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**ESP5402 Group Report**

 Transport Phenomena in Hydrogen Fuel Cells

**Group 6**

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# **1. Executive Summary**

This paper presents the evaluations on two case studies with regards to hydrogen fuel cells (HFCs) as well as the findings of the group’s metacognition and teamwork. Concepts on transport phenomena were used in analysis and mathematical modelling was employed.

# **2. Introduction**

The objective of this project is to evaluate two case studies regarding HFCs – solid oxide fuel cells (SOFCs) used in combined cooling and heating power (CCHP) systems, as well as – and discuss the metacognition and teamwork in the group.

The project was broken down into several stages: metacognition, teamwork, HFC working principle, HFC storage methods, advantages and disadvantages of HFCs, and the two case studies. The group’s metacognition is discussed in Section 3, while teamwork is examined in Section 4. Meanwhile, HFC’s working principle is reviewed in Section 5, and its storage methods are studied in Section 6, before analysing the advantages and disadvantages of HFCs in Section 7. Lastly, the analysis and mathematical modelling for SOFCs in CCHP systems and HFC EVs (Electric Vehicles) are performed in Sections 8 and 9, respectively.

## *2.1 History of HFC*

**1839**

The history of fuel cells began in 1939 when Sir William Robert Grave discovered the generation of electricity and water by combining oxygen and hydrogen in the presence of an electrolyte [1]. However, the energy produced is too subtle to be useful.

**1920-1959**

1920s saw Germany setting the scene for the development of today’s SOFC, but it was not until Francis T Bacon discovered the Bacon cell (Alkaline Fuel Cell) in 1959 that fuel cells became popularised. The Bacon cell uses cheaper nickel electrodes (instead of expensive platinum) with a less corrosive alkaline electrolyte.

**1960**

The advent of the Bacon cell sparked a new revolution in the space industry; it was so successful that it was deployed by NASA in their spacecraft in 1960 as it was light and relatively more compact than the batteries of that time. Furthermore, the by-product of the fuel cell is only water which the astronauts can hydrate themselves with [2].

**1990-2000**

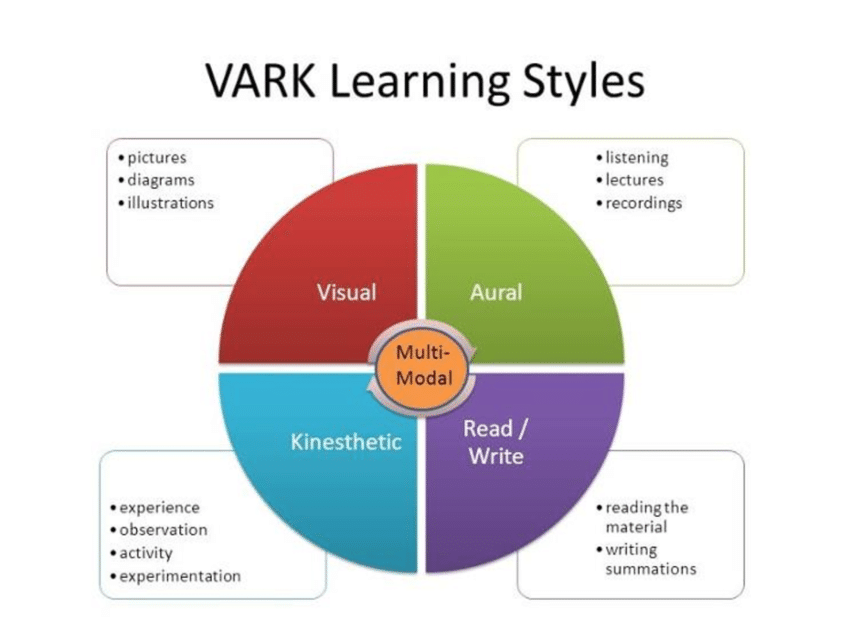
In the 1990s, development of fuel cell technology proliferated as numerous fuel cell-powered transportations emerged, from fuel cell buses to fuel cell cars.

**2013-present**

In 2013, the first commercially produced fuel cell car, “Hyundai Tucson FCEV”, arrived in the market. After which, a series of FCEV sprung to the market in succession such as the Toyota Mirai in 2015 and the Honda Clarity FCV in 2016 [3]. Today, HFC can achieve up to 60% efficiency.

# **3. Metacognition**

Different people have various learning styles. There are four main learning styles under the VARK model: Visual, Auditory, Read and Write, and Kinesthetic.



*Fig. 1: Various VARK learning styles.*

Visual learners are those who prefer observing and analysing visuals, like diagrams and charts, that showcase clear information in order of importance, while auditory learners enjoy learning subject matter that is presented through sound. Similarly, reading and writing learners favour written word and are drawn to text-heavy articles. Lastly, kinesthetic learners find joy in physically acting out events or use all their senses while learning [4]. Figure 1 displays the various VARK learning styles and their respective methods of learning in a chart.

Within the group, Person A is a Visual-Read and Write learner, Person B is an Auditory-Kinesthetic learner, while Person C is Visual-Kinesthetic learner.

Person A is a strong visual learner, as they understand concepts well when illustrations are present. When solving problems, they draw out diagrams and highlights critical information to better analyse the problems at hand. They find auditory learning to be too slow and prefers reading the lecture notes directly due to better control over the learning pace. However, they do not like to write as it does not help them in retaining the knowledge. Moreover, Person A finds kinesthetic learning to be best suited for specific instances such as complex programming tasks, as it can be difficult to trace the algorithm visually and by reading. Due to these, Person A faces many challenges during this project as Person A is unable to thoroughly parse audial feedback from the group. Person A overcomes this by drawing diagrams and typing information into the computer so that Person A can read it again to absorb the information better.

Person B is mainly an Auditory learner as they learn best by listening attentively in class and repeating concepts aloud to help with retention. It is common to find them reciting to themselves when learning, as verbalizing the words helps them understand the concepts better. However, one of Person B’s main weakness is their inability to read texts quickly. They often have to read the same text multiple times aloud before truly grasping the content. This makes learning rather slow for them, making it impossible for them to cram their revision at the very last minute. Thus, to overcome this, Person B puts in consistent effort throughout their learning process, avoiding last minute cramming. Besides being an Auditory learner, Person B also learns kinesthetically. With the new knowledge acquired through auditory learning, Person B must apply the knowledge through hands-on practice questions to deeply internalize the concepts. Therefore, only through both Auditory and Kinesthetic learning can Person B wholly master a new concept.

Despite being a mixture of Visual and Kinesthetic learning, Person C leans more towards the Kinesthetic learning style. Through their learning process, they are able to effectively learn new concepts through applying them to different questions, giving Person C a better appreciation of the problem-solving process more than the answer itself. Whilst doing the problem, visual elements such as graphs and free-body diagrams play a role in aiding their understanding of the constraints within the problem. Some difficulties faced during the research and process of this project were mainly part of the numerous text sources that had to be interpreted. An organization system was created to retain the important information of each source as well as the aid of illustrations and schematic diagrams supplementing the information processed from the texts.

# **4. Teamwork**

Diagram

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*Fig. 2: DiSC model by colour and traits.*

Aside from the difference in learning styles, different people might also have contrasting personalities. One model that aims to characterize people by their personalities is the DiSC model, which stand for the four main behavioural styles outlined in the DiSC model of personalities – D refers to Dominance (red), i stands for Influence (yellow), S is for Steadiness (green), and C is for Conscientiousness (blue) [5]. Figure 2 depicts the DiSC model in a colour wheel.

In the group, Person A is a green, Person B is everything but a blue, and Person C is a yellow and a blue.

Person A tends to be consistent in their work and is easy to work with due to their cooperative nature. They empathise easily with others and listen attentively, providing constructive feedback to the group. Despite being a green, they display hints of other traits when the right moment calls for it. Person A assert their stand when they are confident and of their solution (red) and occasionally, they spark small discussion in the group (yellow) to liven up the atmosphere. When solving problems, Person A is systematic and analytical. However, their empathetic nature makes them afraid to speak up some of their concerns which could be instrumental to the project. Moreover, during the module, Person A actively balances their traits to display more yellow to counter-act with their stronger green, engaging in conversation better so as to feel even more comfortable speaking up.

Being everything but blue, Person B is mostly people-oriented but remains focused on tasks. They are less mindful on the accuracy of their results, instead they place more emphasis on their group mates’ opinions, embodying the spirit of a green. Despite being playful and adventurous at times (yellow), Person B is also able to be dominant when needed (red), guiding their team back to the task at hand. Although having the attributes of three personalities gives them an advantage when interacting with others, Person B’s main shortcoming is their lack of accuracy and credibility regarding their individual work (blue traits). Thus, by working in a group, Person B is able to overcome this by discussing the final results with their group.

Having a mixture of both yellow and blue traits, Person C is rather outspoken in group discussions, often with the goal of ensuring both the presentation content and styles are of the highest standards. They ensure that their peers understand their thought processes and intentions before executing the task. Person C is also not afraid to share their expertise. For example, they guided the group with their design experiences on creating “neat” slides and relevant knowledge from the past modules they have completed.

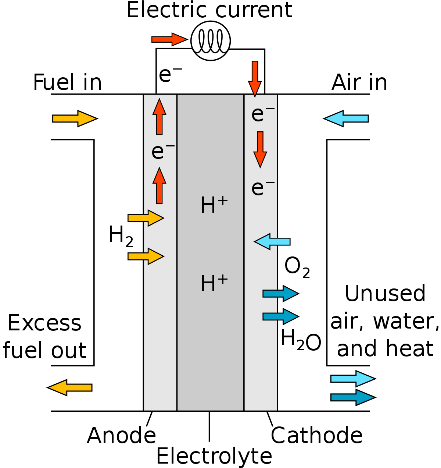
In overall, the group worked well together as there were minimal conflicts arising from clashing personalities. Moreover, when disagreements emerged, the group was able to maneuver through them with the green and yellow characteristics in them. Thus, the group mostly had amicable and productive group discussions.

Moreover, there was sufficient time for this project as all members were able to contribute adequately and deliver quality work. Acknowledging each person’s DiSC and VARK profiles, project tasks were split among the group accordingly. Firstly, as Person A is a strong reader who is able to digest large amount of information quickly, Person A was tasked to perform research on the technical areas of HFCs. Secondly, Person B’s red traits tend to steer and direct the group. Since Person C had prior experience with report writing and slides presentation, Person C tend to verify the details to ensure work quality. To be precise, Jevan prepared the history, trends, and working principles of HFCs; Darren presented the storage methods of hydrogen; while Wei Wen analysed the advantages and disadvantages, as well as the future outlook of HFCs. Lastly, the group collaborated on the investigation and mathematical modeling of the two case studies.

# **5. HFC Working Principle**

HFC employs an electrochemical reaction to produce electricity. This section describes the components of a typical HFC and explains the electrochemical process driving the HFC.

## *5.1 Electrochemical Process*



*Fig.3: Electrochemical Process of HFC.*

In contrast to electrolysis where electrical energy is consumed to produce hydrogen, HFCs split up hydrogen molecules to produce electricity. The chemical reactions at the anode and cathode are illustrated in Figure 3.

|  |  |
| --- | --- |
|  | (1) |
|  | (2) |

Equations 1 and 2 show the chemical reactions at the anode and cathode, respectively.

At the anode, hydrogen gas reacts with the electrolyte and is split up into ions and electrons. The resulting ions flow to the cathode through the electrolyte while the resulting electrons flows to the cathode through the load, providing electricity.

At the cathode, ions in the electrolyte react with oxygen and the resulting electrons from the reaction at the anode to produce water.

## *5.2 Components*

There are various types of HFCs which are usually categorised by the electrolyte used. Proton Exchange Membrane Fuel Cell (PEMFC) is a type of HFC that employs a semi-permeable membrane as the electrolyte.

Diagram

Description automatically generated*Fig.4: Components of PEMFC.*

The following describes the typical components of a typical PEMFC as illustrated in Figure 4:

1. Fuel Inlets
2. Flow field channel
3. Gas Diffusion Layers
4. MEA

**Fuel Inlets**

Fuel inlets are the entry points for the fuels. Hydrogen and oxygen gas are supplied as fuel for the anode and cathode side respectively.

**Flow Field Channels**

As the fuels are being supplied, they flow through paths in the flow field plates known as the flow field channels that is exposed to the gas diffusion layer. Reactants from the flow field channel diffuse to their respective catalyst layers (anode and cathode).

The design of flow field channels is responsible for the reactants flow rates, pressure, heat and water generation, thus affecting the power of the fuel cell.

**Gas Diffusion Layer**

Besides providing a pathway for the reactant to flow to the catalyst layers, gas diffusion layers prevent flooding by removing water outside the catalyst layers. Additionally, it facilitates the heat transfer during cell operations.

**Membrane Electrode Assembly (MEA)**

The MEA consists of 2 components which are the catalyst layers and the PEM. The catalysts layers serve as the anode and the cathode and are typically made of platinum due to its good catalytic activity. The electrochemical reactions occur at the catalyst layers with their respective chemical reactions described in Section 5.1.

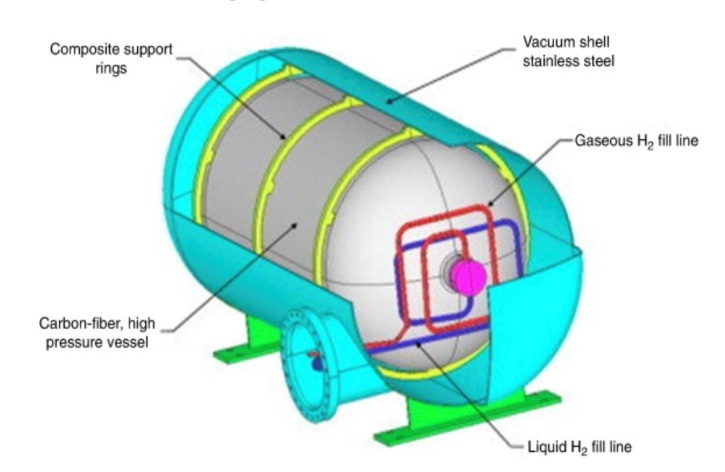
PEM are specially treated material that serves as a filter that only allows protons and hydrogen ions to traverse from the anode to the cathode while preventing the electrons removed from the hydrogen atoms from passing through as this will cause a “short circuit”. In the electrochemical process, it acts as the electrolyte.

# **6. Hydrogen Fuel Storage Methods**

Four distinct hydrogen fuel storage methods are: cryo-compressed hydrogen, liquid organic hydrogen carriers, metal hydrides, and chemical hydrides. These methods will be analysed based on its technical detail, transportation, and long-term economic viability of hydrogen storage.

## *6.1 Cryo-Compressed Hydrogen*

Cryo-compressed hydrogen combines elements of cryogenic and compressed hydrogen [6]. A typical cryo-compressed storage tank contains both a carbon fiber pressure vessel and vacuum shell that is rigid to contain the high pressure and the cryogenic temperatures of hydrogen. Figure 5 below shows a basic schematic of a conventional cryo-compressed hydrogen storage tank [6].



*Fig. 5: Cryo-compressed hydrogen tank schematic.*

Safety is improved as a lower volume and pressure can be achieved in the storage tank for a unit mass of hydrogen compared to that of compressed hydrogen, and there will be lower boil-off losses which occur for conventional cryogenic hydrogen storage [6]. Furthermore, there is an overall cost saving advantage to cryo-compressed storage as a lower cost incurred for carbon fiber implementations in the cryo-compressed vessels as well as lesser implementations to lower the heat transfer from the atmosphere into the tank. Thus, the cost of implementing cryo-compressed storage is relatively lower due to these factors.

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## *6.2 Liquid Organic Hydrogen Carriers*

Liquid Organic Hydrogen Carriers (LOHCs) is a form of chemical hydrogen storage solution that is pioneered by Hydrogenious Technologies GmbH in Germany [7]. It consists of an oil-like organic compound that is in liquid state which undergoes hydrogenation and dehydrogenation to capture and release hydrogen [8].

Diagram

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*Fig. 6: LOHC hydrogenation & dehydrogenation cycle.*

Based on this, the hydrogen bound within the compound is unreactive, creating a safe non-flammable and non-explosive solution, improving the standards of hydrogen storage and transportation [7]. Figure 6 above highlights the cycle of hydrogenation and dehydrogenation of LOHCs and the conditions when hydrogen is converted between mediums [7].

The cost estimations of the LOHC compounds are approximately 5 Euros per kilogram, allowing this to be a scalable solution for different industrial applications of hydrogen fuel [7]. Compared to cryo-compressed storage, LOHCs boast a larger storage efficiency, in which it can yield approximately 6.23% [7]. LOHCs is also a sustainable option that produces green hydrogen as the technology can be integrated with renewable power sources for critical processes [8].

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## *6.3 Metal Hydrides*

Most formed between metal/metalloid cations and hydrogen anions. Hydrogen can be stored in a low-pressure environment with the benefit of high-power density by volume of hydride [9].

Graphical user interface

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*Fig. 7: Hy2green metal hydrides storage conditions & size.*

Figure 7 above shows the different storage conditions achieved through using metal hydrides as compared to conventional gas tanks and high-pressure gas tanks [9].

Based on this, the metal hydride storage solution is less energy intensive than convectional solutions such as compressed gas storage as hydrogen compression is omitted from the hydrogen storage process [10]. Similar to LOHCs, metal hydrides are reversible in storing and releasing hydrogen, allowing for the metal to be recycled in the long-term.

The hydrogen within the hydrides is bonded to the metal, improving safety standards and the ability to store hydrogen fuel for long durations as metal hydrides require activation energy in specific conditions depending on the metal to extract the hydrogen content [10]. Furthermore, the use of powdered metal increases the storage capacity for hydrogen from the larger surface area that can react with hydrogen [9].

## *6.4 Chemical Hydrides*

Chemical hydrides consist of bonds formed between non-metal cations and hydrogen. The reactions to extract hydrogen mainly include chemical hydrides, water and alcohols [11]. Chemical hydrides are mostly in fluid state in atmospheric conditions. Based on this, chemical hydrides can be easily transported using already-implemented transportation infrastructures such as natural gas pipelines.

Table

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*Fig. 8: Period 2 & 3 chemical hydrides* [12]*.*

However, chemical hydride reactions are irreversible and toxic by-products are created in the combustion of chemical hydrides [11]. Figure 8 above show a small array of chemical hydrides made from Period 2 and 3 elements.

Based on the composition of the compounds above, the chemical hydrides and by-products can vary between acidic and basic properties, potentially damaging equipment used to extract hydrogen.

In comparison to metal hydrides, chemical hydrides are considered to be advantageous as a short-term solution. Given a lower mass, chemical hydrides are able to yield a higher hydrogen content and a more feasible option for hydrogen distribution logistically [13]. However, the toxic by-products created can be considered non-compliant with certain government regulations tackling pollution in some countries and creating a waste management problem for the industries utilizing chemical hydrides [11]. Furthermore, chemical hydrides are considered to be more reactive than metal hydrides due to the nature of the compounds, thus having a disadvantage in safety during transportation [13].

# **7. Advantages & Disadvantages of HFC**

Diving deep into the analysis of HFCs, their advantages and disadvantages must be evaluated.

## *7.1 Advantages of HFC*

There are several key advantages of using HFCs: it is a clean energy, it is more efficient than many other energy sources, and it refuels very quickly.

Firstly, HFC technology is clean as its only by-product during electrochemistry is water vapour, which is a less harmful greenhouse gas (GHG) [14]. Referring to Equation 2 in Section 5.1, it is proven that only water vapour, is produced during electrochemistry of HFCs. On the other hand, the combustion of fossil fuels generates large amounts of carbon dioxide along with water vapour [15]. Since carbon dioxide is a harmful GHG that traps heat in the Earth’s atmosphere and hence aggravates global warming, by not producing it, HFCs are considered to be a clean energy.

However, the green credential of HFCs is often undermined by the alternative methods of extracting hydrogen for HFC electrochemistry. There are four main types of hydrogen used in the electrolysis of HFCs – green, blue, grey, and brown. Although it is true that green hydrogen produces only water vapour during electrochemistry, the other colours of hydrogen generate other by-products in the process.

Green hydrogen is mostly extracted using electrolysers that use electricity from renewable sources. Thus, green hydrogen does not emit any GHGs. On the contrary, blue hydrogen is generated through steam reforming, which separates hydrogen from natural gas, producing GHGs. However, carbon capture and storage technologies store those GHGs, preventing emission to the atmosphere. Similarly, grey hydrogen is also extracted from natural gas using steam reforming, but the GHGs produced are emitted into the atmosphere without any carbon capturing technologies. Lastly, brown hydrogen, made from brown coal, are produced via gasification by converting carbon-rich materials into hydrogen and carbon dioxide, releasing GHGs to the atmosphere [16].

Therefore, by using other reactants like natural gas and brown coal to create hydrogen, the electrochemistry of HFCs is essentially not as clean as it is alleged to be. Furthermore, since hydrogen of other colours are almost 3 times less costly than green hydrogen, green hydrogen is less commonly used to produce HFCs [17]. Thus, in reality, GHGs are produced during the electrochemistry of HFCs.

Secondly, HFC technology provides high density source of energy with good efficiency in generating electricity. For instance, PEMFCs have a high efficiency of electricity generation of up to 60%, while molten carbonate fuel cells have a fairly high efficiency of about 50-60% [18]. On the flipside, conventional combustion power plants generate electricity at around 30-40% efficiency [19], whereas solar PV cells do so at 15-20% [20]. This is due to the high gravimetric energy density of approximately 120 MJ/kg, which is 3 times more than diesel, that hydrogen possesses [21]. This means that HFCs have large amounts of energy available per unit mass [22], making them highly efficient.

However, HFCs are less efficient when used in electric vehicles (EVs), primarily due to the phenomena of energy vector transition. When HFCs are used in EVs, large amounts of energy are lost during the energy generation, compression, transportation, and conversion in the vehicle. This accounts for approximately 65% of energy losses in the HFC of fuel cell EVs [23], making HFC EVs to be only about 25-35% efficient [24].

Lastly, HFCs refuel very quickly, to the extent that the duration of refueling fuel cell EVs is alike conventional cars – around three to five minutes [25]. This refueling duration is also much shorter than the charging of battery EVs, which takes thirty minutes to several hours [26]. Additionally, EVs powered by HFCs have a longer range than battery EVs. While most battery EVs can travel between 100 to 200 miles on a single charge, HFC EVs can go up to 300 miles [27]. This is due to hydrogen’s high gravimetric energy density [28], allowing the fuel cell EVs to store a lot more energy per unit mass, achieving long distances.

## *7.2 Disadvantages of HFC*

Despite the many advantages of HFCs, the adoption of HFCs is rather sluggish as it possesses various disadvantages, such as its high costs and storage issues.

Firstly, HFC technology is extremely expensive. HFCs’ costs for fuel, infrastructure, storage, and transportation are very high.

Chart, waterfall chart

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*Fig. 9: Fuel cost per mile of EVs* [29]*.*

From Figure 9, it is observed that the fuel cost of fuel cell EVs is more than two times of that for internal combustion engine vehicles and almost ten times more than that of battery EVs. Additionally, the high cost of HFCs is also a result of the complexity of extraction and the expensive materials used in the electrochemistry of HFCs [30]. For instance, the platinum used as catalyst in PEMFCs is very costly as it is the most valued precious metal [31]. This drives up the cost of HFC production, discouraging governments and individuals from wanting to adopt them.

Secondly, it is difficult to store hydrogen, causing the lack of HFC adoption. Since hydrogen is highly flammable, it is crucial to store it with proper procedures to prevent catastrophe. Hydrogen is the simplest and lightest element, lighter than helium.

Timeline

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*Fig. 10: Gravimetric and volumetric energy density of various transportation fuels* [32]*.*

Figure 10 shows that hydrogen has a very low volumetric energy density, which is three times less than natural gas and 2700 times less than gasoline. As a result, hydrogen must be made more energy dense through compression for storage to be economically feasible for transportation [33]. Thus, the many issues surrounding the storage of hydrogen makes HFCs undesirable.

# **8. Case Study I: SOFCs in CCHP Systems**

## *8.1 Introduction to Solid Oxide Fuel Cells*

Solid Oxide Fuel Cells (SOFC) are a variant of HFCs which produce power through the oxidation of hydrogen fuel. Compared to other fuel cells, SOFCs contain a solid ceramic or oxide-based electrolyte that requires preheating to a molten state, thus resulting in a higher operating temperature for SOFCs than other HFCs.

## *8.2 SOFCs in CCHP Systems*

Since SOFCs have the potential to work with flexible fuels and achieve higher yields of electrical efficiency [34], they are considered as a commercialized solution in various sectors, like in distributed energy systems for buildings and infrastructures. SOFCs exhibit feasibility to be incorporated with other energy conversion systems – such as gas turbine [35], chemical processes [36], and absorption chillers [37] – to increase the total efficiency of the system as they operate at high temperatures.

## *8.3 Dimensional Analysis*

For a given SOFC with reactants A and B, and products C and D:

|  |  |
| --- | --- |
|  | (3) |

The Nernst voltage, is denoted as:

|  |  |
| --- | --- |
|  | (4) |

Where is the standard voltage of the SOFC evaluated at 1 atm pressure for all components, while is the Nernst voltage loss caused by the difference in concentration of reactants at equilibrium potential and that in the flow channel [38]. Also, the subscripts of the reacting species represent their respective thermodynamic activity coefficients.

Expressing the thermodynamic activities in terms of partial pressures, evaluated at the particular electrode where the reaction involving the species occurs:

|  |  |
| --- | --- |
|  | (5) |

At constant temperature, Equation 4 produces an equation that links voltage to pressure, to the change in volume:

|  |  |
| --- | --- |
|  | (6) |

Usually, only gas species produce a significant volume change. Assuming ideal gas law applies, Equation 6 can be rewritten as:

|  |  |
| --- | --- |
|  | (7) |

Where represents the change in total number of moles of gas upon reaction. Hence, pressure turns out to have a minimal effect on Nernst voltage, :

|  |  |
| --- | --- |
|  | (8) |

Where is the reaction quotient of the cell reaction, which is dimensionless.

Thus, it is valid that:

|  |  |
| --- | --- |
|  | (9) |

Dimensions of the dependent variable, E is as follows:

|  |  |
| --- | --- |
|  | (10) |

Dimensions of the independent variables are as follow:

|  |  |
| --- | --- |
|  | (11) |
|  | (12) |
|  | (13) |

Comparing power of kg in equations 9, 10 and 11,

|  |  |
| --- | --- |
|  | (14) |

Comparing power of K in equations 9, 10, 11,

|  |  |
| --- | --- |
|  | (15) |

Comparing power of A in equations 9, 10, 13,

|  |  |
| --- | --- |
|  | (16) |

Substituting in equations 14, 15 and 16 back to equation 9,

|  |  |
| --- | --- |
|  | (17) |

Since R and F are constants, the voltage output of a HFC is mainly dependent on temperature.

As mentioned above in Section 8.2, SOFC operates at higher operating temperatures relative to other forms of HFC, therefore it is able to achieve better efficiencies.

## *8.4 Scaling Analysis*

Scaling analysis is performed to estimate the Nernst voltage loss, .

As proven in Section 8.3 equation 9:

For the SOFC used in the case study’s CCHP system [39]:

|  |  |
| --- | --- |
| R | 8.314 |
| F | 96 485 |
| T | 910 |
|  | 0.938 V |

*Table 1: Parameters of case study’s CCHP system.*

Using the parameters in Table 1, equation 9 becomes:

|  |  |
| --- | --- |
|  |  |
|  |  |
|  | (18) |

Hence, using the value found in equation 18 for the equation (equation 4):

|  |  |
| --- | --- |
|  |  |
|  |  |
|  | (19) |

Estimated is 1.127V while actual is 0.938V.

The actual stack voltage output is given as:

|  |  |
| --- | --- |
|  | (20) |
|  | (21) |

Where voltage losses in the SOFC system are: (total activation loss), (total concentration loss), and (total ohmic loss).

Since the activation voltage loss, in SOFCs is negligible as compared to other fuel cells due to its high operating temperature, SOFCs are ideal in such CCHP systems.

Furthermore, the efficiency of the SOFCs is relatively high, as calculated by:

|  |  |
| --- | --- |
|  |  |
|  | (22) |

As a result of the SOFC’s relatively high efficiency, SOFC is selected to be employed in such CCHP systems.

# **9. Case Study 2: PEMFCs in HFC EVs**

PEMFCs are typically the preferred choice for HFC EVs due to their relatively fast start up time (SOFC takes a few hours to preheat to their operating temperatures). They operate at a relatively lower temperature range of 60C to 80C (high temperature PEMFCs also exists with an operating temperature of approximately 110C) whereby optimal efficiency is achieved, beyond which, humidity in the PEM will be significantly affected and the protons mobility in the medium will start to decrease.

This case study investigates the relationship between the power output of a fuel cell stack used in HFC EVs such as the Toyota Mirai and its weight.

## *9.1 Toyota Mirai*

The Toyota Mirai is a HFC EV (Hydrogen Fuel Cell Electric Vehicle) which has several main components in the drive train assembly as listed in Table 2 below [40]:

|  |  |
| --- | --- |
| Motor | Maximum Output: 113 kW  Maximum Torque: 335 Nm |
| Hydrogen Tank | Working Pressure: 700 bar  Tank Storage Density: 5.7 wt% |
| Fuel Cell Stack | Volume Power Density: 3.1 kW/L  Maximum Output: 114 kW |
| Fuel Cell Boost Converter | Maximum Boost Voltage (Fuel Cell Stack): 650 V |

*Table 2: Specifications of Toyota Mirai.*

The drive train assembly of the Toyota Mirai requires oxygen from the air inflow and hydrogen supplied from the storage tank. The reaction within the fuel cell stack generates electricity to supply both the motor and the battery. The reactions within the fuel cell stack in turn creates water vapor as a by-product as compared to greenhouse gases in internal combustion engine vehicles.

Specification for the Toyota Mirai’s fuel cell stack is described in Table 3 below [40]:

|  |  |
| --- | --- |
| κ | 2.028 |
|  | 56 |
|  | 8.378 |
|  | 114 |

*Table 3: Parameters for Toyota Mirai’s fuel cell stack.*

## *9.2 Rule of Thumb*

It is found that:

|  |  |
| --- | --- |
|  | (23) |

Where is power output of the HFC stack, is the stack weight, is the volumetric energy density per cell in the cell stack, and is the design factor that is a constant specific to the HFC system (varies only with materials and mechanical construction of the stack) [17].

From Equation 23:

|  |  |
| --- | --- |
|  | (24) |

Thus:

|  |  |
| --- | --- |
|  |  |
|  |  |
|  | (25) |

Therefore, a rule of thumb for the power output of HFCs in HFC EVs is derived such that:

|  |  |
| --- | --- |
|  | (26) |

Using this rule of thumb, changes in power output is estimated for small changes in from = 56kg.

|  |  |  |  |
| --- | --- | --- | --- |
| (%) | Actual    (%) | Rule of Thumb    (%) | Absolute Error in  (%) |
| 1 | 1 | 1 | 0 |
| 10 | 10 | 10 | 0 |
| 30 | 30 | 30 | 0 |
| 100 | 100 | 100 | 0 |

*Table 3: Comparison of actual values with values derived using rule of thumb for changes in W.*

From table 3. since absolute error in is 0% for any change in , the rule of thumb is always valid.

To verify the rule of thumb with other variables affecting , abstracting from Equation 23:

|  |  |
| --- | --- |
|  | (27) |

Applying the rule of thumb:

|  |  |
| --- | --- |
|  | (28) |

Using this rule of thumb, changes in power output is estimated for small changes in from = 8.378 kW/m3.

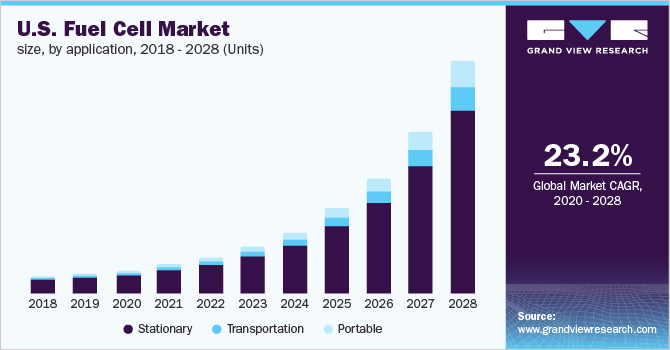
|  |  |  |  |
| --- | --- | --- | --- |
| (%) | Actual    (%) | Rule of Thumb    (%) | Absolute Error in  (%) |
| 1 | 1 | 1 | 0 |
| 10 | 10 | 10 | 0 |
| 30 | 30 | 30 | 0 |
| 100 | 100 | 100 | 0 |

*Table 4: Comparison of actual values with values derived using rule of thumb for changes in .*

From table 4, since absolute error in is 0% for any change in , the rule of thumb is always valid.

# **10. Conclusion**

HFCs could offer a fully renewable and clean power source for stationary and mobile applications in the near future. As fossil fuels run out, hydrogen could be a key solution for the global energy needs.



*Fig. 11: U.S. fuel cell market from 2018 to 2028* [41]*.*

From Figure 11, it is observed that the global fuel cell market size is expected to grow at a compound annual growth rate of 23.2% from 2020 to 2028. Increasing demand for unconventional energy sources, growing private-public partnerships, and reduced environmental impact are several factors anticipated to propel the demand.

However, there are still a few challenges to overcome to realise the full potential of hydrogen as a key enabler for a future decarbonised energy system. There is a need to scale up green hydrogen production and fuel cell manufacture. Further technological advances to lower the associated costs of extraction, storage and transportation are envisaged [42], along with further investment in the infrastructure to support it. For example, researchers have innovated new fuel cell designs that utlilise non-precious metal catalysts, like the HOR electrocatalysts, making HFC manufacturing cheaper and more efficient. The use of nanotechnology in HFCs also improves its efficiency, safety, and affordability [43]. Therefore, with further in-depth research and relevant government support, HFCs could become a key solution for the global energy needs in the near future.

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# **12. Annex**

## *12.1 References*

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