REPUBLIC OF RWANDA

NATIONAL COUNCIL FOR SCIENCE AND TECHNOLOGY

# Hydrogen Fuel Cell Technology for Longer range with High Power Density in Transportation Industry

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National Council for Science and Technology

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## 1. Executive Summary


### Abstract

Fuel Cell Technology is being adopted by developed countries as one of the alternatives that can be used to mitigate the dangers and challenges that are associated with the use of traditional sources of energy. Motivated by what we think is going to play a key role in revolutionizing the energy sector, we have focused our research on developing fuel cells that can generate electricity by using locally produced fuels. For the last three years, ZEOLF was studying and working on developing the key components that are necessary for Fuel Cells to produce energy and how our country can benefit from them.

The functionality, efficiency, high power density and capital cost of a Fuel Cell depend heavily on its catalyst and membrane. A catalyst enhances the activity of a fuel cell to generate electricity whereas a membrane is essential in the selective mobility of some constituents of the fuel cell system while hindering the movement of others. We have developed three different types of membranes and have made extensive research on the manufacturing of various types of catalysts and we think these are necessary components that can be produced in Rwanda.

Hydrogen Fuel Cell will initially enable us to provide energy to industries and businesses such as locus dynamics. Later, we will grow the system to provide for bigger industries and businesses and start working on adopting the technology for use in automobile such as UAV. It will also support our military to develop quitter and yet energy sufficient transportation as well as power backup for antennas and so on. The technology will be used to backup renewable sources such as wind and solar panels in times of no wind or sun light.

The current Challenges observed from batteries can be classified in three major problems, weight, power density as well as time frame of usage on single charge. The aim of our research is classified specifically to developing better product that will be used to in transportation area which in Rwanda has already adopted using of drones in field of medical delivery services. Our expectations relied to give out best quality FC to improve range hence few landing field, power density hence more weight of packages as well as longer time of operation. We have to consider that Fuel cell has the capability to operate to low and high pressure scenario as they have been used in satellite as well as submarines these areas provides good potential to fly higher with UAVs in congested city with high buildings.

## 2. Background and Context

Rwanda like any other nation relies heavily on energy to run its economy and other associated Rwanda like any other nation relies heavily on energy to run its economy and other associated sectors. Unfortunately, in addition to the widely known dangers (greenhouse gases emission, the possibility of the near-future exhaustion, etc.) of using oil as the main source of energy, Rwanda has for so long been at disadvantages of having to import a large portion of the energy the country needs. This reliance on the outside world for energy leaves our country in a danger zone where problems in other countries could trigger unexpected and unwanted events in the country. Despite the importation of energy and great effort of our government to provide electricity to the people, there is still a large part of the country that cannot contribute to the country's economy with full potential because they do not have access to electricity. Even in those areas that have access to electricity there are frequent blackouts that every now and then halt local businesses and God knows how much struggle hospitals and other vital institutions go through to resolve it. Although the country has faced these challenges with bravely and brilliance, these concerns are undeniably obvious and their presence impedes desired progress in certain spheres of the nation like industry, R&D, transportation, communication, health, etc. We have made remarkable progress in the past few years, but if we want to have even stronger competitive advantage on international market, we have to explore new alternative of sources of energy and invest even more effort than before.

Energy related problems are universal and concerned people especially in developed countries are working hard to come up with new or innovate already in place technologies that can be used to produce environmentally friendly and sufficient energy. Since there is no single source of energy that can satisfy our needs, several sources and technologies must be combined to run our energy-dependent systems. Fuel Cell Technology comes at the fore front of commercially viable alternative technologies[1] that might deliver solutions to our problems. Fuel cells are electrochemical cells that convert the chemical energy of a fuel (often hydrogen) and an oxidizing agent (often oxygen) into electricity through a pair of redox reaction. Fuel cells are efficient, environmentally friendly[2] and most importantly their fuel can be locally produced. For example, Hydrogen Fuel Cells use hydrogen as energy carrier to generate electricity; hydrogen can be obtained from water by using electrolysis[3] method which can be done here in Rwanda. Therefore, it would be wise to start working on adopting this technology as early as possible.

Every problem or challenge in society finds a solution only when someone invests their time and effort to find that solution. We, as ZEOLF team, have realized that energy problems constantly require collective effort from individuals who would like to make it their responsibility to find solutions. Aware of the potential Fuel Cells might have on energy sector, we have made substantial research on Fuel Cell Technology; we have studied the fundamentals and developments of the vital parts of Fuel Cells and what it would take to operate them. We believe that they can be feasible in our country and could one day provide solutions we need. Because we want to be a part of the solution and to strive for self-reliance and dignity of our country and society, if opportunities were presented to us we would use them with caution and great responsibility.

ZEOLF team is consisted by members of different fields of engineering with researchers majoring in environmental science and engineering, nanomaterial science, bioengineering and mechanical engineering. Every department in our company has been involved in these key technologies under different fields. For the last three years every department has created key technology needed to develop an entire cycle of FC. Material science has developed catalysts, environmental science and engineering has already developed membrane needed to combine the two and design the final product. It is important to note that ZEOLF doesn't own the technology as it was developed in the 1830 by Sir William Groove. Since then NASA has been using the technology in early Satellite and other space capsule the variety of the technology has been used in other applications such forklifting vehicles and more.[4] The technology lost patent and more open source and hence material development inclines in modern technique of patent. ZEOLF technology has been involved in developing a commercial catalyst that may consist platinum substrates coated with thin layer of Silicon and carbon nanoparticles and/or nanosheets. In order to be able to achieve such milestones we acquired techniques needed by starting to synthesize iron sulfide ($FeS_x$) and study the iron behavior on carbon the test is run unto electrochemical work station.[5]

Based on research published in different research fuel cell journals has evolved as key technology priority that addresses issues with convention engines such as energy efficiency, carbon emission reduction, noise reduction and heating. All the target involved in these criteria are the challenges engine faced in modern civilization for the desire of modern city. If you look at the noise an increase of 10 decibels was noticeable in 2018 while the noise accounted in cities are due machineries such as car, industries, contractions and so on.[6] Carbon emission also has become an important role that threatens the survivability in cities due to the effect of carbon emission. Internal Combustion Engine (ICE) efficiency compare to that of FC based transportation system varies at average of 20% and 85%, respectively, and the potential of FC that creates a reasonable consumption in fuel. In other case the economic viability of ICE is much lower considering to maintenances costs that is required and other mechanical failures in which FC do not account for. We mention heating in as a core importance of FC as core necessity of FC stack up to one megawatt can produce a sufficient heat from exhaustion which intern may be used to heat homes in case of cold condition or showering taps in hotels and other needed luxury places requires high power consumption. The report shows that 1MW of FC stack can produce up 70°C of gas temperature;[7] in the further case a cogeneration process can be applied on even bigger plant to improve FC efficiency at almost 10% addition.

## 2.1. Fuel Cell Background

### 2.1.1. Early development

Fuel Cell is an electrochemical cell that converts chemical energy from fuel to electrical energy. It is important to note that energy cannot be created nor can be destroyed. Therefore, this is the main reason can be considered as free energy. In the early 1838 for the first commercial FC was advanced in 1932.[4] NASA acquired the Fuel Cell in Mid-1960s for satellite usage.

Since few manufacturing industries involved in the technology as it was mostly consisted of American military technology was very expensive. It is not until 2008 Honda car manufacturing released first commercial vehicle powered by fuel cell and companies since then have followed suit including Toyota, Hyundai and Volkswagen and Mercedes Benz at the moment.

With heavy disruption of Li-ion battery technology with mighty of Cobalt and the ingenuity of tesla motor battery mobility in EVs became a focus to many industries. While batteries have created a made believe of fuel cell the question if battery in global scale can meet the expectation[8]. At current moment the recharging time is still long and there is no near future people can expect miracle of battery soon enough. Other important sector of public and heavy transportation and heavy machines that are used in daily basis are needed to conversion right now to renewable at the moment the winner in this field has been classified as FC, things like heavy truck, public buses, train, plane ships. Submarines, concrete mixer and many heavier duty machineries need to be converted to curb carbon emission by 2050.

FC comes in different categories depending to fuel usage here we mention few; Polymer electrolyte fuel cell (PEMFC), Direct Methanol Fuel Cell (DMFC), Alkaline Fuel Cell (AFC), Phosphoric Acid Fuel Cell (PAFC), Molten Carbon Fuel Cell (MCFC), Solid Oxide Fuel Cell (SOFC) and Reversible Fuel Cell (RFC). All mentioned FC work in the same mechanism explained below except the last fuel cell that shows how reversibility helps to store energy in terms of electrolysis process. ZEOLF focuses on two types of fuel Cell PEMFC and DMFC which mostly differ on membrane preparations while modifying PEMFC to work as RFC.

### 2.1.2. Working mechanism of Fuel Cell

As mentioned earlier FC needs fuel to convert chemical energy into electrical energy. Focusing on the key factors, our major focus follows two major fuel sources Hydrogen ($H_2$) and Methanol ($CH_3OH$). As any cell, hydrogen atom reacts with oxygen losing electron that is collected with a load while the ion pass-through a membrane to react with oxygen, on the other side exhausts water as waste.

Here is the chemical reaction----(a)

*Anode reaction*: $H_2 \rightarrow 2H^{+}+2e^{-}$

*Cathode reaction*: $1/2O_2 + 2H^{+}+4e^{-} \rightarrow H_2O$

*Overall cell reaction*: $H_2 + O_2 \rightarrow H_2O$

Compare methanol reaction ------(b)

*Anode reaction*: $CH_3OH + H_2O \rightarrow 6H^{+} + 6e^{-}+CO_2$……. Oxidation

*Cathode reaction*: $3/2O_2 + 6H^{+} +4e^{-} \rightarrow 3H_2O$……………Reduction

*Overall cell reaction*: $CH_3OH + 3/2O_2 \rightarrow 2H_2O +CO_2$…… Redox

In very simple explanation of the equation (a) the process that happens at anode electrode as mentioned above the pure hydrogen is pressured to anode splitting ion and electron. PEM is designed to allow only hydrogen ion to pass through while externally collecting electrons on a load; on the other side oxygen has little time to react by reacting with oxygen to produce water as by product. The same process is repeated on equation (b) after the pure methanol and water mixes anode are absorbed usually both catalysts are made of Pt then loses protons until carbon dioxide is formed. The need of water is to limit energy density of fuel. Similar reaction will be created on cathode but with an exception of carbon dioxide formation hardly noticeable on small scale.

## 3. Project Goal and Specific Objectives

Our research work can be classified in two types such as Fuel Cell development specifically hydrogen Fuel Cells. The objective to develop HFC lies in expanding Rwanda's reach on being sufficient in energy sector specifically for transportation purposes. Thermal energy and solar based energy are what we import. As the world develops in the UN agenda by 2050 on environment regulation through energy sources,[12] we want to be the beacon of key technology suppliers in the field of device production. FC can play a huge role in different economic sector from transport, industrial, security and construction. For the beginning, our work will focus to developing off-grid based fuel cell for rural electrification. The first phase of our research aims to open new market opportunity of energy investment in FC technology, this will boost the potential to outsource material processing needed to make key components of the device.

The approach is based on two development technology such as design and development of HFC by making the prime component catalysts and membranes. At the point we have developed PEM and MEA, and other form of catalysts for trial purposes. The main objective therefore, relies to improve range of transportation which batteries may not offer, reduce weight of power supply to vehicles in order to increase package for better productivity and better efficiency that ICE can not offer. The scope of visualization unto UAV gives us a direct market currently available in Rwanda which in the future will help us develop the product needed in other transportation products such cars, public buses and so on. The case study will determine the potential we will be having to expand on other market opportunity

## 4. Methodology and Approach

### Experiment Procedures

Experiment procedures are divided into three main parts. Two experiments that showed great improvements catalyst and membrane are now completed, the third part of experiment is the grant experiment we are request the funds for.

The experiment is sequenced in the following order:

Using single test is widely used to determine cell performances. ZEOLF will design Membranes and catalysts needed with platinum, nickel and carbon based it will be sandwiched by Nafion based membrane to observe the performance.

The test CCM is fabricated using membranes developed earlier by ZEOLF team members. Before to fabrication of the CCM, membrane samples will be examined for uniformity (no bubbles, debris, fogginess, stretches, cracks, and thickness variations), gas crossover, and flexibility to ensure the membranes are suitable for testing. The CCM is fabricated by spraying a catalyst ink (ionomer, Ni-Pt/C, methanol mixture) on a membrane to achieve a nominal loading of combination with (SA = 800 m2 /g)

Prior to performance evaluation, electrochemical active area (ECA) and H2 crossover (CO) tests are performed on the cell at ambient pressure at room temperature and different temperature with RH percentage. The cathode is the working electrode and the anode, using hydrogen, is the counter as well as the reference electrode. Hydrogen crossover is measured by the limiting current density method with H2 flowing on the anode and nitrogen on the cathode. The cell potential is scanned with different potentiodynamically. Potentiostat and CorrTest software is used to control the potential. The crossover test shows both the level of gas diffusion through the membrane and any electrical short. The level of diffusion is given by the flat portion of the curve and the level of short is calculated from the sloping linear relationship between the applied voltage and the measured current, specifically the measured currents. Shorts must be less than the equivalent of 10mA to be allowable, and to clarify the CV data, the linear slopes resulting from electrical shorts are removed from the data. shows sample CO data and shows sample ECA data as a function of cell temperature. In the CV data, the hydrogen desorption peaks can easily be observed at room temperature. CV and CO tests were repeated before each test condition to provide data in support of the cell analysis.

## 5. Expected Results, Outputs and Outcomes

After obtaining the single cell data we will be able to compute the numeric using the assembly software to determine number of cells required to provide different level of power required and needed to assemble a cell that can be used in UAV. The simulation will also enhance the capacity to develop the final prototype required.

The data will determine fuel efficiency, power density as well as lifecycle for the cell in operation. We are expecting to design a cell with high performances on altitude operation with high and low pressure, 170w light weight between 400-500g with longer lifecycle operation for 3-5years. We also be able to develop Ni-Pt/C for catalyst for commercial use.

### 5.1 Challenges

There are different obstacles that may obscure the progress of our project including, scarcity of primary materials and machines that help to make membranes, catalyst plates. We will run short on advanced material laboratory and electrochemical lab. Our team is not diverse enough to get unto different considerations including pipeline engineering.

To tackle these issues, we are going to acquire semi-finished materials such as fibered membrane then we can cast and do the finishing part, with also catalysts can be outsources and get coated using spray gun. Other laboratory complications our team has partnered with DRD which are finalizing the constructions of advanced laboratory of which a mutual work will enable to have full access. Human resource issue shall be addressed by hiring more scientists in our research group especially females.

## 6. Current Work and Preliminary Results

Current work is developing commercial viable membranes and catalysts. Add to the following we have achieved the making of membranes and catalysts for experimental purposes. To the membrane we have good results that can help us proceed to manufacturing process. Here are the results on the paper published by one of our team member can be found on our website. www.zeolf.com/project in the summary we have shown hydroxide conductivity was increased from 34.3 mS/cm for the pure QPAES membrane to 46.5 mS/cm as for the composite membrane with 0.6 wt%g-$C_3N_4$ nanosheets at 80 °C, resulting from the existence of the covalent interactions between the g-$C_3N_4$ nanosheets and QPAES. Fuel cell performance using QPAES/g-$C_3N_4$-0.6 showed a maximum power density of 68.1 mW/cm$^2$ under a current density of 151.2 mA/cm$^2$ at 60 °C. paper published in 2019 our research specialist Buregeya I. Providence et al.

The development of catalysts was made in thesis research of $NiS_2$.[5] It is important to note that $NiS_2$ Mentioned cannot be commercially viable at the moment as it needs to go through immense tests to be approved however, we can confidently say our research regarding to nanosheets technique proved that metals with nanosheets characteristic can provide a better energy potential as catalysts in FC similar explanation can be found on our official site www.zeolf.com/project. Our findings can be classified as the fabrication of catalysts consists NiS2 that is formed through nanoparticles and nanosheets process. Both tests LSV (Linear sweep voltammetry) and impendence tests, the potentials in the HER were tested vs. the reversible hydrogen electrode (RHE) based on the equation: E(RHE) 1/4 E(SCE) þ 0.279 V in 0.5 M H2SO4 solution. The testing is conducted to an electrochemical workstation with 3 major electrodes three-electrode setup, which includes Pt foil, saturated calomel electrode (SCE) and glassy carbon electrode (3 mm). As a result, the LSV test was 0.23 to 0.245 for NiS2 nanosheet and NiS2 nanoparticles. The impedance Nyquist plots at various potentials from _-100 to _-175 mV.

Publications:https://scholar.google.com/scholar?hl=en&as_sdt=0%2C5&q=buregeya+providence&oq=bure (More of publications regarding membranes)

## 7. Ethical and gender/ inclusivity considerations

Science is broad field with different study discipline that ranges to no limit of capabilities therein. While we are offered the opportunity to execute the project we shall emphasize to competence in engineering experience in physics, mathematics and chemistry to capable women and people with disability who have earned knowledge in mentioned needed areas or related.

We focus to elevate scientific knowledge regardless to nationals, sex or any form of discrimination. While the capabilities to hire more needed researchers ZEOLF will train and equip new members with skills needed to help us in this particular project.

## 8. Implementing Organization and Key Personnel

ZEOLF Technology has the capability to implement the work. Our team has knowledge and expertise since 2018. We have researchers who are already engaging in this type of project. At the moment we are making key components including membranes and grow nanoparticle on fuel cell catalyst. In addition, we are integrating our work with Rwanda Defense to Research and Development (DRD) as our primary users and oversight team. Furthermore, our team leader has members experienced up to PhD level in during research and has experience in research and development.

This project will be implemented by the following team from DRD and external experts:

1. Dr. UWITONZE Nestor (Overall principal investigator)

2. IRAKARAMA JEAN SAUVEUR, CEO, ZEOLF (Principal Investigator-Assembly and production)

3. Dr. BUREGEYA INGABIRE Providence, Chief of Research and Development Department/ZEOLF (Principal Investigator-Experimental works)

4. Dr. KAMANA Emmanuel (Principal Investigator-Materials development)

5. Mss MUKAMURARA Delphine (Research assistant)

- ✓ The Overall Principal Investigator works in Defence Research and Development (DRD) as Electrode expert since 2018. Additionally, he is a member of Rwanda Academy of Sciences (RAS). He received his PhD in Chemistry (Physical Chemistry) from University of Science and Technology of China, in 2018. His special research interests are in Fuel Cells, Batteries and Environmental protection.

- ✓ Principal Investigator-Assembly and production, is B.Sc in Nano material and Technology in the field of material science and has good expierince in material technology with application of catalyst design and through material processing and atomic manipulation. He is the founder of ZEOLF Technologies ltd company dedicated to improve research capabilities in Rwandan scientific society. He has demonstrated good standing level in Research at Herbert Gleiter Institute of Nanoscience in nanoenergy department which awarded him a recommendation of participate in different field of material research in 2019.

- ✓ The Principal Investigator-Experimental is a PhD holder in Environmental Sciences and Engineering/Nanjing University of Science & Technology/China, and has a good experience in membrane technology for new energy applications (fuel cell) and water treatment processes. He has a good record of publications in SCI journals which are more cited by other researchers in the domain related to membrane technology. For this, has been participated in various projects related with renewable energy.A detailed CV is attached.

- ✓ The Principal Investigator-Experimental Materials development is a PhD holder in Applied Chemistry and has good experience in membrane technology applications in various separation processes and fuel cell. He has a good record of publications in SCI journals which are more cited by other researchers in the domain related to membrane technology. For this, has been awarded the Best Prize as Outstanding CAS-TWAS Presidential Fellow (2016) and Excellent International Foreign Fellow (2017) who demonstrated capabilities in doing research in USTC-China according to the Ministry of Education of China.

- ✓ The research assistant is an experienced research in the field of Chemical safety science and engineering at Dalian University of Technology, Liaoning, P.R. China. She is MSc holder and has good background in chemistry especially in material characterizations.

## 9. Project Timeline

| | Year 1 | | Year 2 | | Year 3 | |
|---|---|---|---|---|---|---|
| **Activities** | Q1 | Q2 | Q1 | Q2 | Q3 | Q4 |
| Lab installation | ■ | | | | | |
| Fuel Cell design | | ■ | | | | |
| Kits accessories | | | ■ | | | |
| Test Experiment | | | ■ | ■ | | |
| HFC Prototype | | | | ■ | | |
| Deployment | | | | | ■ | |
| Assembly | | | | | ■ | |
| Data collection | | | | | | ■ |
| Reporting | | | | | | ■ |

(Semester comprises of 6 months (Jan-June); (July -December)

## 10. Project Monitoring and Evaluation

While our project is divided into two separate thus outputting at least two reporting. preliminary work is lab designed project which will use electrochemical work station and computerized pressure detecting system. The final project project shall use fuel stack with in built sensors to detect use of fuel, energy consumption to obtain the device efficiency. As mentioned above the major risk of the projects includes, safety issue such as unexpected Fire which required to be implemented in safe laboratory. In this regard we work with DRD to obtain required laboratory as their electrochemistry has in place all required safe environment. Our team has a prolonged understanding of risks that may occur, due to expertise we have gained, we have trained to contain these kinds of risks.

## 11. References


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## 12. Project Budget

Proposed Budget

State the proposed costs and budget of the project. Also include information on how you intend to manage the budget without tax inclusive.

| | **Description of Work** | **Start and End Dates** |
|---|---|---|
| Phase One | Laboratory equipment supply and Installation | 6 Months Period |
| Phase Two | Fuel Cell lab design, tests, lab simulation design and reporting. | 12 Months Period |
| Phase Three | Prototyping, Computation simulation | 18 month Period |

| | | |
|---|---|---|
| | and real life FC usage with data collection and analysis | |
| | **Total** | **Frw 150,000,000** |

*Estimated date starts from the time this project will begin.*

Funds Distribution

| **RESEARCH BUDGET OF FUEL CELL TECHNOLOGY** | | | | |
|---|---|---|---|---|
| **Description** | **Measurement** | **Quantity** | **U. Price Rfw** | **T. Price Rfw** |
| Membrane material supply and product design | LM | 1 | 9,500,000 | 9,500,000 |
| Catalysis material supply and customizing (Ni-Pt) | Bottle | 50 | 240,000 | 12,000,000 |
| Fuel Cell plates supply | Roll | 20 | 200,000 | 4,000,000 |
| Ethanol/ethanol supply | L | 20 | 100,000 | 2,000,000 |
| N95 Gloves supply | box | 50 | 19,000 | 950,000 |
| Mini UAV for testing Purpose | lump | 1 | 6,300,000 | 6,300,000 |
| 3D printer +acc supply | pc | 1 | 2,000,000 | 2,000,000 |
| CNC Machine + acc supply | pc | 1 | 5,700,000 | 5,700,000 |
| HHO separator supply | pc | 1 | 1,800,000 | 1,800,000 |
| Methanol 99% supply | L | 1000 | 950 | 950,000 |

| | | | | |
|---|---|---|---|---|
| Fuel Assembly + Acc.supply used to assemble fuel cell | pc | 1 | 11,000,000 | 10,000,000 |
| Electronic Sensors supply and install | LM | 1 | 6,500,000 | 6,500,000 |
| Ultrasonic Spraying Machine supply and install | pc | 1 | 17,000,000 | 17,000,000 |
| Muffle Furnace supply | pc | 1 | 8,500,000 | 8,500,000 |
| Membrane tape casting supply and install | pc | 1 | 12,000,000 | 12,000,000 |
| Electrochemical Work station supply and install | pc | 1 | 8,000,000 | 8,000,000 |
| H tank 5000/10000psi supply | pcs | 2 | 1,900,000 | 3,800,000 |
| Water Deionizer | pc | 1 | 3,000,000 | 3,000,000 |
| **TOTAL** | | | | **114,000,000** |
| **SHIPPING** | | | | **9,000,000** |
| **APPLICABLE TAXATION (VAT, Import Tax, Withholding tax, other tax, AU fees)** | | | | **26,500,000** |
| **RWF EXCHANGE (950- 14-JUN-2020)** | | | | **500,000** |
| **TOTAL PRICE IN Rwandan Francs** | | | | **150,000,000** |