flammable or explosive mixture of hydrogen and an oxidant is ignited.

- The minimum energy for the ignition of gaseous hydrogen in air at atmospheric pressure is only 0.02mJ, this explains the fact that hydrogen leaks are very easily ignited.
- Deflagration and detonation waves occur when hydrogen leaked from systems gets exploded.



Figure 15: Minimum ignition energy of different gases [23]

### 2.5.4 Safety planning

Safety planning should be an integral part of the design and operation of a system. Safety approvals should not be afterthoughts or final hurdles to be overcome before a system can become operational. Safe practices in the production, storage, distribution, and use of hydrogen are essential to protect people from injury or death. These practices are also necessary to minimize damage to facilities. A catastrophic failure in any hydrogen project could negatively impact the public's perception of hydrogen systems as viable, safe, and clean alternatives to conventional energy systems, and could reduce the ability of hydrogen technologies to obtain insurance, a necessary step in the commercialization of any technology.

The goals of Safety Planning are to identify hazards, evaluate risks by considering the likelihood and severity/consequence of an incident associated with the hazards and minimize the risks associated with a project. To achieve these goals, various hazard analysis and risk assessment techniques are used, in conjunction with safety reviews. Safety procedures are divided into two parts:

# 2.5.4.1 Laboratory Safety

This section presents best practices for safe laboratory design and operations. While designing a laboratory workspace or operating one, the approach to safety planning and risk assessment should be done based on the quantities of hydrogen involved.

# 2.5.4.1.1 Cylinder Safety

- Cylinders should be handled only by trained personnel.
- Cylinders that are not necessary for current laboratory use should be stored at a safe location outside the lab.
- Cylinders in the laboratory should be equipped with a pressure regulator designed for hydrogen and marked for its maximum cylinder pressure.
- Regulators should be equipped with two gauges, installed to show both the cylinder pressure and the outlet pressure.
- Hydrogen supply lines should have a manual shutoff valve to allow the isolation of equipment. A quick-connect should never be used in place of a shutoff valve.
- Excess flow valves or flow restrictors should be used to control maximum hydrogen flow, particularly when using ganged cylinders.

# 2.5.4.1.2 Electrolyzer

- To prevent the possibility of having hydrogen pumped into a non-ventilated space, you should configure the electrolyzer to shut down if: 1) there is a ventilation system outage, or 2) a laboratory sensor detects hydrogen in the air.
- The laboratory ventilation system should maintain an air exchange rate that is at least two orders of magnitude greater than the maximum hydrogen generation rate of the electrolyzer to prevent the buildup of an LFL (lower flammability Limit) atmosphere.
- Oxygen exhausted by the electrolyzer should be safely vented to the outside.
- An electrolyzer should only be operated in a non-explosive environment.

# 2.5.4.1.3 Storage and Piping

• Manual shutoff valves should be provided near each point of use.

- The point-of-use valve should be located away from the potential hazards and within immediate reach.
- Piping should be designed for pressure greater than the maximum system pressure that can be developed under abnormal conditions.
- Piping systems, including regulators, should not be used for gases other than those for which they are designed and identified unless a thorough review of the design specifications, materials of construction, and service compatibility is made and other appropriate modifications have been made.
- Shut-down controls should be provided and linked to an alarm system.
- All shutoff valves should be marked.
- Permanent hydrogen piping should be labeled as such at the supply point, at each discharge point, and regular intervals along its length. Where hydrogen gas piping penetrates a wall, the piping should be labeled on both sides of the wall. Color-coding may be another way to mark hydrogen piping.

# 2.5.4.1.4 Ventilation

- Normal air exchange should be 0.3 m<sup>3</sup> of air per minute per 1 m<sup>2</sup> of solid floor space or 1 ft<sup>3</sup> of air per minute per 1 ft<sup>2</sup> of solid floor space.
- Laboratories and laboratory hoods in which hydrogen is present should be continuously ventilated under normal operating conditions.
- The minimum ventilation rate should safely dilute hydrogen buildup due to leakage from system components. Ventilation should not shut down as a function of emergency shutdown.
- The air pressure in the laboratory should be negative with respect to corridors and nonlaboratory areas.
- Since hydrogen is lighter than air, the exhaust from exhaust systems should be discharged above the roof.

# 2.5.4.2 Leakage and Flame detection

The design objective is to ensure that detection occurs immediately and operating personnel are notified as appropriate if hydrogen leaks into the atmosphere or a hydrogen fire occur. Recall that gaseous hydrogen is colorless and odorless, the flame without contaminants is difficult to see, and it radiates little heat. Considerations for gas and flame detector use include:

Location - The number and distribution of detection points and time required to shut off the hydrogen source should be based on factors such as leak rates, ventilation rates, and the volume of space in the laboratory. Locations to consider include:

- Permanent installations in indoor storage facilities
- Critical locations where leaks may occur (typically immediately above or where flow isconcentrated) during experiments or the operation of processes involving hydrogen
- Where hydrogen may accumulate.

Response Time - Evaluate the expected response time of the detection system to ensure compatibility with the required response of the safety system or provision.

Alarms - Detection signals should actuate warning alarms and actuate shutdown actions whenever practical. Audio and visual alarms should be provided as necessary.

Ignition - The hydrogen detection system should be compatible with other systems such as fire detection and fire suppression. The detection units should not be ignition sources.

Areas Without Detection - Portable hydrogen leak and flame detectors (e.g., thermal imaging camera or handheld flammable gas detector) should be available if permanent detectors are not installed.

# 2.5.4.2.1 System Checklist

- Always allow enough time for troubleshooting/debugging a monitoring system before it'sused.
- Use inert gas and bubble indicators (soap in water) to identify leaks during system/vessel checkout.
- Piping and equipment leak checks with soap solution should be done before allowing any hydrogen to enter the system.

# 2.5.4.2.2 Fire protection

- The most effective way to extinguish a hydrogen fire is to shut off the flow of hydrogen. Therefore, an emergency shutoff valve on the hydrogen supply piping should be installed in any laboratory that uses hydrogen.
- Depending on laboratory arrangements and the quantities of hydrogen and other flammable

gases in the lab, consideration should be given to the installation of an automatic sprinkler system.

- The following should be given special fire prevention consideration:
  - 1. Handling and storage of gaseous hydrogen.
  - 2. A work permit system for using open flames or spark-producing equipment.
  - 3. Smoking area controls.

# 2.5.4.2.3 Emergency Plan

- Plans for laboratory emergencies:
  - 1. Audible and visible alarm activation
  - 2. Evacuation and building re-entry procedures
  - 3. Methods for documenting and accounting for all visitors and personnel present if anincident occurs
  - 4. Equipment shutdown procedures or applicable emergency operation (planned and posted)
- Instructions should be posted on the laboratory door so that security personnel can notify the cognizant laboratory supervisor about any after-hours emergency or suspect conditions.
- Multiple Exists

Alternative exit routes should be provided from a laboratory when blockage of a primary exit is possible. Some potential hazards are:

- > a fire or explosion hazard
- hydrogen compressed gas cylinders

# 2.5.4.3 Personal Safety

This section presents best practices for safe laboratory Operators. Before laboratory tests are begun, evaluations should be done for hazards that can be encountered or generated during the work [23].

- Immediately notify others or sound the alarm system to make others aware of the danger.
- If safe to do so, shut off the hydrogen supply valves.
- For small, contained fires where it is safe to do so, but the fire out using a fire extinguisher.

- Exit the building by the nearest evacuation route, and proceed to the congregation point.
- Only trained responders should deal with spills, fires, and uncontrolled releases.
- Regular reviews of laboratory operations and procedures should be conducted with specialattention given to any change in materials, operations, or personnel.
- Specify maximum permissible quantities of hydrogen and other potentially hazardous materials, identify personal protective equipment (PPE), and summarize emergency procedures.
- Ensure that participating laboratory personnel have received hydrogen safety training.
- Include a review of shut-down operations and emergency procedures, and ensure that localemergency responders are informed of proposed experiment hazards.
- Wear proper personal protective equipment, including safety glasses, goggles, faceshields,fire-retardant aprons or lab coats, gloves, etc.
- Before entering the proximity of hydrogen-containing laboratories or equipment, consult the status of fixed gas sensors and flame detectors.
- Without fixed sensors, thermal imaging cameras can verify that a hydrogen flame is present. If a flame is not present, confirm with a personal gas detector that flammable mixtures are not present.
- Although hydrogen fires do not produce smoke themselves, the burning of nearby combustible materials can result in smoke. Thus, personnel should be aware that smoke inhalation can be a danger in a hydrogen fire.

# Chapter 3 ANALYSIS, CALCULATION AND AUXILIARY COMPONENT DEVELOPMENT

# 3.1 Analysis and Calculation

Electrolyzer sizing is done by using the mathematical model from equation 1,2,4 and 5. A case specific scenario is developed for the application of model in transportation sector. A load demand of 5 kW fuel cell is taken as the end use of hydrogen. Analysis of Polarization curve, effect of current in different parameters, and storage sizing is discussed in this section. An optimized model for the end use is proposed and sizing of production and storage system is done. Parameters used in the models are:

Constant	Value	Unit	Symbol
	Electrol	yzer	
Temperature	70	°C	Т
No. of cell	160	-	N <sub>cell</sub>
Area of electrode	0.21	m <sup>2</sup>	A <sub>cell</sub>
Pressure	10	Bar	Р
Reversible voltage	1.23		V <sub>rev</sub>
	Fuel c	ell	
Power	5	KW	Р
Nominal voltage	72	V	V
No. of cell	100		N <sub>cell</sub>
Temperature	25	°C	Т
	Pressure	vessel	
Pressure	100	bar	Р
Temperature	25	°C	Т

#### **A)** Polarization Curve



Figure 16: Polarization Curve

Figure 16 shows the relation between voltage of cell and current at different temperature and to model it equation (2) is used. It shows that the overpotential for cell decreases with the increase in operating temperature, which makes electrolyzer more efficient at higher temperature. However, higher operating temperature condition is corrosive, so it is maintained at temperature range of 20-80°C. This curve allows to determine the cell voltage for operating condition at given input power and current/ Current density and temperature.



B) Effect of Current on faradaic eff efficiency and Hydrogen Production rate of electrolyzer

Figure 17: Faraday Efficiency Chart



Figure 18: Hydrogen Production Flowrate

Faradaic efficiency and Hydrogen production rate is influenced by current input which is shown in figure 17,18. Equation (5) and (6) is used to develop the relation in the form of graph and to

obtain the volumetric flow rate from the electrolyzer, hydrogen gas is assumed to be the ideal gas. From figure 18 curve volumetric flow rate can be obtained in relation with the different current input and we can size our buffer storage tank according to the output of the electrolyzer. We can optimize electrolyzer from result obtain from figure 18. For 80% faradaic efficiency, current density for electrolyzer should be about 38 mA/cm<sup>2</sup>. For the electrolyzer of 0.21m<sup>2</sup> electrode, Current input in electrolyzer should be about 80 A. The cell voltage can be obtained from polarization curve; at 70° it is about 1.7 for given current density. The number of cells used in the model is 160, so stack voltage is 272V. At given voltage and current rated power of electrolyzer is 30K and hydrogen production rate is 0.056 mol/s.

Calculation from parameter obtained:

Hydrogen flow rate = 0.056 mol/s

Mass flow rate = 
$$0.056 * Molecular weight of H_2$$

= 0.056 \* 2 = 0.112

Volumetric flow rate at normal pressure and temperature,

$$PV = z^* n^* R^* T \tag{20}$$

Where,

 $R = 0.083144621 L bar K^{-1}mol^{-1}$ 

T = 273.15 + (25) = 298.15 K

 $z \approx 1$ , For pressure below 30 bar at temperature 298.14K. (from figure (13))

$$V = \frac{1 * 0.056 * 0.083144621 * 298.14}{1}$$
$$V = 1.388 NL/s$$

So, volumetric flow rate of hydrogen gas through electrolyser is 1.388NL/s

Available storage vessel,

Volume = 171

Hydrogen molar Volume for pressure Vessel at 10 bar pressure and 298.15K

$$n = \frac{10 * 17}{0.083144621 * 298.14}$$
$$n = 6.86 \ mol$$

Energy content for pressure vessel at 10 bar pressure,

$$E = n * \Delta H$$
$$= 6.86 * 286 kJ.mol^{-1}$$

Filling time for 1 Buffer storage,

time<sub>filling</sub> = molar flow rate of hydrogen \* molar volume

$$= \frac{6.86}{0.056}$$
  
= 122.5 sec  
= 2.04 minute

#### C) Effect of current on hydrogen consumption for fuel cell

This is the model to assume energy demand for the PEM fuel cell of 5KW system. The figure below shows the relation between current output and hydrogen consumption rate.



Figure 19: Hydrogen consumption Vs Output Current

For the 5KW and 72V nominal voltage system, the nominal current is about 69.4 A and the hydrogen consumption rate for the fuel cell at such condition is 59.43 NL/min i.e. 145 mol/hr. The fuel cell requires about 580 mol from a stationary storage source to operate for 4 hours.

#### **D)** Storage sizing

Real gas law has been used to obtain the relation between number of moles and volume of the hydrogen gas at the pressure of 100 bar and 298.15K.



Figure 20: Volume Vs No. of moles

From the curve shown in figure 8, it requires 150L vessel to store 580 moles of gas. To run laboratory fuel cell for four hours, a stationary storage system that can store 150 L of vessel at 298.13K and 100 bar pressure should be made. For eg: it will require 9 storage tanks of 17L in series to store such amount of gas.

## **Specification for Electrolyzer through our Mathematical Model**

This model is prepared for end-use demonstration for transportation sector the result does not in cooperate with the model available in Green Hydrogen Lab.

Parameter	Value
Power	30KW
Operating temperature	70°C
Operating pressure	10 bars
Number of cells	160
H <sub>2</sub> Production rate	0.056 mol/s
Nominal current	80 A

# Specification for Hydrogen compressor according to our model

Compressor Parameter are placed according to need for storage of the system. Discharge rate is assumed to be 8Kg/hr to meet the demand to fill high storage vessel within 8 minutes.

Parameter	Value
Suction pressure	10 bars
Discharge pressure	100 bars
Discharge temperature	50° C
Discharge rate	8 Kg/hr
Power	?

Power of compressor can be calculated

Power of compressor = 
$$W_{comp} = 8/3600 * \left[ \left( \frac{1.06 * 298.15}{0.7 * (1.06 - 1)} \right) \left( \left( \frac{100}{10} \right)^{\frac{1.06 - 1}{1.06}} - 1 \right) \right]$$
  
= 8/3600 \* 7524.73 \* 0.13  
= 2KW

### 3.2 Auxiliary Component Development

Green Hydrogen Lab has a 1 kW Hydrogen production system and Type IV Storage Tank. An attempt has been made to develop the auxiliary component for the ease of equipment handling of production and storage system.



Figure 21 Production and Storage equipment at Green Hydrogen Lab, KU

# 3.3 Auxiliary Component

# 3.3.1 Hydrogen Cylinder Stand

The 3D model of the Hydrogen Cylinder stand is developed for fabrication. The design is especially used foe the cylinder used in the Green Hydrogen Lab, Kathmandu University.



Figure 22: 2D drawing of the Hydrogen Cylinder stand



Figure 23: 3D Views of the Hydrogen cylinder stand

# **3.3.2** Electrolyzer trolley

The 3D model of the Electrolyzer trolley is developed for fabrication. The design is especially used foe the Electrolyzer used in the Green Hydrogen Lab, Kathmandu University



Figure 24: 2D drawing of Electrolyzer trolley



Figure 25: 3D Views of the Electrolyzer trolley

# Chapter 4 Work Schedule

# 4.1 Gantt Chart

		(2021) Dec					(2022) Jan			(2021) Feb				(2021) Mar				(2021) Apr				2022 May			
S.N.	Work	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
1	Preliminary Research																								
2	Literature review																								
4	Market survey																								
5	Design																								
б	Assembly																								
7	Mathematical Modeling																								
8	Analysis and improvement																								
9	Repot submission, Final Presentation																								

Work done	
Work Remaining	

Budget Expenditure

S.N	Material	Quantity	Price
1.	Caster Wheel	4	3500
2.	Wheel	2	1200
3.	Bearing	2	300
4.	Spray Pint	2	790
5.	Nut and Bolts	16	200
	Total		5990

### **Chapter 5** Conclusion

The project is about the development of a hydrogen production and storage system for demonstration in the transportation sector of Nepal. Green hydrogen is a possible future of energy and the study is done to understand hydrogen production and storage methodology. Different hydrogen production system is studied and the possible method is described considering factors like environmental impact, sustainability and maturity. The alkaline electrolysis process is advance method to production which has technical maturity and system cost is relatively lower than other electrolysis method. The hydrogen storage system is also studied to identify their scope and limitation. The gaseous storage method is identified as suitable method for laboratory as it has fast charging and discharging capability. The balance of plant is developed which defines the system layout and configuration to design laboratory. Component used for whole laboratory setup is shown in layout. The auxiliary component for laboratory is designed through 3D CAD modeling and The parameter for operation of electrolyzer and storage system is identified and based on the parameter mathematical model is studied. The mathematical model is further simulated in EXCEL to analyze the behavior of electrolyzer and storage system. Based on result and analysis optimum electrolyzer model. The energy demand for 5KW fuel cell is also analyzed and the optimum storage system is developed. The parameter obtained through the result is used for the specification of alkaline electrolyzer and compressor is also developed. The research was also done to develop different safety code for laboratory operation. The result of the model can be used to scale up production and storage system. The research is not done for the compressor modeling and energy demand for the drive cycle of vehicle. The dynamics of hydrogen during filling is not studied which can be case for further study to develop more optimized model for laboratory development of hydrogen production and storage system.

# Chapter 6 REFERENCE

- [1] R. B. G. M. S. M. Sameer Lamichaney, "Clean Energy Technologies: Hydrogen Power and Fuel Cells," Kolkata, 2018.
- [2] The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D needs, Washington, DC: The National Academies Press, 2004.
- [3] "Data Commons," Data Commons, 2020. [Online]. Available: https://datacommons.org/place/country/NPL?category=Environment. [Accessed 12 May 2021].
- [4] T. M. Letcher, Future Energy Improved, Sustainable and Clean Options for our Planet, Third ed., Kwazulunatal, South Africa, 2020.
- [5] E. H. W. R. D. M. B. KhuzaimahArifin, "Bimetallic complexes in artificial photosynthesis for hydrogen production: A review," International journal of Hydrogen Energy, vol. 37, no. 4, pp. 3066-3087, Feburary 2012.
- [6] M. H. McCay, "Hydrogen: An energy Carrier," in Future Energy, Melbourne, fl, United state, 2004, p. 19.
- [7] F. S. M. J. M. A. F. J. V. a. A. J. C. Julio José Caparrós Mancera, "An Optimized Balance of Plant for a Medium-Size PEM Electrolyzer: Design, Control and Physical Implementation," MDPI, p. 871, 2020.
- [8] "State of Planer," 7 Jan 2021. [Online]. Available: https://news.climate.columbia.edu/2021/01/07/need-green-hydrogen/. [Accessed 28 May 2021].
- [9] D. R. Symes, "Development of On-Demand Low Temperature Electrolysers and Their Systems," University of Birmingham, Birmingham, 2015.
- [10] T. Lipman, "An Overview of Hydrogen Production and Storage Systems with Renewable Hydrogen Case Studies," 2011.
- [11] J. M. Ogden, "PROSPECTS FOR BUILDING AHYDROGEN ENERGY INFRASTRUCTURE," pp. 227-279, 1999.
- [12] "HYDROGEN PRODUCTION FROM BIOMASS AND BY PHOTOBIOLOGICAL PROCESSES," in The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs, National Academies Press, 2004, pp. 101-102.
- [13] S. H. J. A. H. a. M. B. M. Sune Dalgaard Ebbesen\*, "High Temperature Electrolysis in Alkaline Cells, Solid Proton Conducting Cells, and Solid Oxide Cells," Chemical Review, p. 10697–10734, 6 oct 2014.
- [14] G. L. J. Z. a. Y. L. Yujing Guo, "Comparison between hydrogen production by alkaline water electrolysis and hydrogen production by PEM electrolysis," 2019.
- [15] "NPROXX," NPROXX, 30 May 2019. [Online]. Available: https://www.nproxx.com/different-types-of-pressure-vessel/. [Accessed 3 May 2022].
- [16] D. R. K. P. P. S. D. P. P. M. Dr. Sanjay Bajpai, "India Country Status Report on Hydrogen and Fuelcell," New Delhi, 2020.
- [17] H. B. Katia Barral, "Hydrogen high pressure tanks storages: overview and new trends due to H2 Energy specifications and constraints," p. 10, 2006.

- [18] D. A. J. K. K.A. Kavadias\*, "Modelling and optimisation of a hydrogen-based energy storage system in an autonomous electrical network".
- [19] M. G. Petronilla Fragiacomo, "Developing a mathematical tool for hydrogen production, compression and storage," Internation Journal of Hydrogen Energy.
- [20] F. Barbir, "Fuel Cell Electrochemistry," in PEM Fuel Cells: Theory and Practice.
- [21] A. E. N. R., E. G. Krishna Reddi\*, "Two-tier pressure consolidation operation method for hydrogen refueling station cost reduction," Hydrogen Energy, 2017.
- [22] B. J. S. S. Zhao. L, "Dynamic analysis of a self-sustainable renewable hydrogen fueling station," 2014.
- [23] "H2 Tools," 2016. [Online]. Available: h2tools.org/bestpractices/hydrogen- comparedother-fuels.. [Accessed 21 May 2021].
- [24] H. Barthélémy, "Compatibility of Metallic Materials with Hydrogen Review of the," Paris, France, 2006.
- [25] C. o. A. a. S. f. F. H. P. a. Use, The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D needs, Washington, DC: The National Academies Press, 2004, p. 256.
- [26] F. S. M. J. M. A. F. J. V. a. A. J. C. Julio José Caparrós Mancera 1\*, "An Optimized Balance of Plant for a Medium-Size PEM Electrolyzer: Design, Control and Physical Implementation," MDPI, p. 871, 2020.
- [27] M. R. Hannah Ritchie, "Our world data," [Online]. Available: https://ourworldindata.org/co2/country/nepal.
- [28] L. B. a. M. James, "Hydrogen applications and research activities in its production routes through catalytic hydrocarbon conversion," Review in chemical Engineering, vol. 34, 2017.
- [29] M. K. a. E. I. Gkanas, "Hydrogen Technologies for Mobility and Stationary Applications: Hydrogen Production, Storage and Infrastructure Development," Renewable Energy, 2018.
- [30] "Aspen Plus model of an alkaline electrolysis," Internaton journal of Hydrogen Energy.