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THE COMPETITIVE ADVANTAGES OF HYDROGEN FUEL CELLS

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Chapter 1: Introduction	*1,814*
Chapter 2: Literature Review	*4,648*
Chapter 3: Methodology	*3,671*
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Summary / Overview

This study consists of five sections: introduction, literature review, methodology, findings, discussion, conclusion, and recommendations. The five sections are closely related, borrowing from the previous section to build on arguments and provide supporting evidence. The introduction includes the background information, the problem statement, the significance, the research question, the aim, and the objectives. The literature review shows what has been done, the inconsistencies and gaps identified, and suggests the need for a study. The methodology shows how the researcher realises the objectives. Similarly, the findings present what the researcher discovered from the secondary data sources. The discussion section integrates the findings with the literature reviewed to demonstrate the competitiveness of hydrogen fuel cells.

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The Competitive Advantages of Hydrogen Fuel Cells

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1 CHAPTER ONE: Introduction

1.2 INTRODUCTION

This study sought to investigate the competitiveness of hydrogen fuel cells. It was driven by the researcher's interest in the subject and the growing need for energy security. The study combines qualitative and quantitative data from secondary sources like research articles, government publications, reports, and other academic sources. The data was analysed using thematic, descriptive statistics, cross-tabulation, trend analysis, and computer software to analyse the secondary data. The findings are presented in the results sections of this study. The methodology was appropriate to the research context; thus, the results can be generalised, and findings can be used to inform policy decisions and future primary studies on the subject.

1.3 BACKGROUND INFORMATION

The debate on the ability of hydrogen fuel cells to power future energy needs continues to raise mixed reactions. On the contrary, hydrogen fuel cells are promoted as clean energy sources with low carbon footprints. This is further driven by climate change, the ever-rising cost of fossil fuels, and the desire for sustainable development. Likewise, nations are formulating emission guidelines focused on reducing greenhouse gases from the transport sector, one of the major pollutants (Hartman et al., 2013). However, concerns over technical aspects hinder hydrogen fuel cell uptake. For instance, storage, cost of production, available infrastructure, and fuel efficiency continue to affect the hydrogen economy, as studies show that hydrogen use as an energy source still faces significant challenges (Sdanghi et al., 2019). Despite current limitations, hydrogen remains an environmentally friendly energy source to power future energy needs and address pollution caused by non-renewable energy sources. This study seeks to investigate the competitive advantage of hydrogen fuel cells.

1.4 ENERGY AND SUSTAINABLE DEVELOPMENT

Climate change, diminishing energy resources, volatile global prices, and health-related issues continue to dominate the debate on non-renewable energy sources like fossil fuels. For instance, a study by Vohra et al. (2021) shows that fossil fuel contributes to environmental pollution and health-related issues when people inhale small particulate matter from combustion engines. The study argues that burning fossil fuels like petrol and diesel produces airborne particulate matter and greenhouse gases, contributing to mortality and diseases. Russell et al. (2022) supports this argument noting that fine particulate matter contributes to ill health, particularly cardiopulmonary diseases. Russell et al. (2022) argue that air pollution is the most significant environmental threat to health. To curb the adverse effects of air pollution on human health, the world health organisation frequently updates air quality guidelines to regulate or lower the annual mean particulate matter exposure. The renewed interest in renewable energy like hydrogen has also led to new strategy papers and roadmaps to facilitate the transition (Love et al., 2022). Through the strategy and policy papers, nations are trying to reduce greenhouse gases to address environmental pollution, health-related issues and concerns over diminishing natural resources like fossil fuels. The developed economies face the biggest challenge of reducing their emissions since they contribute 78% of the greenhouse gases (Ibrahim and Ajide, 2021). Other stakeholders are also striving to address pollution caused by non-renewable energy sources. For example, the Hydrogen Council (2020) argues that continued production of carbon at the current rates means only ten years remain in the global budget before reaching the one-and-a-half-degree Celsius threshold, thus the need for immediate action. The limitations on greenhouse gas emissions aim at realising climate neutrality and zero emissions by 2050 (Love et al., 2022). These targets mean that nations must adopt sustainable energy sources that will continue driving development while taking care of the environment.

CHAPTER ONE

The quest for economic growth while maintaining sustainable global warming limits of less than 2 degrees Celsius and the quest for a one-and-a-half-degree Celsius limit continues to elude the world as non-renewable energy sources play a critical role are major pollutants (Ibrahim and Ajide, 2021). Countries are now focusing on sustainable development to continue developing while using resources sustainably. Sustainable development focuses on the economic, social, and environmental aspects to ensure that countries develop while maintaining the natural built and social systems. The drive for sustainable development has resulted in current calls to address growth and environmental conflicts that can threaten the atmospheric ecosystem. According to the Hydrogen Council (2020), governments are instituting ambitious decarbonisation targets promising to meet net zero carbon in 2050. For example, 25 States formed a climate alliance aimed at reducing greenhouse gases emission by 26%-28% in 2025 below the 2005 levels. The UK is also determined to lower its greenhouse gas emission with its ambitious programme aiming to realise 95% of its energy from low carbon by 2030. The programmes aim to expand investment in renewable energy sources like solar, wind, and hydrogen (GOV.UK, 2022). Similarly, China is committed to its climate policy goals of realising peak emissions in 2030 and targeting 20% primary energy demand from renewable sources while continuing to invest in sustainable technologies (Hydrogen Council). Such ambitious targets present new opportunities in the renewable energy sector as investors seek new opportunities by providing clean energy sources that will ensure sustainable development.

Hydrogen fuel cells can provide clean energy to meet the increasing demand driven by globalisation, diminishing fossil fuel reserves, industrialisation, and increased usage. Hydrogen usage is also growing as new technologies facilitate production, storage, transport, and use across sectors (Love et al., 2022). As the demand increase, investors are looking for new technologies that produce quality hydrogen at a cheaper cost. Similarly, there is an increase in the production of renewable hydrogen from renewable energy sources like wind and solar, whose production cost has declined by 80% in the past decade resulting in a 60% decline in the production cost of renewable hydrogen (Hydrogen Council, 2020). As this trend continues, renewable hydrogen production will report further cost reductions. This will further be necessitated by modern technologies that will boost the hydrogen economy. Increased attention on the hydrogen economy will drive investment in the sector, creating new export markets and opportunities in hydrogen production, storage, and distribution. Further, it will facilitate job creation, enable countries to be fuel self-sufficient, and reduce overreliance on fossil fuels (Love et al., 2022). Additionally, it will enable countries with excess electricity to generate hydrogen through electrolysis, thus contributing to economic growth.

1.5 THE POTENTIAL OF HYDROGEN FUEL CELLS

Hydrogen remains the most abundant element despite current challenges with its extraction. It is an abundant and renewable energy source with the potential to meet current and future heat and power needs in different sectors. Hydrogen can be converted to different energy forms using high-efficiency conversion processes (Felseghi et al., 2019). According to Nazir et al. (2020), hydrogen is broadly used in industry, where consumption of the pure form in 2019 was about 70 million tons. Similarly, the production market for industrial use in 2017 was estimated at $115 billion and is expected to expand to $155 billion in 2022 (Nazir et al., 2020). Hydrogen fuel cells are a clean energy source with no contaminants. Further, energy efficiency remains higher than fossil fuels. Felseghi et al. (2019) note that hydrogen is a non-polluting energy carrier since it does not contribute to global warming when produced using renewable sources like wind and solar. Similarly, it has wide applications like transport, decentralised systems, portable, and stationery. Currently, hydrogen is highly used in the chemical industry and provides new opportunities as the world moves towards zero emissions. According to the Hydrogen Council (2020), there is a sudden increase in interest in hydrogen as an alternative energy source driven by the realisation that it can enable the world to meet its climate objective. Hydrogen's ability to decarbonise different sectors previously thought impossible is driving the current efforts toward the hydrogen economy. Likewise, hydrogen can be produced from various sources, thus enabling countries to be self-sufficient and reducing their overreliance on other nations. For instance, a global increase in oil prices adversely affects the global economy, yet this could not be the case if nations were fuel self-sufficient.

Despite the benefits, there are challenges with hydrogen extraction, initial costs required, inadequate regulations, storage, and supporting infrastructure. An article published in Forbes magazine argued that ten years ago, hydrogen was one of the contenders to replace fossil fuel, with the other being electricity. However, electric vehicles took longer to recharge; thus, hydrogen was likely to be the preferred option because of the fast recharging and high fuel efficiency. However, a decade later, battery electric cars seem to dominate as the preferred environmentally friendly transportation means (Morris, 2022). The articles show that by the end of 2019, 7500 hydrogen cars were sold globally, yet by 2018, more than five million electric vehicles were sold globally. Battery electric vehicles reported 55% annual growth rates and, by May 2020, accounted for 4.3% of the overall car market (Morris, 2022). However, growth in hydrogen-fuelled cars remains low, as shown in an IDTechEx report, which examined the production and sales of fuel-cell electric vehicles by Toyota, Honda, and Hyundai. Toyota and Hyundai reported increased sales, while Honda ceased producing the cars citing weak demand and inadequate hydrogen infrastructure as the cause for their decision. Fuel cells electric vehicles from Toyota and Hyundai have been growing since 2017, when total sales were 2741 to 15538 in 2021 (Wyatt, 2022). The increasing sales were driven by government and company interventions which substantially reduced the cost of acquiring and maintaining hydrogen-fuelled electric cars. Hydrogen presents new opportunities for environmentally friendly fuel cars but still faces other challenges that can reduce its competitiveness compared to other energy sources like battery electric cars and fossil fuel-propelled cars. This study seeks to understand this subject by examining the competitive advantage of fuel cells, thus becoming the future energy source for the transport sector.

1.6 SIGNIFICANCE

The hydrogen transition summit held alongside COP27 in November 2022 brought together regulators, investors, and decision-makers to discuss how to make the hydrogen economy competitive. The summit was organised at a crucial moment when world leaders discussed reducing carbon emissions and other greenhouse gas emissions (Hydrogen Transition Summit, 2022). There is a consensus that nations must limit global warming, with decision-makers, scientists, and leaders grappling with the best intervention to overcome the unprecedented challenge of decarbonisation. For instance, a study by Vohra et al. (2021) established that one in five people die globally from air pollution caused by fossil fuels. The study shows that the number of deaths is more than twice the estimates showing the need for renewable energy sources. Hydrogen fuel cells can provide an alternative to fossil fuels since it is environmentally friendly and has better fuel efficiency. A study on its competitiveness can provide new insight for informing policies, addressing current concerns on the hydrogen economy, and helping inform decisions. Similarly, the study will provide relevant information that investors can use to make investment decisions. For example, a researcher can identify current shortcomings and opportunities that make business sense and evaluate the returns on investment before investing. The findings from this study will also inform decisions on current investment by demonstrating whether companies should continue investing in fuel-cell cars or other infrastructures. The study will also provide valuable information for researchers and students interested in the subject. Likewise, it presents possible gaps and inconsistencies, thus informing future studies.

1.7 AIM

This study investigates the competitive advantages of hydrogen fuel cells.

1.8 OBJECTIVES

- To identify factors impeding hydrogen fuel cells usage as an alternative energy source.
- To explore hydrogen fuel cells environmental, social, and economic benefits.
- To determine strategies to increase the use of hydrogen fuel cells.

1.9 RESEACH QUESTION

- Can hydrogen fuel cells rival other energy sources like fossil fuel to create a competitive advantage?
- Can hydrogen fuel cells be the future energy sources for the transport sector and stationery application?

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2 CHAPTER TWO: Literature Review

2.1 OVERVIEW

This literature review examines what has been done on the subject, the technical concerns, social, environmental, and economic benefits, and alternative strategies to enhance the use of hydrogen fuel cells. Similarly, the review focuses on the theoretical framework and challenges like cost implications and production of quality hydrogen affecting the optimisation of hydrogen fuel cells. It integrates two theories; green economics and theory of ecological carrying capacity to defend arguments on hydrogen fuel cells. The literature review uses information from sources like academic papers, publications, and conference papers to understand what has been done and identify gaps, thus justifying the study on the competitive advantages of hydrogen fuel cells.

2.2 THEORETHICAL FRAMEWORK

2.2.1 THEORETICAL PERSPECTIVE

The world grapples with climate change, dwindling oil reserves, and increasing crude oil price, exploring the competitive advantage of hydrogen fuel cells is necessary. In line with the aims of this study, the researcher borrows from the sustainability or sustainable development framework. The model is based on a 1987 Brundtland Commission report that recognised sustainability, describing it as development towards attaining the requirements of the current generation while ensuring that future generations will access the necessities (Mensah, 2019; Mittelstaedt et al., 2014). The report identified a sequence of economic, ecological, and social issues experienced by people and suggested three stances. The first point recognises that development, energy, and the environment are inseparable. The second point is that the earth's resources and power are limited for human developmental necessities. The third point recognises that the pre-set developmental criteria need transformation for the current and future population (Shi et al., 2019; Mielke et al., 2016). The sustainable development model is appropriate for this study since it balances ecological, economic, and social aspects. Shen, Muduli, and Barve (2015) agree with this observation noting that sustainable development seeks to realise the correct balance between economic, social, and environmental concerns. Cloutier and Pfeiffe (2015) show that sustainability not only revolves around the three pillars but is a business strategy that integrates financial, social, and environmental considerations to ensure the future generation will acquire significance from already realised outcomes. According to Gajdzik et al. (2020), sustainability requires organisational transformation like product redesigning, business models, technologies, and approaches that generate innovation. The following section presents applicable theories.

2.2.2 THEORY OF ECOLOGICAL CARRYING CAPACITY

This study borrows from the theory of ecological carrying capacity (ECC), which recognises the ever-increasing pressure from natural resource demand by a rapidly growing population. According to Zhu et al. (2022), industrialisation, urbanisation, consumption, and threats to the national environment have raised concerns over future generations. On this premise, ECC tries to address emerging challenges by providing a long-term solution. The ECC approach calls for sustainable management of resources to meet growing needs while safeguarding the same for future generations. Its focus is to understand the economics, technological and social progress to ensure sustainable use of arable land, fossil fuel, forests, grass, construction land, and water. According to Świąder et al. (2020), ECC can help address carbon footprint biocapacity by ensuring that resources as sustainably used. Hydrogen fuel cells can ensure sustainable use of energy sources, reduced greenhouse gas emissions, and energy security.

2.2.3 GREEN ECONOMICS THEORY

Sustainable development calls for new technologies for production and consumption. The new technologies must have the least adverse effects on the environment. As climate change continues to affect nations, there is growing interest in technologies that mitigate the negative impact. For instance, hydrogen fuels are a carbon-free energy source that can address current problems, including meeting growing energy needs. However, according to Söderholm (2020), sustainable technological change is a political, societal, organisational, and economic endeavour that involves various non-technical challenges. According to Cato (2012), green economics are principles and ideas rather than intellectual positions that consider the relationships between equity and sustainability. The theory argues that it is only possible to realise balance with the environment if there is social justice. Green economists are likely to be campaigners and politicians advocating for equality. Hydrogen fuel cells can provide equality by safeguarding against environmental degradation through over extraction of fossil fuels and carbon emissions into the atmosphere.

2.2.4 THE CONCEPT OF FUEL CELLS

There is growing interest in alternative fuel sources to address environmental challenges and increasing global fuel prices. As the demand for energy increases and traditional sources like fossil fuel decline, there is a growing interest in fuel cells to produce electricity from the chemical energy in the fuels. Fuel cells can continuously produce energy when fed with fuel, thus not requiring charging. Felseghi et al. (2019) support this statement noting that the electric cell can be fed fuel to sustain indefinite electric current production. The cells transform fuel and oxidant chemical powers producing electricity. Lucia (2014) agrees with this conclusion in addition to stating that fuel cells hold the promise of a commercially efficient, clean, and viable electrochemical power source. Kundu and Dutta (2016) agree with this statement noting that the efficiency of fuel cells can be enhanced by increasing the fuel quantities and unit capacity and thus can be used for small or large systems. Körner et al. (2015) support this argument, noting that fuel cells can be used in cars, mobile phones, laptops, delivery ships, power and heat generators, buses, and vehicles.

The principle behind fuel cells was first presented by Christian Schoenbein in 1838. Future discoveries and developments led to modern-day fuel cells. The module includes an anode, an electrode, and a membrane between the two. Electric current and heat are formed when fuel and oxygen in the energy cell react. Fuel, in this case, can be hydrogen, methanol, natural gas, or coal. However, this research paper focuses on hydrogen fuel which can be produced from natural gas, oil, coal, or water (Isorna Llerena et al., 2019). The choice of raw material used determines the methods of producing hydrogen. There are three hydrogen production options: (1) thermochemical involving the reforming of natural gas heavy fuel oil, biomass, or ethanol, (2) electrolytic, and (3) photolytic. The three processes are at different developmental stages, whereas the most advanced and scalable option is steam methane reforming, currently producing 95% of hydrogen, and electrolysis producing 4% of hydrogen used globally (Brandon and Kurban, 2017). According to Ball and Weeda (2015), Giorgi and Leccese (2013), and Behling et al. (2015), fuel cells that use hydrogen as the primary energy source are known as hydrogen fuel cells. Despite the increased usage of hydrogen fuel cells due to their energy densities, there are concerns over their competitiveness. For example, the European Commission (2017) argued that energy densities, efficiencies, and costs must be competitive with the existing batteries to ensure future commercialisation. More research can provide new insight into hydrogen fuel cell usage and its ability to create a competitive advantage. The study can determine the most efficient energy source from an economic, social, and environmental perspective. The following section presents a detailed discussion of the three aspects.

2.3 THE COMPETITIVE BENEFITS OF HYDROGEN FUELS CELLS

2.3.1 ENVIRONMENTAL BENEFITS

The environmental benefits have been the driving force of research and related work. Different studies agree that hydrogen fuel cells can address environmental pollution by providing a cleaner energy source that can power current needs (Thomas et al., 2020; Abdelkareem et al. (2021). For instance, there is growing evidence that hydrogen fuel cells produce water and heat as significant by-products and not produce harmful gases or pollutants (Thomas et al., 2020). Abdelkareem agrees with this claim arguing that hydrogen in fuel cells has zero hazardous air substances like sulphur dioxide, nitrogen dioxide, or carbon monoxide. A different study by Hwang and Varma (2014) to determine the environmental benefits of hydrogen fuel cells concluded that using vehicles powered by hydrogen cells eliminates nitrogen oxides, erratic organic compounds, and particulate matter. Hardman, Steinberger-Wilckens, and Van Der Horst (2013) reinforce this argument, noting that even though hydrogen production from some processes produces some pollutants, it is easier to monitor and control emissions from static sources. According to Fan et al. (2021), hydrogen is a leading clean energy carrier and the most abundant chemical element accounting for 75% of normal matter by mass and more than 90% by the number of atoms. These attributes make hydrogen an emerging energy vector providing new uses from the traditional role as an industrial feedstock for producing methanol, ammonia, and petroleum refining (Fan et al.). The high efficiency and low emission attributes make hydrogen ideal in power generation, transportation, and militarised equipment.

Hydrogen fuel cells reduce greenhouse gases like methane and carbon dioxide emissions into the atmosphere. According to Clune, Crossin, and Verghese (2017), building up such gases has adverse effects on the global climate. However, using hydrogen fuel cells reduces the emission of such gases. Sgobbi et al. (2016) support this argument, noting that hydrogen fuel cells create an opportunity to address greenhouse gas emissions since it is possible to decouple carbon production from power generation and energy use, thus reducing carbon dioxide emissions into the atmosphere. Baroutaji et al. (2019) drew a similar conclusion in a mixed-method study investigating hydrogen in the aerospace and aviation industry. Tanç et al. (2019) and Körner et al. (2015) corroborated these arguments noting that hydrogen fuel cells produce little or no greenhouse gases like carbon dioxide, unlike conventional energy sources. Despite different studies agreeing on the environmental benefits of hydron fuel cells, none examined the cost implications and technological requirements for the fuel cell to be competitive. For instance, the different studies agree that the by-products are water and heat, which has no adverse environmental effects. Yet, there is no consensus on replacing conventional energy sources with hydrogen. However, more studies can provide new insight and recommend how the energy source can create a competitive edge over traditional sources like coal or fossil fuels.

2.3.2 ECONOMIC BENEFITS

Economic development requires abundant, affordable, and reliable energy. As global prices keep changing following significant shocks like the COVID-19 pandemic and the Russian-Ukraine war, which disrupt distribution, there is a growing interest in alternative fuels. Hydrogen can fill this gap by providing reliable, uninterrupted energy to spur growth and development. Mekhilef, Saidur, and Safari (2014) support this argument in their quantitative study noting that hydrogen fuel cells create new opportunities for improving energy production and use. Hydrogen fuel cells can promote energy security by ensuring uninterrupted supply since hydrogen is manufactured from locally available materials, reducing the impact of external forces and spikes in fuel prices. Consistent with this view, Dodds et al. (2015) and Itaoka, Saito, and Sasaki (2017) argue that hydrogen fuel cells can help conserve fuel, diversify energy needs in the transport sector, and establish resilient structures. It implies that hydrogen can help in attaining national and global energy needs since, unlike fossil fuels, hydrogen can be produced from local resources like solar energy, natural gas, landfills, and biomass. Ehteshami and Chan (2014) drew similar conclusions in their quantitative study investigating the role of fuel cells and hydrogen in storing renewable energy to meet changing demands. Hydrogen fuel cells can also promote a centralised and decentralised energy system ideal for regions or countries with unequal economic development (Staffell et al., 2019). However, hydrogen can be an alternative fuel source if it provides stable, affordable, and reliable energy for different uses.

Hydrogen fuel cells can catalyse new business opportunities spurring economic growth. It can offer economic growth pathways for integrated power for transportation fuels, electricity generation, cooling, and heating, thus creating employment and technical abilities across these areas (Manoharan et al., 2019). Hydrogen can also promote the development of new commercial centres in rural and urban areas that lack adequate investment in the centralised energy system. Giorgi and Leccese (2013) drew a similar conclusion in their qualitative study that explored the technical applications of hydrogen fuel cells in automobiles, generators, devices, and power stations, promoting exports and job creation. Hart et al. (2016) supported the argument on job creation noting that investment in the hydrogen fuel cell has created high-quality jobs in Europe and other developed countries. However, studies still need to focus on developing economies that still need to catch up despite high globalisation and technological changes.

Nations can improve their revenues by investing in hydrogen fuel cells. They can export such cells or use them locally, thus reducing overreliance on imported crude oil thus having a favourable trade balance. Sdanghi et al. (2019) agree with this statement in their study that examined the technologies used and hydrogen compression for automotive and stationary use, arguing that exporting fuel cell technologies can generate revenues for infrastructural development and economic growth. Niakolas et al. (2016) provide a similar conclusion noting that the export of hydrogen technologies by the U.S. automobile industry creates new income streams boosting tax collection and investment in other areas. Similar outcomes can also be observed in different countries, as evidenced by Pudukudy et al. (2014). They used a mixed-method study to investigate hydrogen use in Asia and concluded that fuel cells provide new opportunities for countries to serve the domestic and international markets to power vehicles, IT centres, and hospitals since they provide high-energy quality. Hardman, Steinberger-Wilckens, and Van Der Horst (2013) conducted a qualitative analysis investigating battery electric cars and hydrogen fuel cells and established that companies producing and using fuel cells are also the dominant buyers of computer chips, rubber, steel, vinyl, plastic, lead, copper, and textiles an indication of the interdependencies and foreign exchange inflows created by the technology. These findings show that hydrogen fuel cells have significant potential to spur economic growth and development in all nations by creating new products, markets, and jobs and promoting foreign exchange earnings. However, there needs to be more research on the competitiveness of hydrogen fuel cells since the findings in these studies only show the positive aspects of determining the drawbacks that can affect the full commercialisation of such cells. Additional studies can provide valuable information on the competitive advantage of such fuels.

2.3.3 SOCIAL BENEFITS

In addition to above benefits, hydrogen fuel cells have social benefits. There is evidence that fuel cells promote the creation and investment in services that comprise the social framework, thus conserving social capital (Fereidounizadeh, 2021). The cells ensure resource security, environmental justice, and improved human health critical in any society. Shang (2014) made a similar observation in the paper that examined the role of fuel cells and hydrogen for ultra-carbon cars using experimental design, concluding that fuel cells offer social values like health improvement, work opportunities, and technological advancement that enhance living standards. Additionally, fuel cells ensure fuel security critical for social cohesion and the formation of new connections and networks among people. Leben (2018) added that fuel cells could help communities attain meaningful health and educational outcome. Additionally, energy from fuel cells can be used as a resource for learning. Despite the social benefits derived from hydrogen fuel cells, there are concerns over their competitiveness. More studies can help address this issue by determining if hydrogen fuels have any competitive edge over conventional fuel sources like fossil fuels or natural gas.

2.4 CHALLENGES IMPACTING HYDROGEN FUEL CELL USE

Different studies by Li et al. (2020) have shown that hydrogen fuel cells can help countries meet their energy needs by providing alternative cleaner energy sources. Similarly, hydrogen fuel cells can solve current mobility requirements by delivering environmentally friendly fuels (Chakraborty et al., 2022). Despite the high number of studies showing the benefits of hydrogen fuel cells, there has yet to be an agreement on such energy sources providing a competitive advantage. For example, the European Commission (2017) argued that despite the benefits of hydrogen fuel cells, their power density, energy efficiency, and cost must be competitive compared to existing batteries to ensure successful commercialisation. Dodds et al. (2015) reinforces this argument noting that designing hydrogen fuel cells was more complicated unlike other batteries, and thus might not be feasible for commercialisation. Hamacher (2016) presents a different perspective noting that hydrogen fuel cells cannot act as a central energy resource and thus cannot replace conventional sources like coal or gas. These arguments show that despite being a sustainable and alternative energy source that is environmentally friendly, there are concerns over the competitiveness of hydrogen fuel cells. More research can provide valuable insight for determining if hydrogen fuel cells can provide a competitive advantage and present a lasting solution to global energy requirements.

2.5 COST IMPLICATIONS

In addition to the highlighted challenges, there are other concerns over hydrogen fuel cells. Cost-related factors emerge first when discussing hydrogen fuel cells since it is one of the most critical and significant obstacles to commercialisation. Different studies show that cost can hamper the adoption and full commercialisation of hydrogen fuel cells. For example, Maestre, Ortiz, and Ortiz (2021) conducted a mixed-method study using an experimental design to investigate the prospects and challenges of renewable hydrogen-based fuel studies. The study established that materials like polymer electrolyte membranes needed for manufacturing hydrogen fuel cells are costly, accounting for half of the fuel cell cost. Despite being regarded as next-generation power devices because they are highly efficient and produce low emissions, polymer electrolyte membranes require costly electrocatalysts, primarily platinum-based materials (Wang et al., 2020). Sapkota et al. (2020) add to this point by stating that the cost of proton-conducting membranes is still high, yet their durability is low.

The replacement of platinum-based catalysts is also challenging since the performance of its alternatives is different. Maestre, Ortiz, and Ortiz (2021) further state that using hydrogen fuel cells though more effective than conventional technologies, fails to account for the high initial costs. Baroutaji et al. (2019) drew similar conclusions in their study that extensively evaluated fuel cells and hydrogen technology in aviation and aerospace, arguing that the initial cost of producing fuel cells is higher, unlike other fuel sources. Wang et al. (2020) noted that hydrogen fuel cell production, particularly for large-scale use, is still costly compared to traditional sources. The cost implications of hydrogen fuel cells can significantly affect their competitiveness over other conventional energy sources that are not environmentally friendly. However, there are inadequate studies investigating the competitive advantage of such cells, thus a need to interrogate this issue and conclusively determine if the cells have the edge over existing energy sources.

2.5.1 PRODUCTION OF HIGH-QUALITY HYDROGEN

Another challenge affecting the development of hydrogen fuel cells is the ability to produce high-quality hydrogen. There are concerns over balancing cost and quality to ensure that cells can be produced cost-effectively and safely Baroutaji et al. (2019). A critical consideration is an ability to produce quality hydrogen fuel cell fuels to meet growing demands and specific requirements. Impurities in the hydrogen produced affect the hydrogen oxidation reaction, thus affecting cell performance (Isorna Llerena et al., 2019). For instance, producing hydrogen fuel cells requires precision and the highest quality materials. However, the hydrogen is produced from different production processes that lead to various impurities like carbon monoxide, hydrogen sulphide, and helium that adversely impact the quality of hydrogen delivered (Beurey et al., 2021). The proton exchange membranes possess high power density making them the dominant hydrogen fuel cell.

The proton cells need high-purity hydrogen otherwise, fuel cell performance and longevity are severely affected (Du et al., 2021). Isorna Llerena et al. (2019) agree with this statement in a study that determined the impact of impurities, establishing that impurities like ammonium contaminate the hydrogen affecting its efficiency. Ezquerra Silva (2019) reported similar findings in a study investigating the optimisation of production costs of hydrogen cell fuel-powered electric vehicles. The study established that impurities could pollute platinum loading, thus adversely affecting the quality of hydrogen produced. Ezquerra Silva further showed that impurities lead to additional hydrogen costs, thus making such cells less economical. Du et al. (2021) supports this statement by noting that different raw materials affect the composition and impurity contents of hydrogen generated using various technologies, thus the importance of deploying efficient purification technologies to remove the impurities and produce high-quality hydrogen.

It is possible to enhance the quality of hydrogen produced by using technologies that produce pure hydrogen or incorporating purification processes, leading to additional costs, thus affecting the competitive advantage of hydrogen fuel cells. Du et al. (2021) stresses the importance of generating such technologies to support extensive scale utilisation of hydrogen energy in the transport sector. Beurey et al. (2021) agree with this statement, noting that different studies and bodies emphasise the importance of purification technologies to ensure producing quality hydrogen fuels. Du et al. (2021) reviewed different technologies like pressure swing absorption, metal hydride separation, and membrane separation and concluded that the existing purification methods are limited; thus, it is challenging to realise the purity level standards for fuel cell cars using a single separation and purification method. Further, according to Isorna Llerena et al. (2019), once some impurities like ammonia contaminate a cell, its performance deteriorates even if pure hydrogen is introduced later after the poisoning. These findings show the challenges of using hydrogen fuel cells and how impurities can affect their competitiveness. Despite evidence showing the impact of impurities, no studies examined the competitive advantage of hydrogen fuel cells, thus the need to conduct the current study.

2.5.2 PERFORMANCE-RELATED ISSUES

Another challenge affecting the uptake of hydrogen fuel cells is performance. However, performance is a complex issue affected by temperature, pressure, electrode conductivity, membrane thickness, and hydrogen and oxygen input pressure (Yilmaz and Ispirli, 2015). Wilberforce et al. (2017) examined the manufacture of hydrogen fuel cells using a mixed-method study. They established that the power and energy density of portable hydrogen fuel cell applications should be higher than conventional batteries to remain competitive. The reaction rate must be higher to realise higher power and energy density. However, the reaction rate can be affected by impurities or hydration. Greene, Ogden, and Lin (2020) support this statement noting that hydrogen fuel cells use a nafion membrane as the polymer electrolyte membrane to transfer the electrons from the anode to the cathode chamber, which requires 100% hydration to perform effectively. The requirements impede hydrogen cell performance at higher and typical atmospheric temperatures. Kundu and Dutta (2016) present a different perspective noting that hydrogen is produced from hydrocarbons through water-gas reaction, thus remains polluted by one per cent carbon monoxide that activates catalyst contamination at the anodes, particularly at low operations. Carbon monoxide poisoning can be eliminated under high operating temperatures. However, Merino-Jiménez et al. (2012) and Alves et al. (2013) argue that higher operating temperatures affect the requirements for managing water. Competitive advantage can arise if the polymer electrolyte membrane can operate at low hydration environments to realise the highest proton conductivity and carbon monoxide tolerance. However, this is not the case with hydrogen fuel cells.

2.5.3 HYDROGEN FUEL STORAGE

Modern applications with enhanced functionalities are associated with increased sizes of devices and the desire for increased energy density. In some situations, the energy derived from hydrogen fuel cells can be used in implantable applications. However, there are concerns over the storage of hydrogen. For example, Lindorfer et al. (2019) examined hydrogen, methane, and fuel cells using a qualitative study and concluded that storage issues arise, particularly in portable applications and energy systems. Storage affects cost, volume, efficiency, weight, and safety considerations. Hwang and Varma (2014) drew similar conclusions in their study examining the storage of hydrogen fuel cells. Hwang and Varma argue that storage affects the manufacture of hydrogen-powered cars since it affects weight, safety, and power efficiency. Ajanovic and Haas (2021) used secondary data sources to examine the prospects and challenges of fuel-cell cars. They concluded that the storage costs are significantly high, impeding the use of hydrogen-powered vehicles. Storage challenges continue to affect hydrogen fuel cell production and commercialisation, thus impacting their competitiveness.

2.6 ALTERNATIVE STRATEGIES TO INCREASE THE USE OF HYDROGEN FUEL CELLS

Challenges like storage, quality cost, and performance continue to affect the use of hydrogen fuel cells across different sectors in Europe and the rest of the world. Interventions to address the obstacles have not resulted in the desired outcome, and the uptake of fuel cells still needs to be higher. However, it is possible to devise alternative approaches to promote the uptake of fuel cells and thus capitalise on their benefits. For example, Hames et al. (2018) recommended the creation of a cost-effective, lightweight, and protected storage to enhance commercialisation. Hames et al. believed that cryogenic tanks are the most effective storage facilities. Behling et al. (2015) supported these recommendations noting that appropriate storage equipment like cry-compressed tanks and chemical hydrides can increase the uptake and use of hydrogen fuel cells. Baroutaji et al. (2019) and Nojavan, Zare, and Mohammadi-Ivatloo (2017) supported these observations showing the importance of storage in the uptake and commercialisation of hydrogen fuel cells. The different articles agree that storage should guarantee safety while, at the same instance, ensuring lightweight to ensure better handling, efficiency, and use. The storage tanks should also withstand undue thermal loads for extended periods, particularly in rapid flight scenarios. Solid and lightweight storage material can address current challenges and enable better handling and fully commercialising fuel cells.

As suggested by the European Commission (2017), a clear policy framework can provide valuable direction for hydrogen fuel cell usage. However, a regulatory framework can ensure full commercialisation and long-term competitiveness. Ajanovic and Haas (2021) support this argument noting that the full commercialisation of hydrogen fuel cells depends on the future targets and policy framework. However, nations have unique capabilities or characteristics, and one framework cannot apply to all nations. Under the current macro environment, products from one country will inevitably be sold in another. However, challenges arise if policy frameworks conflict. Likewise, there are limited protocols and guidelines on hydrogen fuel use, and there can be areas for improvement in their application, mainly if it involves cross-border engagement. Inadequate protocols hinder the competitiveness of hydrogen fuel cells by creating loopholes and constraints that interfere with commercialisation. According to Hames et al. (2018), there is a need for regulatory and fiscal protocols that promote the commercial development of fuel cells. Ball and Weeda (2015) support this argument by underscoring the importance of robust policy frameworks to support the development and commercialisation of hydrogen fuel cells. Otherwise, an appropriate framework can help the adoption by creating bottlenecks that create confusion and slows the process.

As hydrogen fuel cells gain traction, there is a growing interest in workable strategies that will promote competitiveness. However, this is not the case at the moment since issues continuously slow down fuel cell uptake and commercialisation. For example, according to Hart et al. (2016), fuel cells do not incentivise short-term users to spend significantly on the technology, yet they can acquire conventional batteries. Niakolas et al. (2016) agree with this observation in addition to emphasising the need for appropriate strategies that can promote cost reduction, establish alternative markets and strengthen the industry to reduce government support. However, Tanç et al. (2019) deviate from this statement noting that government intervention is needed since it will promote the production and usage of fuel cells while supporting different players with resources and skills to ensure successful commercialisation. Government support can provide an environment for technology to grow and including research and technical support critical for addressing the identified challenges. Similarly, such support can help in pooling resources to ensure successful testing, installation of necessary infrastructure, development of appropriate safeguards and goodwill. Lastly, government support is instrumental for long term success and continuity since it is possible to integrate strategic plans and development budgets on improving existing infrastructure or providing technical support.

2.7 LITERATURE GAP

The literature reviewed shows the benefits of hydrogen cells to developed and emerging economies. It demonstrates what has been done and identifies inconsistencies that need further research. For example, the review showed the economic, social, and environmental benefits, yet studies have yet to deal with the competitive advantages of fuel cells. Challenges like cost, quality, storage, and production outweigh the benefits and are likely to affect the competitive advantage of hydrogen fuel cells. Similarly, most studies have focused more on the technical aspects like the functioning of the membrane, anode, and cathode, yet there needs to be more research on creating economic sense by reducing associated costs of acquiring or replacing the cells. Additionally, carbon or ammonia poisoning of the cell is irreversible; thus, measures are needed to ensure high-quality hydrogen is required. Failure to establish such systems means that the cells will not function optimally and will need periodic replacement. A thorough consideration of these issues and the need to ensure full commercialisation of the fuel cells require an in-depth inquiry to understand their competitiveness. An integration of theories on sustainability provides credence for conducting the study based underlying theoretical arguments that perceive sustainability as the best approach to address resource requirements driven by industrialisation, growing population and globalisation. This study will provide new insight for understand hydrogen gas use in developed and developing countries in addition to identifying possible interventions to enhance full commercialisation.

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3 CHAPTER THREE: Methodology

3.0 OVERVIEW

This chapter covers the Research Methodology to be used. The aims and objectives of the research approach within a Framework. Describing the Philosophy, Strategy and research ethics. This Chapter also explains why these methods were used and the limitations of such. Concluding that the research will be of benefit by informing policy decisions and future primary studies on the subject.

3.1 RESEARCH AIMS AND OBJECTIVES

This mixed method uses secondary data from academic sources to address the research gaps in the reviewed literature. The study seeks to investigate the competitive advantage of hydrogen fuel cells. It was driven by the desire to understand their environmental, social, and economic benefit and the strategies to increase their use. The study answers the research question of whether the fuels generate clean and sustainable energy. The study is relevant because it shows the importance of hydrocarbons on energy security, thus addressing current and future shortages driven by global demand. The uptake of hydrocarbons is also instrumental in an ever-changing environment where nations are looking for alternative energy to meet their growing demands. The study provides valuable information to academia and policymakers and informs social change by demonstrating the importance of hydrocarbon fuels. The descriptive study deals with the descriptions, identify facts, and uses supporting evidence to show the current state and possible strategies to enhance the use of hydrogen.

Overall Aim

The researcher's study shall investigate the competitive advantages of hydrogen fuel cells.

Objectives

- To explore hydrogen fuel cells' potential environmental, social, and economic benefits.
- Determine strategies to increase the use of hydrogen fuel cells.

3.2 RESEARCH FRAMEWORK

The study follows the research onion structure shown in Fig 3.1. Similarly, it integrates the main points in the dissertation handbook methodology guidelines.

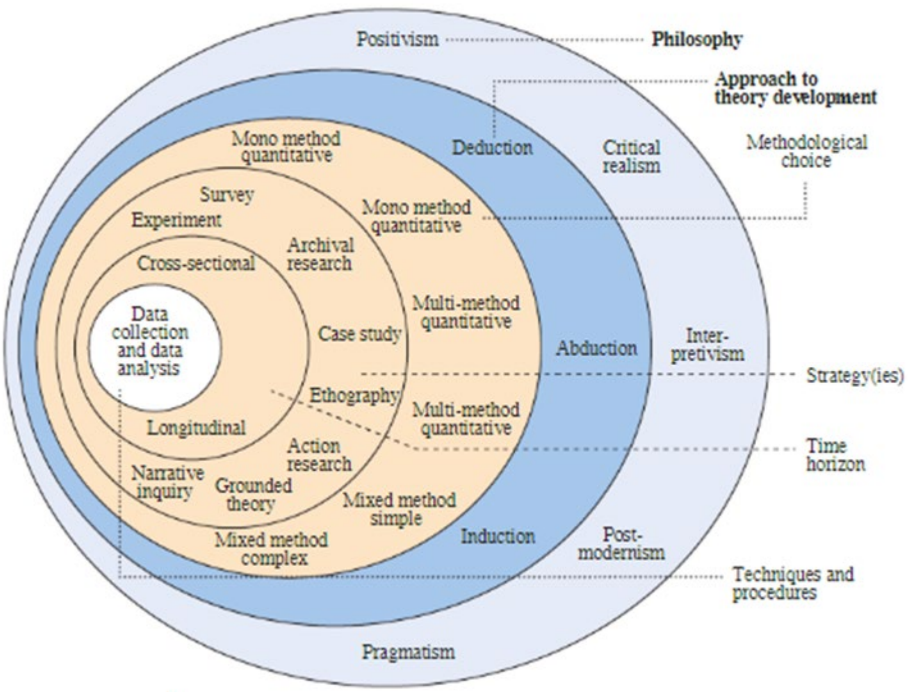

Fig 3.1: Research Onion (Saunders, Lewis, and Thornhill, 2016).

3.2.1 RESEARCH PHILOSOPHY

Saunders, Lewis, and Thornhill (2019) describe research philosophy as the beliefs and assumptions held by a researcher. It implies the process of knowledge development in a specific field. A researcher holds assumptions about the realities they encounter, human knowledge, and the extent to which their values influence the entire process. The premises, in this case, shape how a researcher understands the methods used to address the research questions and interpretations of the findings. In such a situation, consistent and well-thought-out assumptions form the philosophy that underpins the entire research process (Creswell and Plano Clark, 2011). This study uses pragmatism philosophy which involves focusing on the outcome of a study. In this case, one looks at the situation, the actions, and the consequences as opposed to the antecedent, which is the case in post-positivism. Pragmatism also deviates from positivism which views the universe the way it is and thus analyses physical evidence where a researcher uses facts and material evidence to conduct an investigation. In such a case, a researcher is an independent observer of the universe. Post-positivism deviates from positivism, arguing that a researcher's identities and ideas influence their observation and conclusion. A different philosophy is an interpretivism which believes in the absence of objectivity. A researcher, in this case, focuses on subjective knowledge gained through observations and discussion (Saunders, Lewis, and Thornhill, 2019). Of importance is the problem under investigation, not the methods used. Pragmatism is ideal for the study because it does not restrict the researcher to a single system of philosophy. Similarly, the researcher is free to use methods, techniques, and procedures that best meet the purpose and needs of a study. Likewise, it eliminates the tendency to see the world as an absolute unity, thus allowing for the use of different approaches rather than focusing on a single way of collecting and analysing data.

The researcher believes that people have different experiences; thus, their world views cannot be the same. However, people have different degrees of shared experiences; their degree of shared beliefs varies. This means that the shared beliefs on a particular situation influence how people act in a similar situation and assign the same meaning to the outcomes of such actions (Saunders, Lewis, and Thornhill, 2016). In this case, the researcher evaluates and solves practical problems using secondary data from different sources like journal articles and government publications. In doing so, one assumes knowledge acquisition is through action or practice. Further, the researcher believes in the change process where people move from traditional energy sources like fossil fuel to hydrogen (Saunders, Lewis, and Thornhill, 2019; Kothari and Garg, 2004). Under such change, it is necessary to appreciate the different ways of interpreting the world (Saunders, Lewis, and Thornhill, 2016). It implies that no single perspective can present the entire picture, thus the need to appreciate multiple realities.

3.2.2 RESEARCH APPROACH

The study uses abductive reasoning to answer the research question. Abductive is appropriate because it overcomes the weaknesses in inductive and deductive approaches. For instance, deductive reasoning lacks clarity on theory selection and testing using formulated hypotheses. On the other hand, induction fails to promote theory building no matter the volume of empirical data availed. Abductive adopts a pragmatist perspective using incomplete observations to make the best predictions that may be true or not. Unlike deductive reasoning, which uses general rules to draw specific conclusions that must be true (Saunders, Lewis, and Thornhill, 2016). Likewise, it differs from induction which relies on specific observations to make generalised conclusions that may be true or not. However, the three approaches are similar in that they are used to make logical inferences and develop theories. Abductive studies start with puzzles or surprising facts and strive to establish explanations (Bryman and Bell, 2011). For instance, in the current study, the researcher uses facts on hydrogen fuels and tries to explain how they are best suited to the changing world occasioned by ever rising demand for fuels across nations. The facts, in this case, stem from different encounters with the empirical phenomenon that lacks adequate or relevant theories for explaining them

(Creswell and Plano Clark, 2011). In such a situation, the researcher selects the best explanations from different alternatives, thus explain surprising facts identified at the initial stages of a study.

3.2.2.1. *TYPES OF RESEARCH*

The researcher uses exploratory design to gain an understanding and new insight on hydrogen fuel cells. The design is appropriate for the study because of the flexibility and unstructured nature of the research process. Since the information needs are loosely defined, the researcher can use a small, non-representative sample to collect topic-specific data for understanding hydrogen fuel cells (Kothari and Garg, 2004). This is unlike conclusive design, which tests hypotheses and relationships using large representative samples and heavily relies on quantitative data (Saunders, Lewis, and Thornhill, 2016). In exploratory designs, a researcher investigates problems that are not clearly defined to obtain a deeper understanding of an issue. Exploratory designs enable the researcher to start from a general idea of the use of hydrogen fuels and then identify inconsistencies and gaps that need further investigation. The flexibility in the study allows an investigator to alter the direction subject to new information from the secondary data (Saunders, Lewis, and Thornhill, 2019). In such a situation, the researcher can answer questions like what, how, and why hydrogen fuel cells can provide fuel security. The researcher gathers secondary data from sources like published primary research, reports, books, and publications.

3.2.3 RESEARCH STRATEGY

This study uses archival research to understand the competitive advantage of hydrogen fuel cells. Saunders, Lewis, and Thornhill (2016) advocate for explorative strategy in mixed method studies using archival data to inform an issue of interest. The strategy is appropriate for this study because the subject is not adequately studied since hydrogen fuel cells are new, thus the need to understand multiple futures and possible developments. The researcher combines online research and public libraries to gather data (Cohen, Manion, and Morrison, 2017; Dawson, 2009). Secondary data research is appropriate because it allows the researcher to combine data from different sources and analyse past primary studies, thus gaining insight into hydrogen fuel cell use. While collecting data from online sources, the researcher uses keywords like hydrogen fuels, energy, competitive advantage, alternative fuels, fuel cells, clean energy, renewable energy, energy efficiency, environmentally friendly fuels, and the social and economic benefits of hydrogen fuels. The researcher combined the keywords using Boolean operators like AND to search all articles with the keywords, OR to identify sources with one keyword or the other, and NOT to eliminate articles or materials with selected terms (Devi, 2017; Saunders, Lewis, and Thornhill, 2016). The materials were analysed using the Currency, Relevance, Authority, Accuracy, and Purpose (CRAAP) criteria. Further, the researcher checked the methodological quality of selected materials using the Critical Appraisal Skills Programme-CASP.

The secondary data sources include articles in the international journal of energy research, ProQuest, SocIndex, EBSCOhost, Psych Info, Science Direct, ResearchGate, Elsevier, Joule, and applied energy. Other secondary data sources include statistics from government agencies like afdc.energy.gov, ukhfca.co.uk, reports on hydrogen fuels, and publications from reputable organisations like CNBC, hse.gov.uk, and the conversation. Similarly, the researcher included data from non-government agencies dealing with energy and environmental conservation, public libraries, educational institutions, and commercial information. The study excludes all materials from .com websites, opinions, blogs, unpublished personal sources, and diaries. Similarly, the researcher excludes material that is more than seven years old from the date of publication. Similarly, the researcher excluded secondary data sources that are not correctly referenced (Dawson, 2009). A blend of the different energy sources enables the researcher to get more data, including the latest literature and commentaries on the subject.

3.2.4 RESEARCH METHODS

The mixed method study uses secondary data only from different sources to answer the research question. The researcher combines quantitative and qualitative techniques and analysis (Sahin and Öztürk, 2019). Saunders, Lewis, and Thornhill (2016) advocate for a mixed method where a researcher would like to avoid adopting a single philosophical position and thus align with pragmatism. The methodological choice is informed by the research context, questions, and consequences (Creswell and Plano Clark, 2017; Dawson, 2009). The researcher used a concurrent method which involves collecting both quantitative and qualitative data in a single phase, and the two interpreted together. The researcher then compared how the two datasets supported each other. Figure 3.2 shows the different types of mixed methods. Concurrent was appropriate because it enabled the researcher to obtain a comprehensive outcome of research which is not the case with mono methods.

3.2.4.1 QUANTITATIVE DATA

Quantitative data was collected from reports, government publications, and research articles on hydrogen energy cells. For example, the researcher collected data on trends, economic contribution, rate of adoption, and cost savings. The articles, in this case, are from external sources and integrate commercial and published records.

3.2.4.2 QUALITITATIVE DATA

The researcher collected qualitative data from commercial and published data. Data collection was based on themes like hydrogen cells' economic, social, and environmental benefits. Similarly, the study collected data on strategies for improving the adoption of hydrogen fuel and benefits accruing from the Usage. Other qualitative data included the efficiency of hydrogen cell fuels, the likelihood of replacing fossil fuels, and policy issues to promote its adoption.

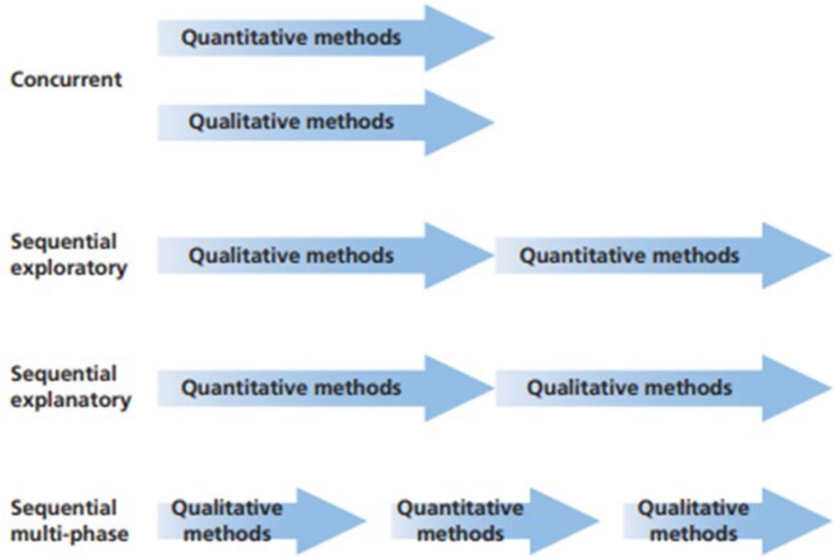

Fig 3.2: Types of mixed methods (Saunders, Lewis, and Thornhill, 2016)

3.2.5. TOOL DEVELOPMENT

This study used electronic database search or desktop research to identify relevant articles and collect data on hydrogen fuel use. According to Saunders, Lewis, and Thornhill (2019), secondary data can include a document-based survey and data compiled from multiple sources. Based on this understanding, the researcher used research journals like the international journal of energy research, international journal of hydrogen energy, energy for sustainable development, science direct, IAEE journal, energy and environmental science, advances in applied energy, international journal of green energy, directory of open access journals and journal of modern power systems and clean energy. Additionally, the study used survey articles and reports to collect secondary data. Electronic database search or desktop research was ideal because there is adequate and current information on hydrogen fuel cell usage, thus the need to collaborate ideas from different sources to answer the research questions. The researcher subjected each article or report to an initial appraisal involving an evaluation of the authors, publication date, publisher, title of the journal, and edition. The next step was to carefully analyse the content, like the introduction and methodology, to determine the participants, design, and flaws in the article (Bordens and Abbott, 2022). Upon satisfactory evaluation and analysis of the articles, the researcher recorded the selected articles in a summary form. The form included the author, title of the study, type of study, year of publication, journal methodology, findings, limitations, and gaps or inconsistencies.

Author	Title	Year	Study type	methodology	Findings	Limitations	Gaps

Table 3.1. Data capture form

3.2.6. TIME HORIZON

The researcher adopted a cross-sectional study, a type of observational design where one measures the findings at a particular time. Unlike longitudinal studies, where researchers observe the subject over a long time, cross-sectional allow one to use the inclusion and exclusion criteria to select secondary data sources. The time horizon is appropriate because it is inexpensive and faster. Further, it allows for comparison between different sources, thus answering the research question. However, it can be challenging to establish causal relationships. In some instances, they are prone to biases (Setia, 2016). For example, a researcher can decide to narrow the inclusion and exclusion criteria, thus eliminating helpful material which could otherwise change the course of the study or provide additional information.

3.2.7. DATA COLLECTION AND ANALYSIS

Unlike primary research, where a researcher owns the data, secondary research relies on previously published data. It is fast, easy, and useful when the researcher wants to gain a broader understanding of the phenomenon (Sapsford and Jupp, 2006). An investigator identifies an area of interest, followed by locating research sources and collecting secondary data (Saunders, Lewis, and Thornhill, 2016). It is necessary that before combining and comparing the data, a researcher first identifies secondary data sources that meet the inclusion and exclusion criteria for the study. The next step is determining their relevance to the study by checking if arguments are well-supported, correctly argued out, and referenced (Hox and Boeije, 2005; Devi, 2017; Cohen, Manion, and Morrison, 2017). The researcher summarised and collated the secondary data to enhance the entire study. Data collection differed from one source to another (Saunders, Lewis, and Thornhill, 2019). For instance, while collecting secondary data from the internet, the researcher used desk research to identify and download sources that meet the inclusion criteria. This was different from secondary data from government and non-government agencies. The researcher first searched for online materials from various agencies before engaging relevant personnel to obtain additional information unavailable on the websites (Patten and Newhart, 2018; Sapsford and Jupp, 2006). Further, the researcher visited public libraries and gathered data from earlier studies. The public libraries provided valuable information on hydrogen fuels, market statistics, and other directories.

3.2.7.1. ***VALIDITY, RELIABILITY, AND GENERALISABILITY***

Validity in a study implies the appropriateness of the process, tools, and data to the problem under investigation. It is a broad aspect covering the entire research process. For example, the research question should be valid for the anticipated outcome, while the design must be appropriate for the methodology. Similarly, the data collection, analysis, results, and conclusion should be valid for the context (Creswell and Plano Clark, 2017). It was necessary to ensure that the study measured what it was intended, thus contributing to internal validity. Doing so is critical if the results are meaningful and generalisable (Patten and Newhart, 2018). The researcher ensured the results were significant and relevant by ensuring that the instruments measured what was intended and not anything else. This was realised by ensuring that the research question, objective, and aims aligned to the study, and collected data helped fill identified gaps in the competitiveness of hydrogen fuel cells. A measure, in this case, should not focus on other forms of fuels like fossils, thus guaranteeing construct validity. Similarly, the secondary data sources were comprehensively and systematically representative of the subject under investigation, thus contributing to content validity (Devi, 2017). Additionally, the test should subjectively measure what was intended, meaning that the study should look like it is measuring the competitiveness of hydrogen fuel cells.

The researcher was cautious while using secondary data to determine the competitive advantage of hydrogen fuel cells. It was desirable to scrutinise the sources and avoid the tendency to take the collected data at its face value. The researcher was guided by Kothari and Garg's (2004) guidelines for using secondary data. It was necessary to test the reliability by understanding who collected the data, their sources, the methods used, the timing, the possibility of biasness by the compiler, and the level of accuracy anticipated and whether it was realised. Likewise, it was necessary to ensure the suitability of the collected data. The researcher achieved this by scrutinising different concepts, definitions, and usage of keywords in the respective articles. The research issue's objective, scope, and nature further informed the choice of secondary data source (Creswell and Plano Clark, 2017). The researcher further checked the data for adequacy. Any source that failed to meet the basics of reliability, suitability, and adequacy was discarded, and a different source was searched. However, the data was not discarded blindly in some situations (Saunders, Lewis, and Thornhill, 2019). For instance, if it was from an authentic source and suitable for the study, the researcher uses the data even though it might be inadequate for the current inquiry.

Klassen et al. (2011) argue that the need for new methodological choices is driven by the desire to enhance the quality and scientific studies to solve emerging problems. With such developments, mixed method studies have gained prominence in social and behavioural science as researchers deviate from the extremes of qualitative or quantitative studies and instead combine the two (Saunders, Lewis, and Thornhill, 2019). The results from mixed method studies are generalisable to different contexts and used for policymaking and inform future studies. The merging, connecting, and embedding of varying data types and analysis techniques allows the researcher to develop a broader understanding of the subject and produce verifiable, detailed, and informative results (Sahin and Öztürk, 2019; Creswell and Plano Clark, 2017). Further, the ability of mixed methods to address the shortcomings of qualitative or quantitative techniques leads to better findings that can be generalised in different situations. In this case, generalisation is possible despite challenges in conducting mixed studies like inadequate resources, over-dependence on a researcher's experience, the possibility of using misleading secondary data, and analytical and interpretive concerns.

3.2.7.2. *<u>DATA ANALYSIS</u>*

The methodological and personal preferences dictated the data analysis techniques used in this study. For instance, data validity and reliability informed quantitative analysis techniques. It was critical to ensure that the methods measured what the study intended and that the measurements were consistent and stable (Saunders, Lewis, and Thornhill, 2019; Sahin and Öztürk, 2019). The researcher analysed the data concurrently during collection.

While collecting qualitative data, the researcher summarised it using a summary form that captured the details like authors and the year of publication of each secondary data source (Creswell and Plano Clark, 2017). Similarly, the form captured each article's methodology, data analysis techniques, findings, and limitations. The researcher then identified emerging themes and captured relevant notes. The study used thematic analysis and comparative analysis, where the researcher moved backwards and forward between notes and research literature (Cohen, Manion, and Morrison, 2017; Terry et al., 2017). The process was repeated until the researcher was satisfied with the collected data and no new information was forthcoming.

The researcher used descriptive statistics, cross-tabulation, trend analysis, and computer software to analyse quantitative data. The descriptive statistics, in this case, include mean, median, and standard deviation. Cross tabulation involves simple forms that draw inferences from different sources (Creswell and Plano Clark, 2017; Kothari and Garg, 2004). Trend analysis enabled the researcher to establish significant changes over time, thus understanding how hydrogen fuel cell use is developing.

3.3 RESEARCH SITE

The researcher used online research to gather relevant data from journal articles and other relevant sources. Online research is appropriate because it enables the researcher to collect volumes of data cheaply. Additionally, the researcher uses literature research, an inexpensive method to gather data from books, magazines, and other published academic articles (Bryman, 2012; Patten and Newhart, 2018). A defined process involving determining the problem guides the researcher, conducting a literature review to identify gaps and inconsistencies, conducting further research to identify relevant secondary data sources, and categorise them into different classes (Saunders, Lewis, and Thornhill, 2019). The choice of exploratory design was informed by the nature of the research problem, the need for flexibility, cost implications, ability to gather relevant data and analyse the same.

3.4 RESEARCH ETHICS

Research issues emerge in secondary studies. This is particularly the case with the emergence of new technologies that facilitate data compiling, sharing and storage. Issues of security and confidentiality arise in secondary research. In some situations, a review by the ethical board is needed if the data has personally identifiable data or the primary source is not appropriately coded; thus, its use can potentially harm the participants. However, the selected materials had no identifying material; thus, their use could not harm the original participant (Saunders, Lewis, and Thornhill, 2019). In such a situation, the board confirmed the information was anonymous and no need for a complete review. The researcher recognises that permission to use secondary data available on the internet and in public libraries is implied; thus, it was necessary to acknowledge the respective authors (Bryman, 2012). The researcher was guided by the principles of adequacy, relevance, and appropriateness and did not use any misleading information, deception or report deceptive or false information, or engage in omission. Other unethical practices the researcher avoided include fabricating secondary data sources, falsifying, and plagiarising the secondary data sources (Creswell and Plano Clark, 2017). Likewise, the researcher did not engage in copyright violations like producing unauthorised copies and distributing them to others.

3.5 RESEARCH LIMITATIONS

Mixed method studies are complex to conduct. Further, it is time-consuming and requires experience and expertise while using secondary data sources. Although an exploratory design is appropriate, it is time-consuming, requires an in-depth evaluation of all sources and their content, and is not structured; thus, the researcher can deviate from the subject (Kothari and Garg, 2004; Saunders, Lewis, and Thornhill, 2019). Further, exploratory is inclusive, and the information obtained can lead to biasness. Additionally, using few secondary data sources can affect the accurate interpretation and generalisation of the results (Bryman, 2012). Lastly, the data from secondary sources can be old and not up to date.

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4 CHAPTER FOUR: Data Analysis

4.0 OVERVIEW

This chapter covers Data gathered as described in the Previous Chapter and the detailed analysis of the data.

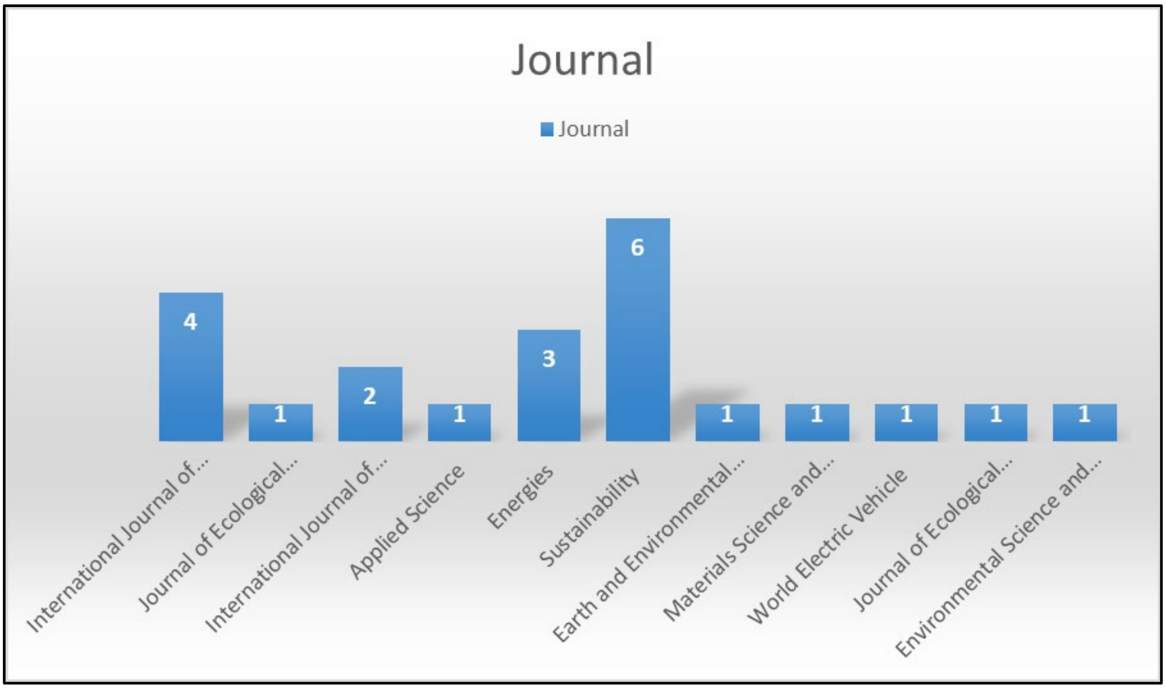
4.1 DATA ANALYSIS

This study sought to investigate the competitive advantage of hydrogen fuel cells. The study had two objectives: (a) to explore hydrogen fuel cells' potential environmental, social, and economic benefits and (b) to determine strategies to increase the use of hydrogen fuel cells. It used secondary data from different sources, including articles in the international journal of energy research, ProQuest, EBSCOhost, Psych Info, Science Direct, ResearchGate, Elsevier, Joule, and applied energy. Other secondary data sources include statistics from government agencies like afdc.energy.gov, ukhfca.co.uk, reports on hydrogen fuels, and publications from reputable organisations like CNBC, hse.gov.uk, and the conversation. The researcher used trend and comparative analysis to analyse quantitative data and thematic analysis in qualitative data. Twenty-six articles that met the inclusion and exclusion criteria were selected from 180 papers from different sources. The 180 included research papers, reports, conference papers and unpublished studies. Preference was given to articles published in the past five years because of the changing nature of hydrogen fuel cells and emerging studies that provide new information that can help determine the fuel cells' competitive advantage. The search keywords included hydrogen, fuel cells, clean energy, sustainability, alternative to fossil fuels, storage of hydrogen fuel, challenges of hydrogen fuel cells, and impurities in hydrogen fuel cells. The keywords search was conducted concurrently to enhance the accuracy of search results. The articles were from journals like the international journal of energy research, journal of ecological engineering, international journal of hydrogen energy, applied science, Energies, energy, sustainability, earth and environmental science, material science and engineering, and world electric vehicles. The selection of secondary data sources was based on Currency, Relevance, Authority, Accuracy, and Purpose (CRAAP). Each article was evaluated for quality, appropriateness, and ability to meet the objectives of this study. Table 4.0 shows a breakdown of the secondary data sources used in the study.

Table 4.0. Breakdown of the sources (Author, 2022).

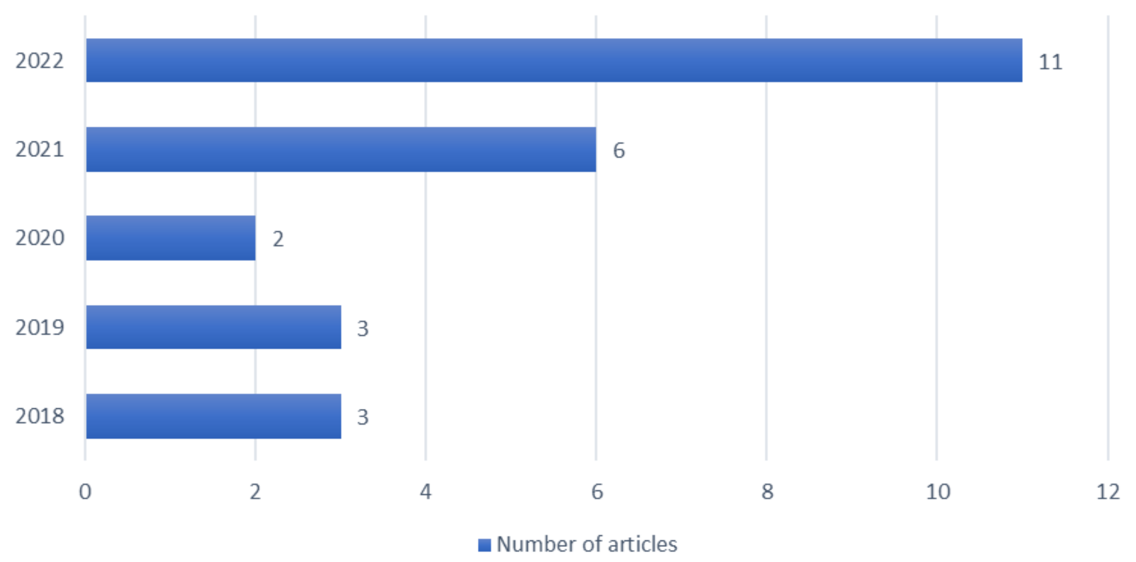
Source	Number
Journal articles	22
Reports	3
Conference	1

Fig 4.0. Breakdown of the journal sources (Author, 2022).



Secondary data sources year of publication

Fig 4.1. Number of articles published in the year



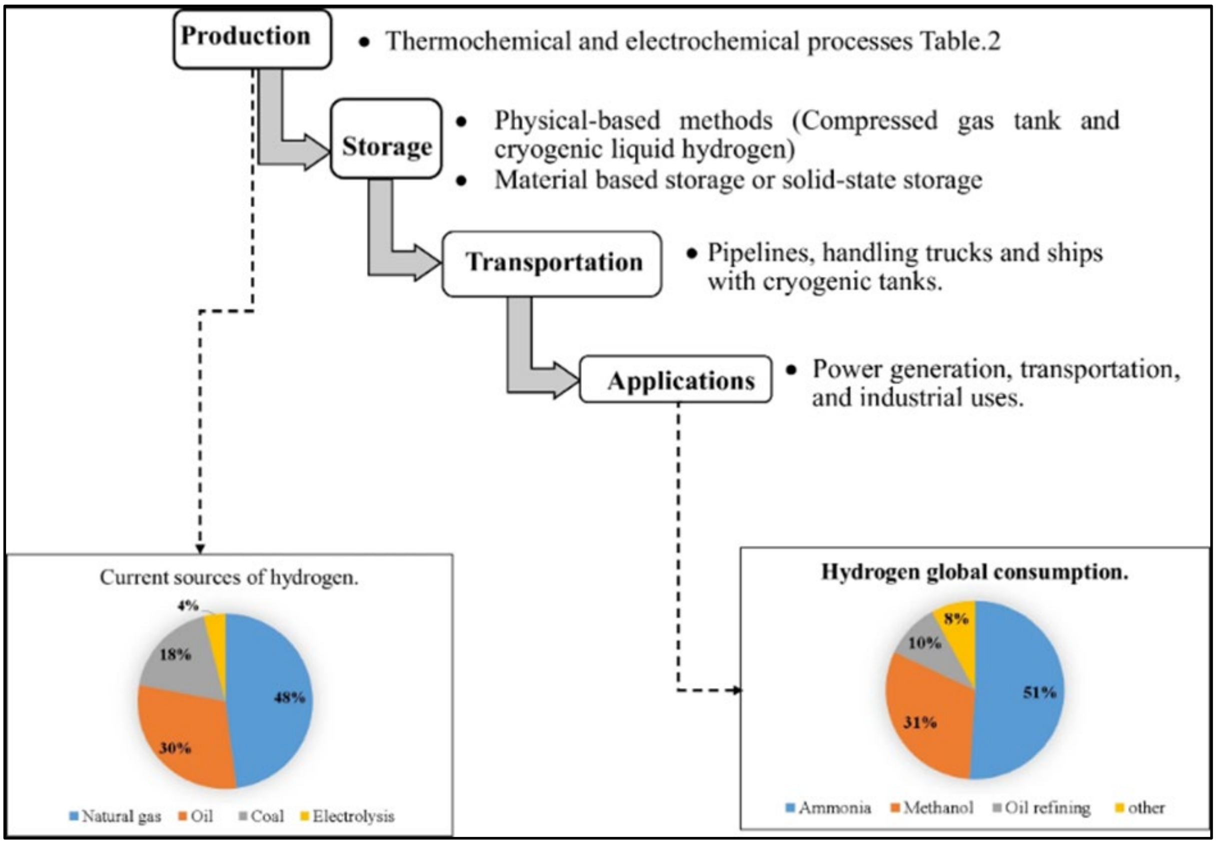
4.2 QUANTITATIVE RESULTS

The researcher collected data on producing or maintaining fuel cells and compared it with the cost volume of energy generated from fossil fuel using the same investment. This study used the hydrogen economy which includes production, distribution, storage, and application. The following section presents the quantitative results of different aspects that constitute the hydrogen economy.

4.2.1 FEASABILITY OF HYDROGEN FUEL

A hydrogen consumption test under six standard cycles by Duan et al. (2021) showed minimal differences (12%) between calculated and tested driving ranges. As the number of cycles increased, the differences between the calculated average and actual mileage decreased. Perez et al. (2021) assessed the feasibility of hydrogen fuel for very heavy vehicles to determine demand, availability, and pricing. The study compared hydrogen with equivalent diesel fuel consumption. The study established that heavy vehicles use less hydrogen (8.5 PJ) than diesel (14.7 PJ) for the same travel distance. The competitive advantage of hydrogen fuel cells can be obtained by increasing efficiency in the entire process, which involves production, storage, transportation, and application. Figure 4.2 shows the hydrogen industry, current hydrogen sources, and global consumption.

Figure 4.2. Hydrogen Economy. Source : Nasser et al. (2022)



4.2.2 ENERGY EFFICIENCY

Studies show that hydrogen fuel cells have the potential to replace traditional energy sources. For example, Zhang et al. (2019) argued that hydrogen fuel cells have a high energy conversion efficiency of 60%-80% or close to 200% higher than conventional firepower points. Baba et al. (2021) note that compressed hydrogen gas has a high energy density (about 1000 Wh/kg) than lithium-based batteries. Proton exchange membranes, mostly used in small applications, hybrid cars, and residentials, can be used for other purposes because of their relatively low temperature, ability to produce electricity and efficiency. Table 4.1 shows the proton exchange membrane (PEM) system performance compared to solid oxide fuel cells (SOFC) based on a demonstration project (Cigolotti et al., 2021). The SOFC field data differed from lab findings on optimal conditions where thermal efficiency was 46% rather than 53%. Similarly, electrical efficiency was 37% rather than 42%. This was unlike the proton exchange membrane, where the field results perfectly matched lab results. According to Nasser et al. (2022), proton exchange membrane has advantages like dealing with load fluctuation because of their rapid response. Similarly, produced hydrogen has a 99.999% purity level. However, it is costly because of the material used in the electrolyser.

Table 4.1: PEM and SOFC performance. Source: Cigolotti et al. (2021)

Attribute	**PEM**	**SOFC**
Electric capacity	0.3-5	0.7-2.5
Thermal capacity	14-22	0.6-25
System efficiency	85-90	80-95
Electric efficiency	35-38	35-60

A study by Dash et al. (2022) shows that fuel cells have an efficiency rate of 60% while combustion-based power plants have an efficiency of 33-35%. Dash notes that a gasoline engine in a normal car is about 20% efficient in converting energy into power used to move the vehicle in normal driving conditions. This is unlike hydrogen fuel cell vehicles that use

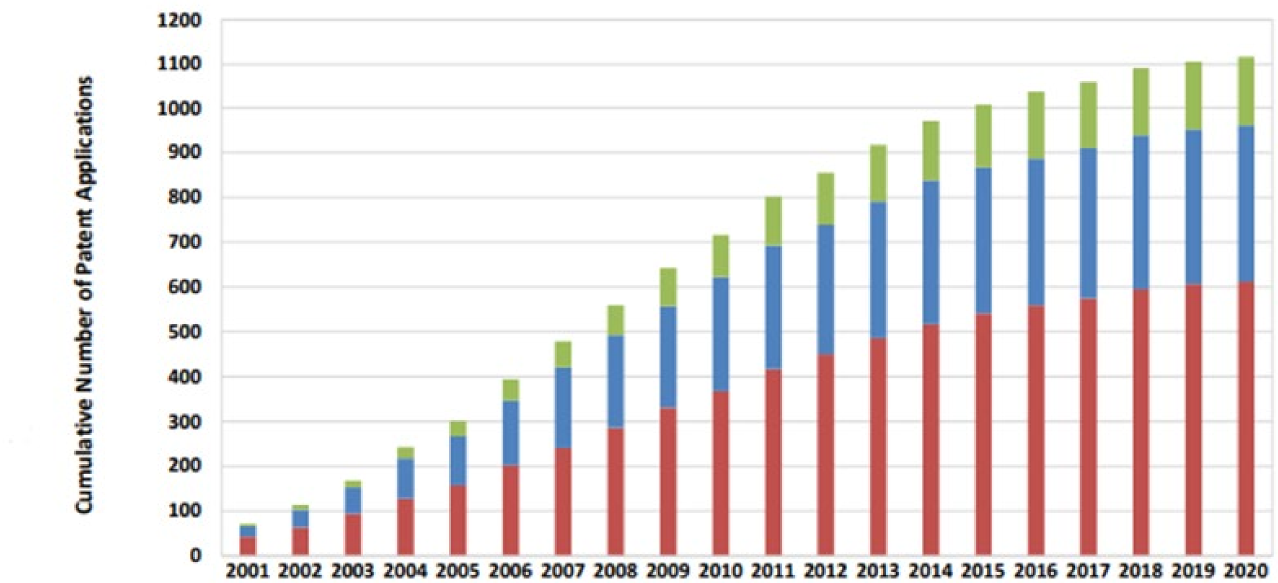
40-60% of the energy translating to 50% lower fuel consumption compared to internal combustion vehicles.

4.2.3 CURRENT USAGE AND FUTURE USE

The demand for hydrogen fuel cells continues to grow as countries resort to renewable energy sources. The demand continues to drive research and investment in the sector. Chart 4.4 shows global demand for hydrogen from 1975-2018. A surge in demand also led to an increase in patents as more companies seek to exploit the hydrogen economy by patenting new technologies that will ensure adequate supply. For example, the U.S. has reported significant increase in patents on fuel cells, hydrogen production, storage and delivery. Chart 4.3 shows growth in patents from 2000-2020. As the chart shows, patents on fuel cells (highlighted in the chart) were more than 50% in the twenty years under consideration. For instance, there were 1117 patent applications in 2020 with fuel cells accounting for 612 translating to 55% while production and delivery were 349 or 31% while storage was 156 or 14%.

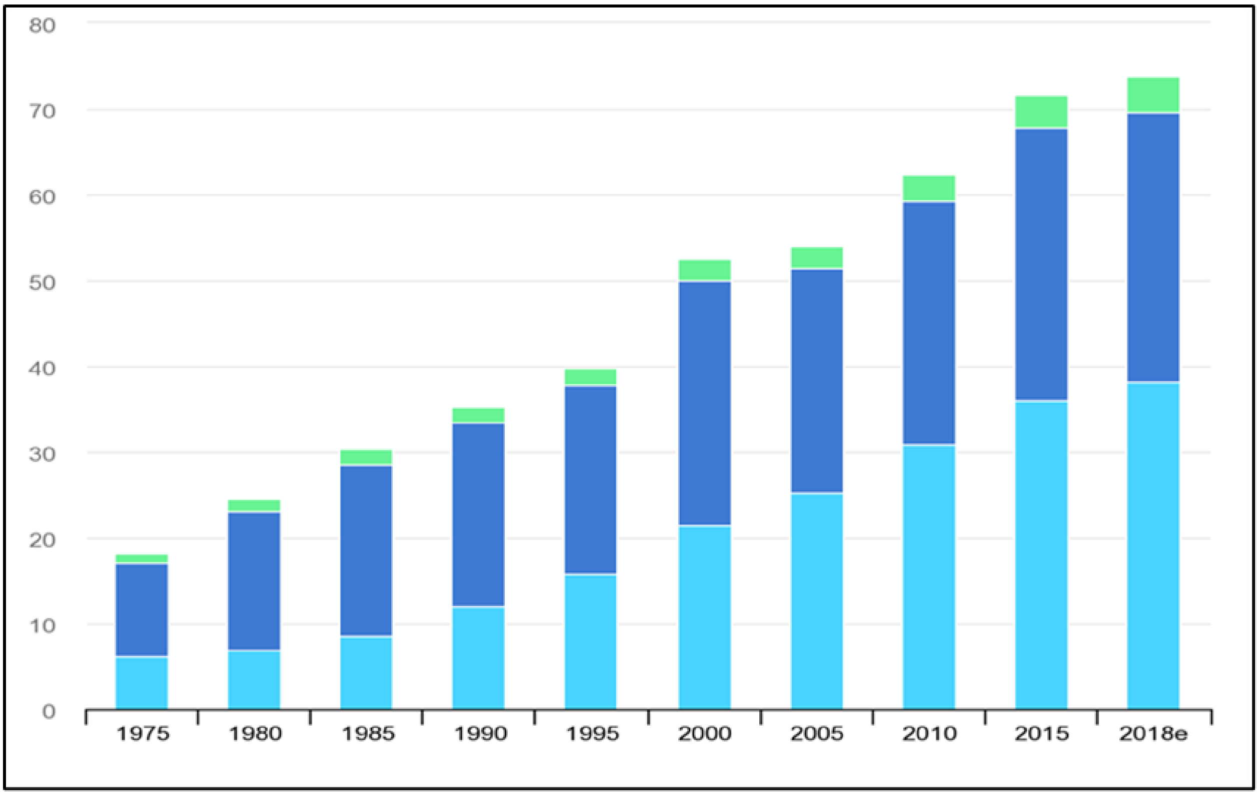
CHAPTER FOUR

Chart 4.3. Cumulative patents awarded 2000-2020. Source: Steele (2020)



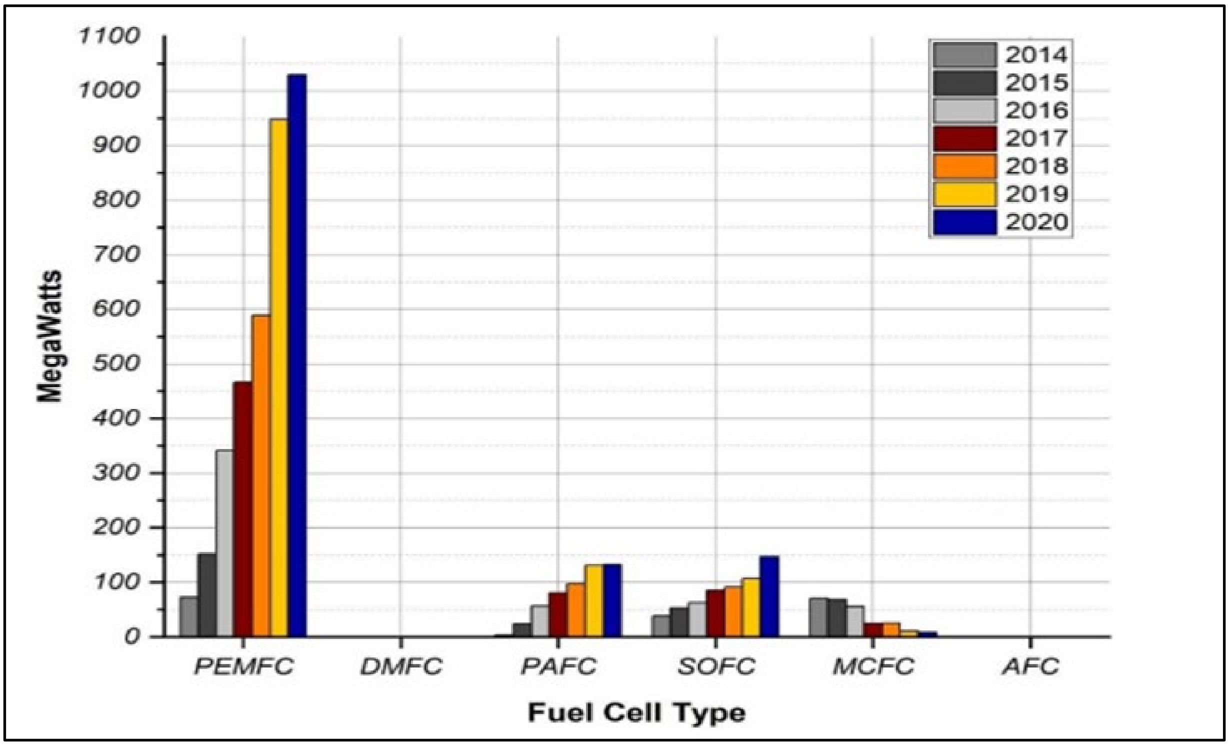
	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Storage	6	11	15	25	34	47	58	66	85	93	109	116	126	133	140	149	151	153	154	156
Production/Delivery	23	39	59	90	109	145	180	207	226	255	276	289	305	321	326	328	335	344	345	349
Fuel Cell	43	64	94	128	158	202	241	286	331	368	417	450	486	517	541	559	575	595	607	612
Total	72	114	168	243	301	394	479	559	642	716	802	855	917	971	1007	1036	1061	1092	1106	1117

Chart 4.4. Global demand for pure hydrogen. Source: Steele (2020).



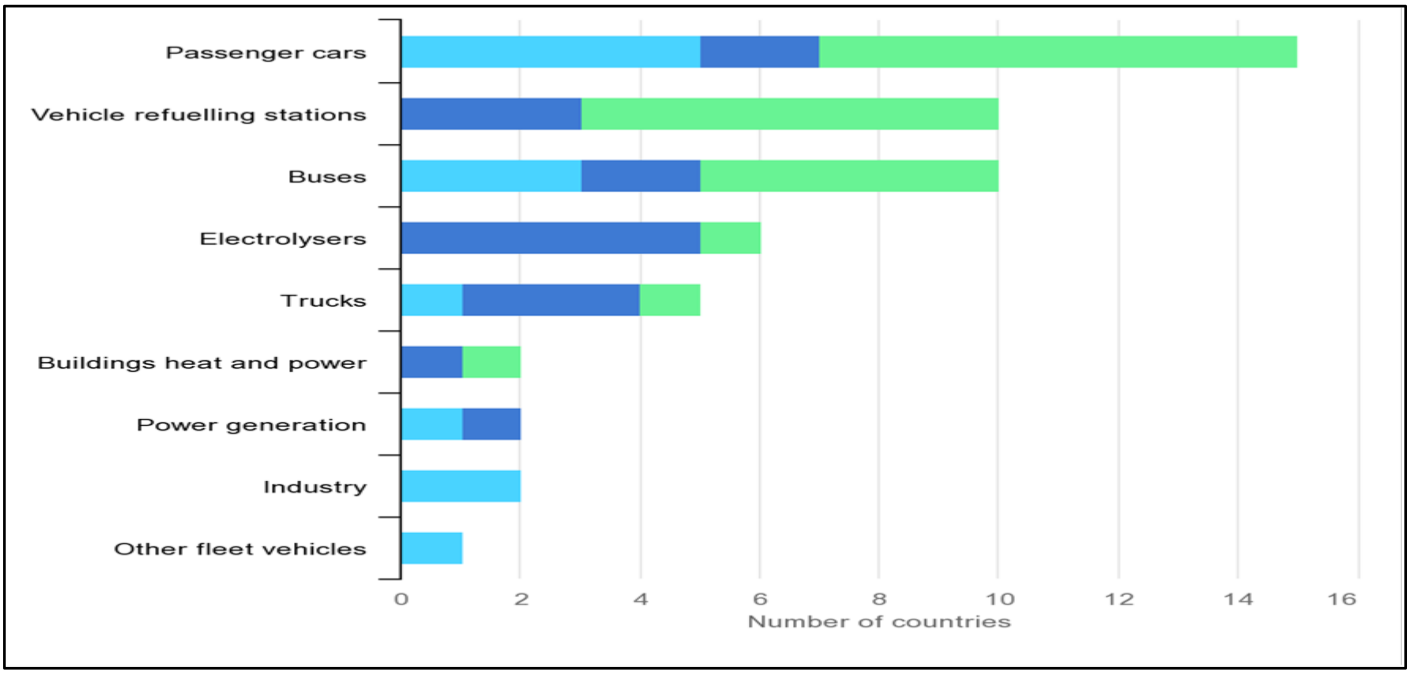
Baharuddin et al. (2021) examined fuel cell use in different countries and established significant cost savings and potential for growth. For example, the study showed a significant potential for fuel cells to power the transport sector, which is the largest energy consumer in China at 20%. In Denmark, where the transport sector contributes 25% of carbon emissions, fuel cells can help reduce this emission by driving toward a 70% reduction in carbon by 2030. The U.S. had 80 fuel cell power plants by the end of 2019, contributing 190 megawatts, with the largest generating 27 megawatts. The fuel cells can address carbon emission, which stands at 46%, with the transport sector contributing the largest proportion. Currently, fuel cell installation differs in type and use. For example, the proton exchange membrane is the most highly used and shows growing trends, whereas sodium oxide fuel cells are the second, followed by the phosphoric acid fuel cell. Chart 4.5 shows the fuel cell size installations from 2014-2020.

Chart 4.5: Fuel size installation 2014-2020. Source : Cigolotti et al. (2021).



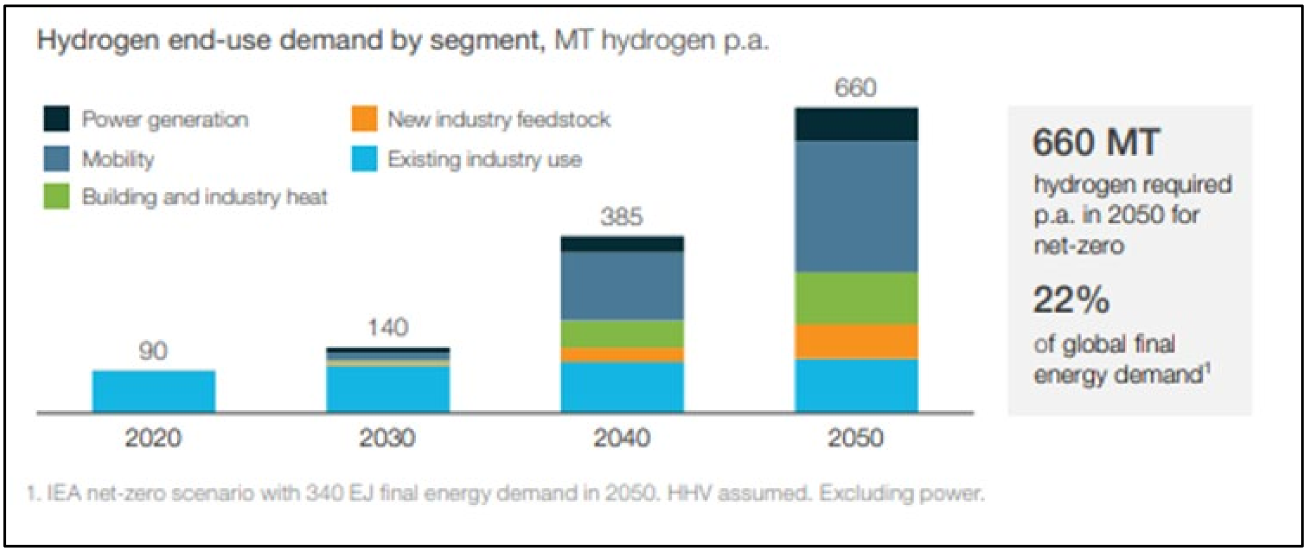
Different countries are supporting hydrogen fuel cell use by developing frameworks and policies that promote investment in hydrogen economy. The support targets different areas with particular interest on the transport sector which is the leading contributor of greenhouse gases. Chart 4.6 shows policy support for the hydrogen economy by the year 2018.

Chart 4.6. Policy support by different countries and target 2018. Source: iea.org (2018).



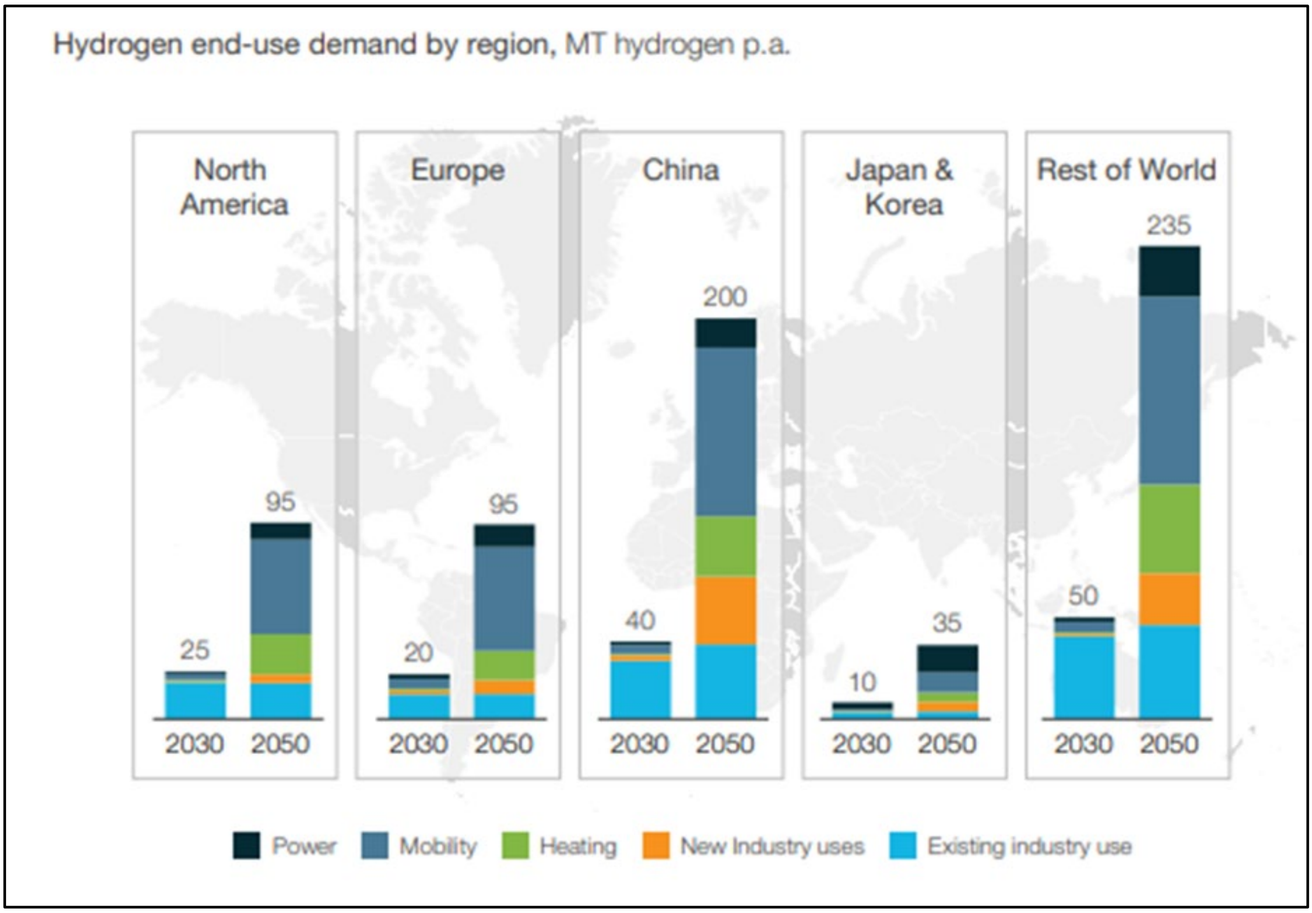
A report by McKinsey shows that the demand for hydrogen will continue growing as countries move towards net zero scenario. The global hydrogen demand by different segment will continue growing from the current 90 to 660 million metric tons per annum in 2050 accounting for 22% of the global final energy demand.

Chart 4.7. Hydrogen end use by segment. Source: Rattan (2021).



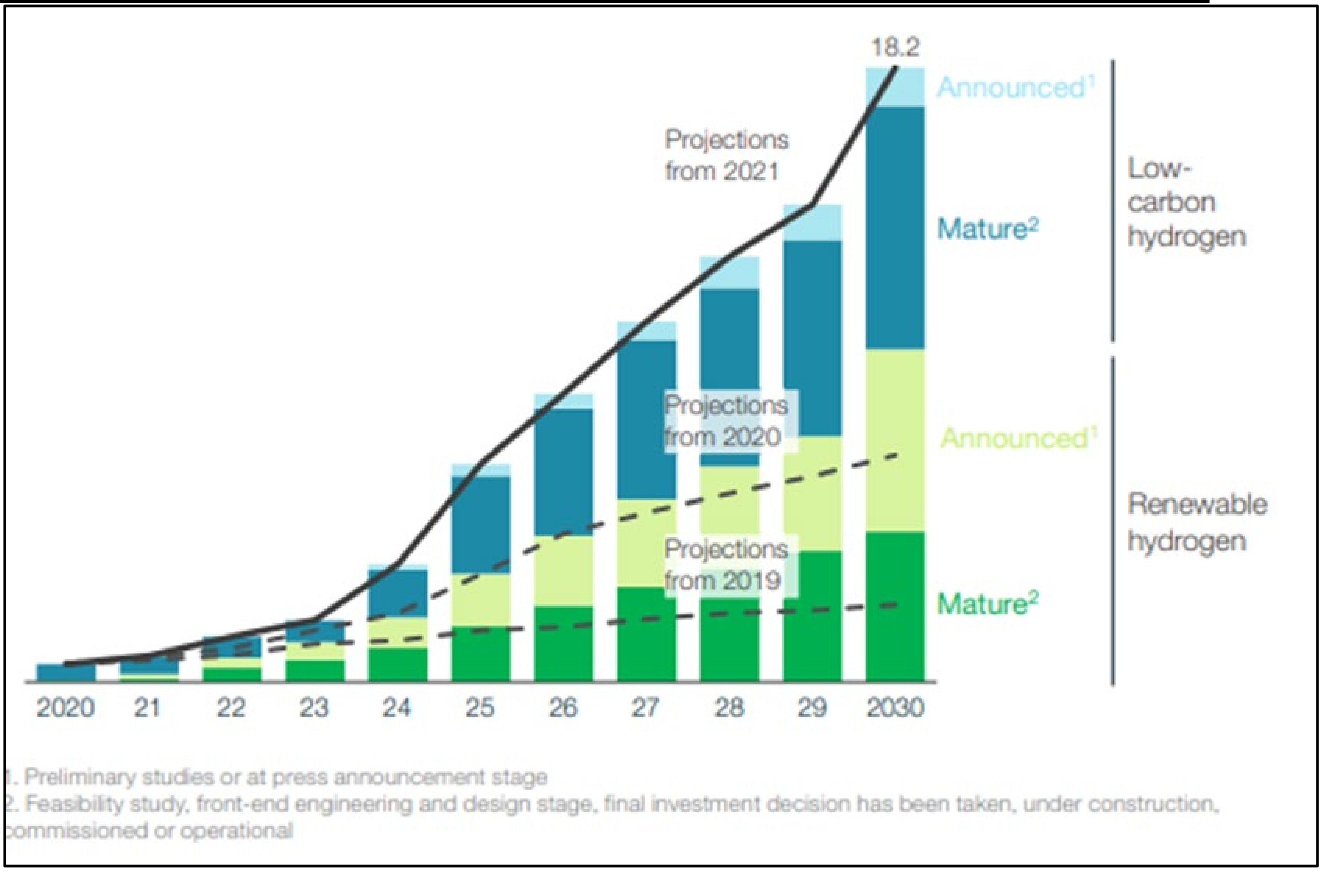
Hydrogen demand across regions will also differ depending on the economic activities and level of production. For example, it is expected that the markets with the highest demand will be China followed by North America and Europe. Chart 4.8 provides a detailed examination of the projected demand.

Chart 4.8. Hydrogen demand by region in 2030 and 2050. Source: Rattan (2021).



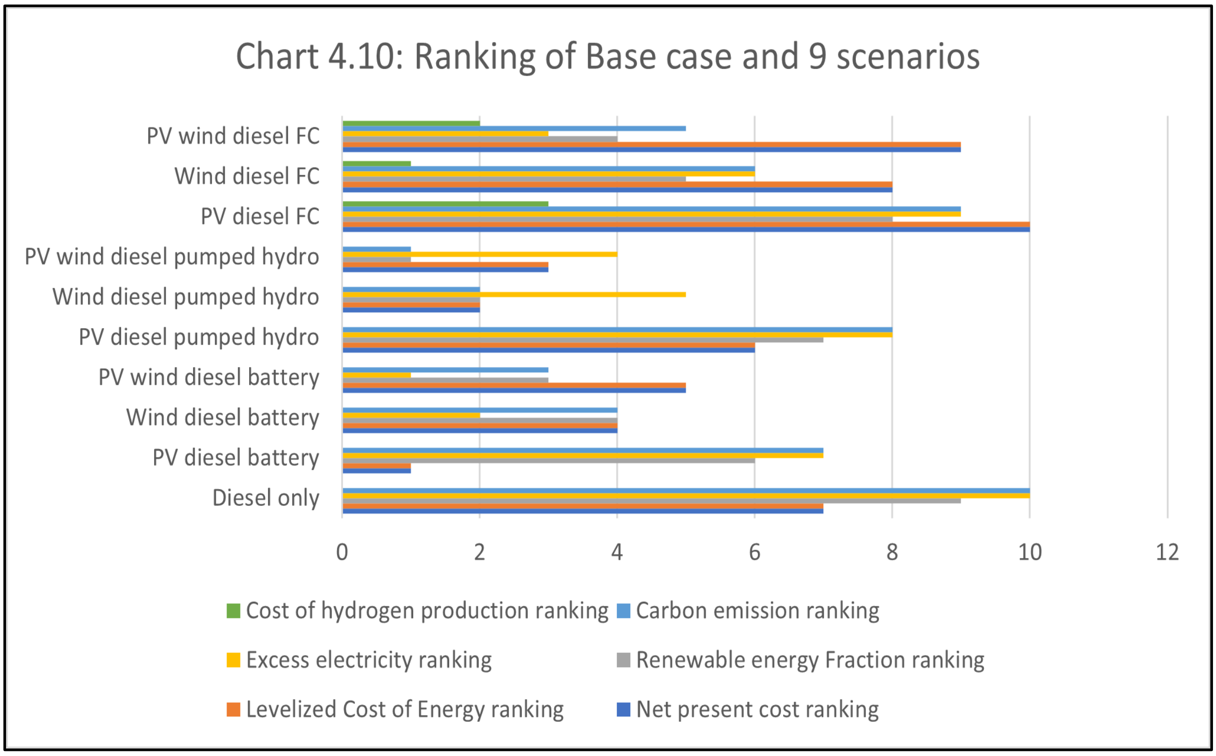
As the desire from renewable energy increase, there is increased investment in the hydrogen economy where players estimate an additional 18 million metric tons by 2030 and an additional 13 million metric tons after 2030.

Chart 4.9 shows renewable hydrogen and low carbon hydrogen by 2030.



4.2.4 SYSTEM PERFOMANCE

Awan et al. (2018) analysed the techno-economic performance of HRES (hybrid renewable energy system using batteries, hydrogen-based storage, and pumped hydro-based storage units. The study used nine scenarios to establish the optimum size of different components in each scenario based on net present cost. The study evaluated the scenarios on the Levelized energy cost, payback period, carbon dioxide emission, renewable energy fraction, and excess electricity. Chart 4.10 shows the rankings of the nine scenarios. The comparison shows different outcomes, but the photovoltaic diesel battery was the most economically viable. In contrast, photovoltaic diesel fuel cells were the least economical. Wind diesel fuel cell was the most economical in the hydrogen-based category. The study established that systems with a storage battery and pumped hydro storage were the most economically feasible compared to those with hydrogen-based storage. Nasser et al. (2022) compared green hydrogen production using renewable and non-renewable energies and found that traditional power sources like nuclear and coal have the lowest Levelized energy cost yet negatively affect the environment. However, renewable energy sources have higher costs, yet they are environmentally friendly.

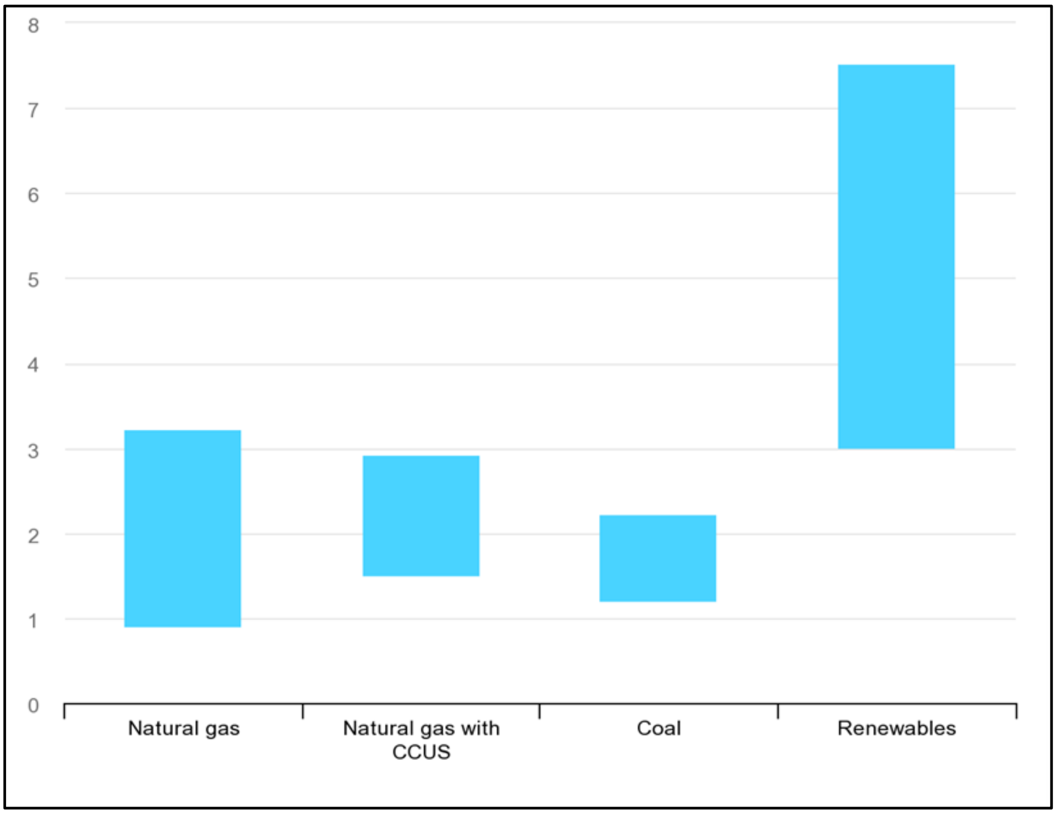


Source : Awan et al. (2018)

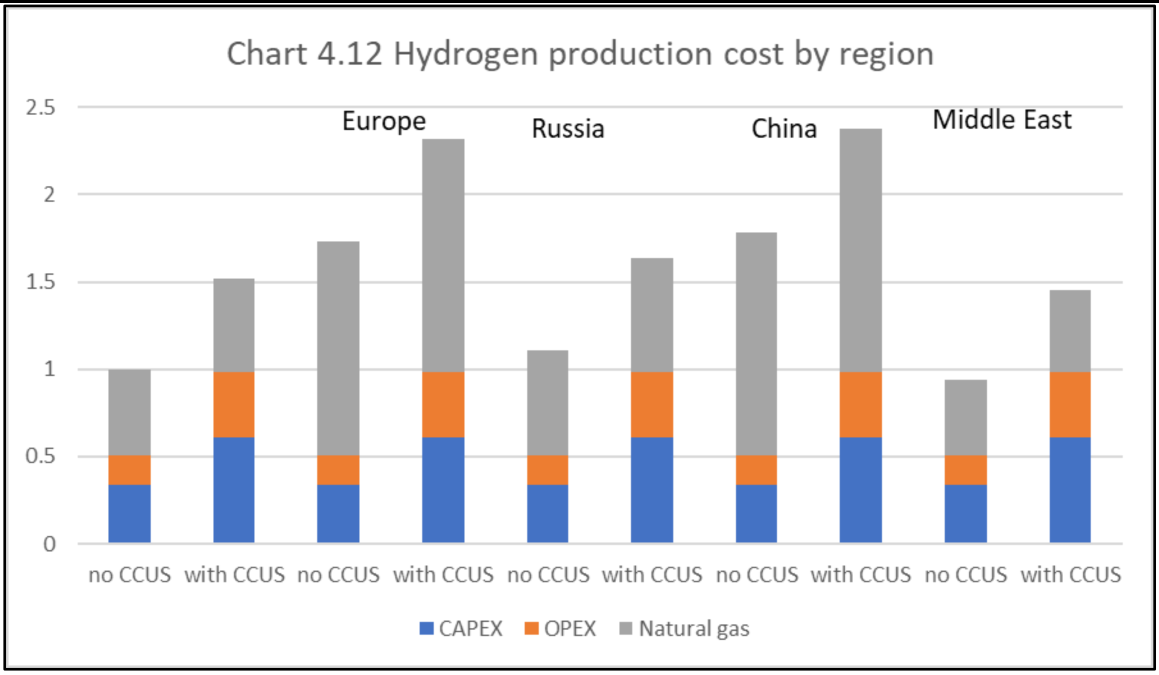
4.3 COSTING

Studies show that hydrogen production, electrolyser capital cost, electricity input, operations and maintenance costs, and the electrolyser's capital recovery affect the fuel cells' competitiveness. Costing, in this case, applies to the entire hydrogen economy from production, storage, transportation, and application which influence the competitiveness of the fuel cells. Costs varies depending on the technology used. Figure 4.11 shows that coal (1.2-2.2 USD/KG) and natural gas (0.9-3.2 USD/KG) have the lowest cost while renewables have the highest 3.0-7.5 USD/kg.

Figure 4.11. Hydrogen production cost by source 2018. Source: iea.org (2018).

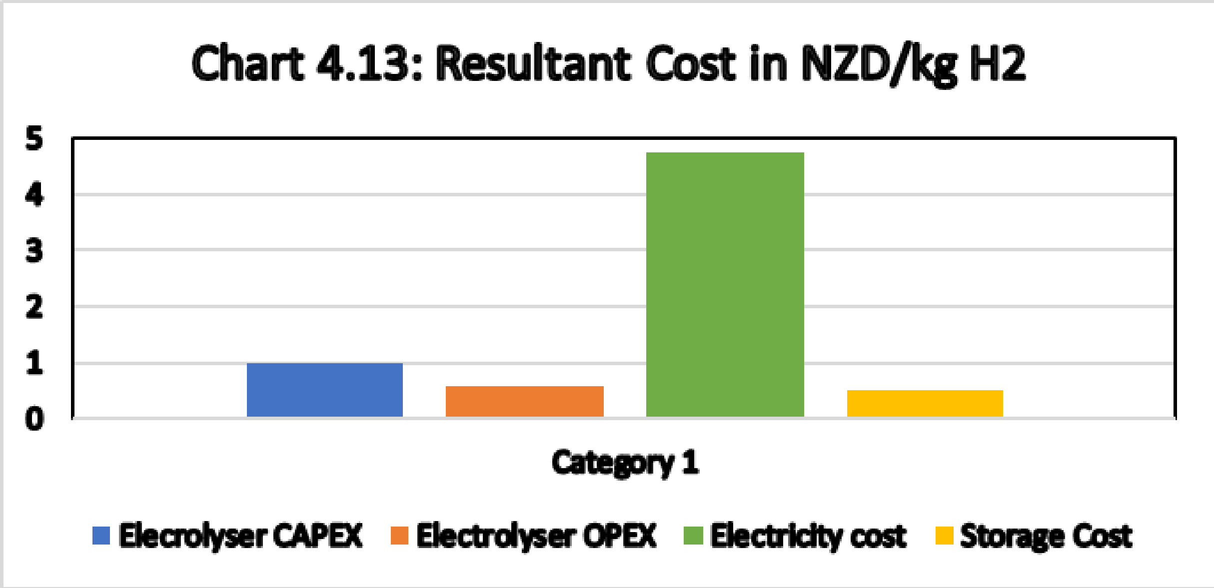


Natural gas production cost varies from one region to another depending on the deposit volumes. For example, chart 4.12 shows hydrogen production cost in 2018 using natural gas in selected regions. The chart shows that some regions like the United States, Russia, and the Middle East can produce hydrogen at lower cost compared to Europe and China.



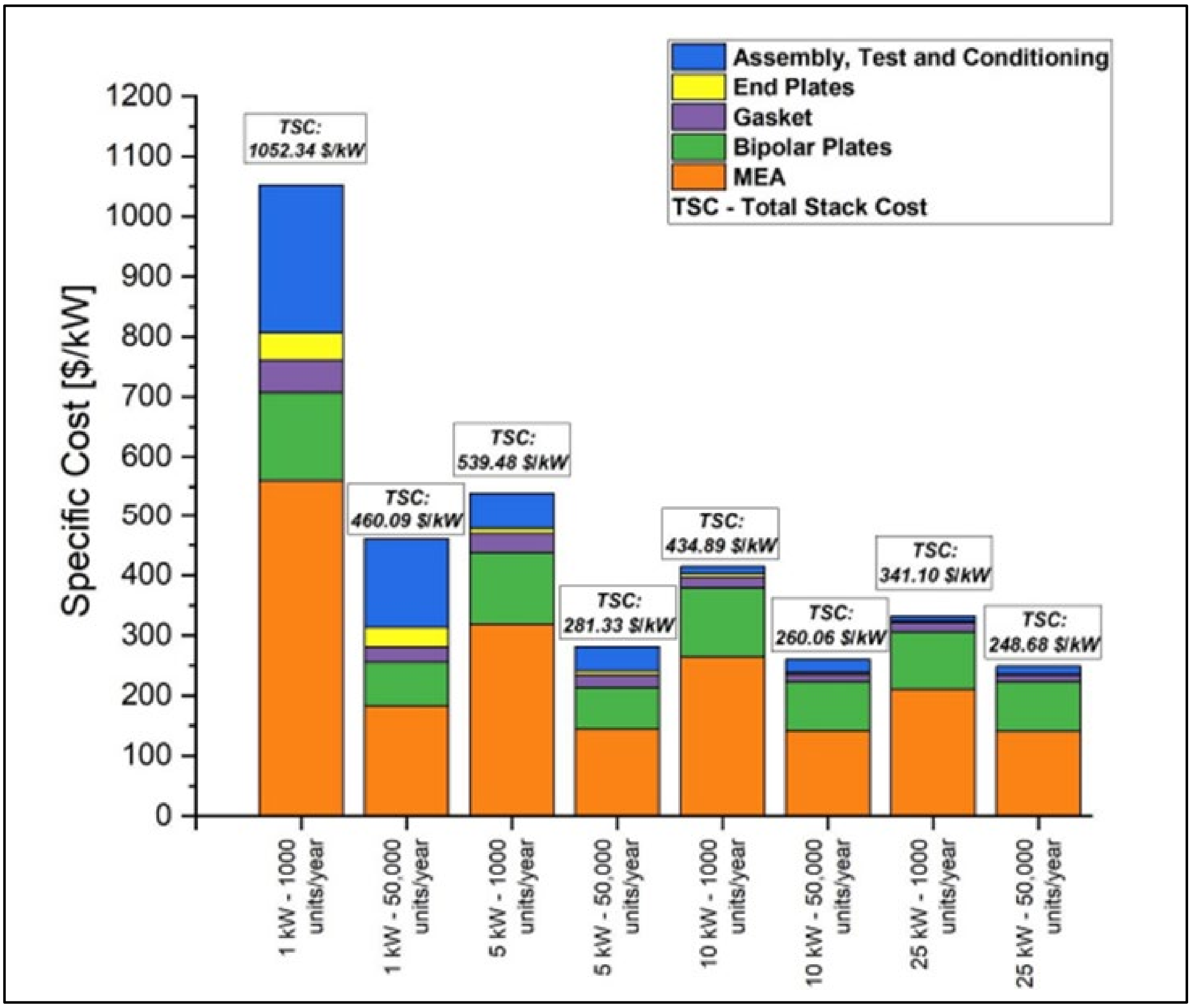
Source: iea.org (2018)

Chart 4.13 shows the resultant costs in New Zealand dollars per kilogram of hydrogen. Another study by Cigolotti et al. (2021) evaluated the cost at the component level of four heat and power systems of different sizes (1Kw-25Kw). The studies involved proton exchange membranes and solid oxide fuel cells and evaluated the hypothetical market and potential of the two systems. The study included cost variation using 100 -50,000 units per year. Chart 4.14 shows the analysis. The study established that large-scale production would lead to cost reduction. For example, an additional kilowatt leads to a 50% decline in proton exchange membrane stack costs from $1052.34 per kilowatt to $460.09 per kilowatt. Similarly, solid oxide fuel cell costs decline with large-scale production. For instance, the cost declined from $8482.5 per kilowatt when only one unit is produced in a year to $1183.04 per kilowatt when 50,000 units are produced in a year.



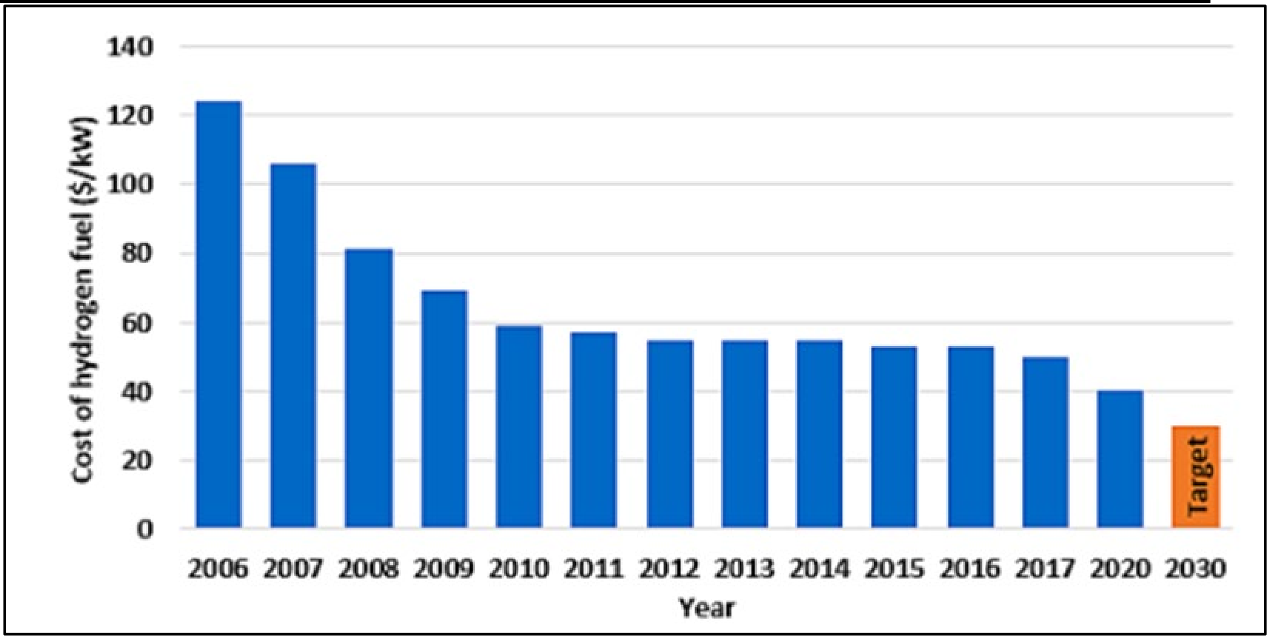
Source : Perez et al. (2021)

Figure 4.14. Fuel cell stack potential cost breakdown. Source: Cigolotti et al. (2021).



According to Gallas and Stobnicki (2022), the production cost continues to decline and is expected to be $30 per kilowatt. Chart 4.15 shows the decline in production cost from 2006 to 2020 and the projected cost by 2030.

Chart 4.15. Historical cost of hydrogen fuel. Source: Gallas and Stobnicki (2022).



4.4 QUALITATIVE RESULTS

This study borrows from the comparative advantage model which determines the opportunity costs or hydrogen fuel cells that can be produced using the same resources as used in conventional fuel sources like fossil, natural gas or wind. The researcher developed a working analytical framework based on selected themes aligned with the research objectives and identified gaps. The key themes from the study include energy security, environmental impact, social impact, economic impact, hydrogen production, transport and distribution, storage, and safety issue. The qualitative data from different sources were compared, and results were synthesised based on the methodological criteria.

4.4.1 ENERGY SECURITY

The secondary data shows that hydrogen fuel cells can ensure energy security by producing clean, affordable energy that meets environmental and developmental needs. For example, Zhang et al. (2019) presented a detailed explanation of fuel cell applications in decentralised power stations, vehicles, and portable power. For instance, the author argued that hydrogen fuel cells' energy conversion is higher compared to traditional energy sources. Similarly, the noise and pollution are small, yet devices can be small or large and very flexible, thus offering a broad application range. Baharuddin et al. (2021) showed how fuel cells could ensure energy security across countries like the U.S. Japan, Denmark, China, and Germany. Yang et al. (2022) explored hydrogen fuel cell-based transportation technologies likely to enhance energy security and identified hydrogen tanks, convertor, proton exchange membranes, catalysis technology, and hydrogen railway/ locomotive. Baba et al., 2021 argue that high-temperature fuel cells can be used for stationery systems, while low-temperature fuel cells are useful in portable applications. For instance, proton exchange membrane fuel cells and polymer electrolyte membrane fuel cells are mostly used in applications related to nomadic electronics and electric vehicles, while other fuel cells like phosphoric acid, solid oxide, direct methanol, alkaline, microbial, and molten carbonate fuel cells are used for other purposes. Baba et al. note that most transportation-related studies use proton exchange membrane technology since it has low operating temperatures and is thus easier to handle, unlike high-temperature cells like solid oxide. Cigolotti et al. (2021) noted that proton exchange membranes could primarily be used in micro-cogeneration systems by residential users.

4.4.2 ENVIRONMENTAL BENEFITS

Hydrogen fuel cells can help reduce overreliance on fossil fuels, contributing 28% of greenhouse gas emissions (Dash et al., 2022). Hydrogen fuel cells are environmentally friendly since they only produce water vapour, hot air, and no greenhouse gases. Manoharan et al. (2019) note that the cells do not produce harmful emissions, unlike internal combustion engines, which are the major pollutants. A fuel cell allows the conversion of chemical energy into electrical energy in an environmentally friendly way. The technology is efficient (60%) compared to combustion technologies (33-35%) (Dash et al., 2022). Gallas and Stobnicki (2022) support this argument noting that hydrogen fuel cells can enable countries to meet their energy requirements while protecting the environment. The author used different case studies of hydrogen trains and the technologies used.

4.4.3 SOCIOECONOMIC BENEFITS

Results show that hydrogen has the potential to address global greenhouse gas emissions. It contributes to the energy mix while reducing its carbon footprint. It can help counter the rising average temperatures (Dewangan et al., 2022). Li et al. (2022). Based on the sustainable model described in the literature review section, it is possible to establish a connection between the secondary data collected and how hydrogen can socially benefit society. For example, Bethoux (2020) shows that there is a need to develop alternative energy sources to replace oil reserves which are likely to be depleted in fifty years. Similarly, the shift towards cleaner energies like electric trains has shortcomings like capital requirements to electrify the entire line, which can be costly, particularly for low-income countries (Gallas and Stobnicki, 2022). Hydrogen can address this shortcoming by providing an alternative fuel source. An alternative energy source can help society to continue living a productive life. Reducing the over-dependence on fossil fuels and shifting to renewable energy has health-related benefits since its by-products are only warm air and water vapour.

4.4.4 ECONOMIC BENEFITS

The hydrogen economy creates employment for thousands in fuel cell production, distribution, storage and application. It will enable countries to meet their energy demand and thus continue producing products and services that contribute to their growth. The adoption of renewable energy allows governments to plan their energy needs, reduce the adverse effects of climate change and improve livelihoods. For instance, according to Gallas and Stobnicki (2022), countries in the EU reported a significant decline in toxic substances released into the atmosphere following the adoption of renewable energy sources. On a positive note, the reduction in greenhouse gases emission was associated with growth in GDP. Chart 4.16 shows the changes from 2000-2018.

Chart 4.16. Relative changes in greenhouse gases emission in EU 2000-2018. Source: Gallas and Stobnicki (2022).

A press release from the UK government shows that the country wants to invest in the hydrogen economy aimed at creating 9000 jobs and unlocking four billion sterling pounds by 2030 (Gov.uk, 2021). The UK has also developed a hydrogen strategy to enhance investment

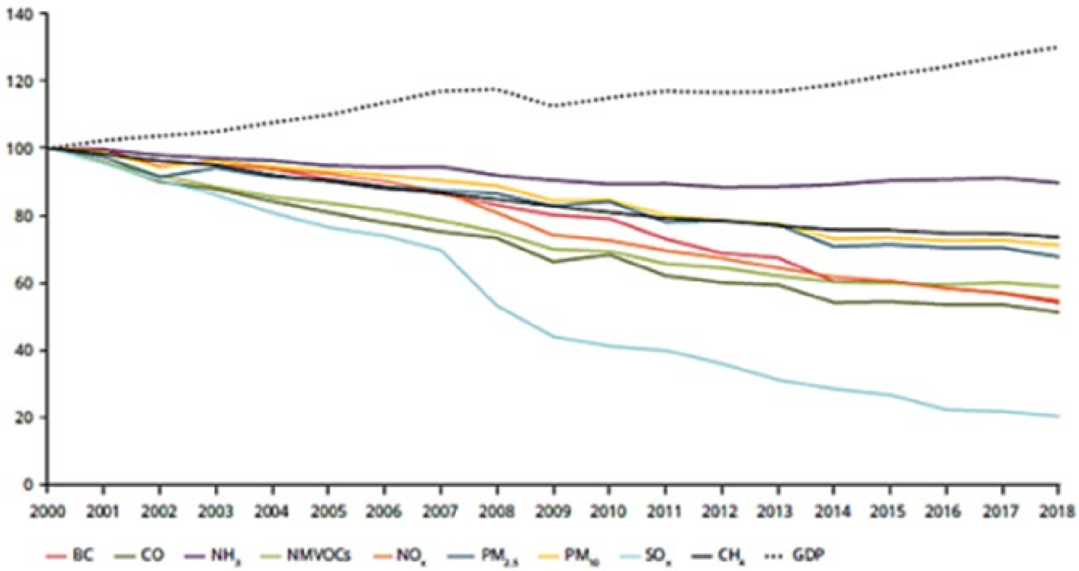


Figure 1. Relative change in the emissions of toxic compounds in EU-28 since 2000 (BC – soot, CO – carbon monoxide, NH_3 – ammonia, NMVOCs – non-methane volatile organic compounds, NO_X – nitrogen oxides, $PM_{2.5}$ – particulate matter under 2.5 µm, PM_{10} – particulate matter in the range 2.5-10 µm, SO_X – sulfur oxides, CH_4 – methane, GDP – cumulative Gross Domestic Product) [Report 2020]

in the hydrogen economy as it transitions to net zero. The strategy aims to decarbonise the UK economy, including the hard-to-electrify industrial sector. The country believes in its expertise, geology and infrastructure to become a global leader and secure economic opportunities.

4.4.5 COMPLEXITY OF FUEL CELL

Fuel cells are structurally complex, complicating the management and use of hydrogen as renewable energy. According to Bethoux (2020), complexity arises from the fuel cell, while management arises from the storage tanks. The two factors affect fuel cells' optimal operating conditions and ability to provide electric power. Bethoux further notes that the fuel cell system is less efficient, particularly when the power load is low. This is unlike mid-hybrid and range extender architecture, which allows for decoupling and thus facilitates peak-to-peak power demand. Increasing fuel cell efficiency leads to increased costs which can limit high-volume manufacturing. Manoharan et al. (2019) observe that fuel cell vehicles encounter new challenges like low power density that requires the installation of supercapacitors and fuel cell batteries. Hydrogen fuel cells can address the current energy needs since they have unique characteristics like fast refuelling compared to battery charging, high tolerance to low temperatures, high expected lifetime, and the potential to share hydrogen infrastructure and establish strategic partnerships to promote the hydrogen economy.

4.4.6 TRANSPORT AND DISTRIBUTION

Hydrogen production technology determines transport and distribution. For instance, Wulf and Kaltschmitt (2018) argue that hydrogen produced at the refuelling station using alkaline and proton exchange membrane electrolysis will only be distributed by the refuelling station. The station compresses the hydrogen to 800 bars to ensure faster dispensing to the vehicles. Onsite-produced and dehydrogenation hydrogen has lower pressure, unlike delivered hydrogen, which is transported in high-pressure tanks at 500 bars. During dispensation, hydrogen releases energy when it is expanded from 800 bars; thus, it must be precooled to -40ºC to avoid any possible damage. Bethoux (2020) points out that proton exchange membranes have mechanical strength issues and must be maintained at temperatures (below 100 degrees centigrade). The temperature range leads to excessive water in the electrodes, partially blocking them and impairing electricity production.

4.4.7 STORAGE

Hydrogen storage is a limiting factor in the competitiveness of fuel cells despite showing significant potential to address current and future energy needs. According to Yadav et al. (2022), despite being a promising alternative to fossil fuels, practical application is hampered by the difficulty in storage because of safety and energy density issues. Storage issues affect the viability of hydrogen fuel cells, as shown by Awan et al. (2018), who noted that hydrogen storage systems are less economical compared with battery-based systems. Manoharan et al. (2019) further noted that hydrogen requires pressurised tanks of enough strength. Tank volumes are problematic since, unlike other gases, hydrogen has a low density and thus cannot be stored in some tanks. Also, storing liquid hydrogen gas at low temperatures is inappropriate for everyday vehicle use. Another challenge is that hydrogen stored daily in the storage system declines daily by 1% through boiling, yet liquid hydrogen needs high refrigeration to maintain hydrogen at 20 K (Manoharan et al.). Baba et al. (2021) advocate for the development of hydrogen storage technology to address the current problem.

4.4.8 PRODUCTION COSTS

The potential of hydrogen fuel cells to replace conventional energy sources has its drawback that will limit its competitiveness. For example, according to Baba et al. (2021), fuel cells have shortcomings when used in hybrid vehicles because of their heavy weight, short range, and overheating during loading. Baba et al. argue that fuel cells can create a competitive edge if their performance, cost, reliability, availability, public satisfaction, and durability are comparable to traditional energy sources. Nasser et al. (2022) reported similar findings and concluded that hydrogen production is expensive compared to conventional sources and will remain so if there is no government intervention. Wulf and Kaltschmitt (2018) concluded that hydrogen supply chains have higher costs compared to conventional energy sources like fossil fuels and biomass. Awan et al. (2018) reported that systems with fuel cells, hydrogen tanks, and electrolysers have a lower return on investment compared to systems with pumped hydro and batteries. Li et al. (2022) further observed that the transition to hydrogen fuel cells is affected by the total costs and competition from cheaper alternatives like fossil fuel.

Despite increased research on the ability of fuel cells to address current energy needs, most fuel cell cars are still at the conception stage since mass production of fuel cells is restricted by the high cost (Qudrat-Ullah, 2022). Another study on the cost of deploying a hydrogen refuelling network compared pipeline distribution system and ownership of low-emission technologies and established that heavy-duty fuel cell electric vehicles are uncompetitive in all aspects because of the high powertrain costs. A study conducted in China showed that truck drivers are unwilling to buy heavy-duty fuel-cell electric vehicles partly because their prices are higher than diesel-powered vehicles (Gallo and Marinelli, 2022). However, production costs continue to decline as countries develop new technologies or increase production volume. The next chapter presents a detailed discussion of the results. It integrates the literature reviewed to determine the competitiveness of hydrogen fuel cells.

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5 CHAPTER FIVE: Discussion, Conclusions and Recommendations

5.0 OVERVIEW

This chapter discusses the research results and the conclusions based on such and provides recommendations going forward.

5.1 DISCUSSION

5.1.1 FEASIBILITY AND ENERGY EFFICIENCY OF FUELS CELLS

This study's findings show the potential of hydrogen fuel cells as an alternative to conventional energy sources. For instance, the secondary data sources show that calculated and test results show similar outcomes, thus supporting arguments that hydrogen can be used as a cleaner energy source replacing conventional sources like fossil fuels. Further, the findings show that hydrogen has more energy conversion efficiency than non-renewable sources like diesel and thus can be used to power heavy commercial vehicles. High energy efficiency rates give hydrogen fuel cells an edge over conventional energy sources. The cells can be used to produce electricity for different applications. These findings agree with the literature reviewed by Felseghi et al. (2019), Lucia (2014), and Kundu and Dutta (2016) on the functioning and working of fuel cells to produce electricity. Hydrogen fuels from proton exchange membranes can be used in small applications, hybrid cars, and residentials since they operate at relatively lower temperatures, are more efficient, and generate electricity. These findings align with Körner et al. (2015) argument in the literature reviewed, noting that fuel cells can be used in cars, mobile phones, delivery ships, power and heat generators, and buses.

5.1.2 BENEFITS OF HYDROGEN FUEL CELLS

5.1.2.1 ENVIRONMENTAL BENEFITS

The current study found substantial environmental benefits derived from hydrogen fuel cells. It can replace fossil fuel which contributes to 28% of greenhouse gasses. Hydrogen is a highly efficient renewable energy source compared to conventional fuel sources like gasoline or diesel. Hydrogen by-products are water vapour and hot air, unlike fossil fuel which has a low fuel efficiency rate and produces greenhouse gasses as by-products. Dash et al. (2022) established that hydrogen has an efficiency rate of 60%, almost double that of combustion technologies ranging from 33-35%. However, the gasoline engine in a typical car is only 20% showing that hydrogen fuel-powered vehicles consume less energy, yet they do not pollute the environment. Hydrogen's high energy conversion efficiency makes it ideal for powering industries, vehicles, and other applications, thus reducing carbon footprint. This argument is supported by Zhang et al. (2019) and Baba et al., who appreciated hydrogen's high energy conversion efficiency and density. Cigolotti et al. (2021) demonstration project showed that the proton exchange membrane primarily used in hydrogen fuel cells has a high energy efficiency rate comparable to lab results. Environmental benefits can also increase when renewable energy sources like solar or wind are used to produce hydron gas. This was evidenced in Awan et al.'s (2018) study, which showed that the wind-diesel fuel cell scenario was the most economical under the hydrogen-based category.

Despite high levelized costs, hydron fuel cells have no negative impacts on the environment, unlike non-renewable energy sources, which have lower levelized costs yet negatively affect the environment (Nasser et al., 2022). This study's findings align with the literature reviewed, which showed that hydrogen fuel cells significantly benefit the environment. For example, Thomas et al. (2020), Hwang and Varma (2014), Abdelkareem et al. (2021), Clune, Crossin, and Verghese (2017), Sgobbi et al. (2016), Baroutaji et al. (2019), Tanç et al. (2019) and Körner et al. (2015) argued that hydrogen fuel cells provide cleaner energy thus reduce pollution. Since they only produce water and heat, the fuel cells have no hazardous pollutants like sulphur dioxide, carbon monoxide, nitrogen dioxide, erratic organic compounds, and particulate matter. The literature reviewed showed that hydrogen is a leading clean energy carrier, and though its production uses non-renewable energy sources, like fossil fuels or natural gas, it is possible to monitor and control their emission (Fan et al., 2021; Hardman, Steinberger-Wilckens, and Van Der Horst, 2013). The little or no greenhouse gas emission creates an opportunity for more investment in hydrogen fuel cells and the development of policy frameworks to promote the uptake and research that can enhance the hydrogen economy as nations move towards zero-emission, thus creating a competitive advantage. Further, the benefits align with the theories of green economics and ecological carrying capacity discussed in the literature reviewed.

5.1.2.2 ECONOMIC BENEFITS

The findings from this study show that the hydrogen economy has significant economic benefits ranging from increased production, fuel security, efficiency, and investment in storage, distribution, and other infrastructure. Hydrogen is a leading energy carrier that is abundantly available; thus, nations are guaranteed adequate and reliable energy to power the transport sector, manufacturing, and other industries critical for economic development. The findings show that the hydrogen economy can create employment, promote growth in different sectors and enable governments to develop strategic plans that align with their energy needs, counter the adverse effects of climate change and ensure sustainable development. This argument aligns with the literature reviewed, where Manoharan et al. (2019), Sdanghi et al. (2019), Giorgi and Leccese (2013), Hart et al. (2016), Niakolas et al.

(2016) and Pudukudy et al. (2014) showed how hydrogen cells can promote economic growth, create new business opportunities, create employment, promote exports and enable countries to develop new revenue streams. A decline in greenhouse gases and increased economic activities lead to GDP growth while opening new sectors and securing economic opportunities. The findings are consistent with the past literature showing that the hydrogen economy could ensure affordable, reliable, and abundant energy to fuel all sectors. For instance, Mekhilef, Saidur, and Safari (2014) showed that hydrogen fuel cells could create new opportunities in energy production and use, thus enabling countries to be self-sufficient and avoid overreliance on fossil fuels that are prone to fluctuations. Dodds et al. (2015) and Itaoka, Saito, and Sasaki (2017) further reinforced this observation by demonstrating how hydrogen fuel cells can help diversify energy sources and needs and fuel conservation, thus enabling countries to develop resilient structures. This is particularly critical in a globalised world where issues like pandemics, wars, and geopolitics can adversely affect supply and demand.

Other studies in the literature reviewed that reinforced the importance of hydrogen fuel cells include Ehteshami and Chan (2014), Staffell et al. (2019), Hardman, Steinberger-Wilckens, and Van Der Horst (2013). The economic benefits of hydrogen fuel cells can outweigh the high investment cost needed by the hydrogen economy. Hydrogen fuel cells can spur economic growth and development in developed and developing countries while ensuring sustainable production in all sectors. Nations can capitalise on areas of their speciality in the hydrogen economy to create a competitive edge and continue their growth trajectory. Further, the findings align with sustainability theories like green economics.

5.1.2.3 *SOCIAL BENEFITS*

Findings from this study show that hydrogen fuel cells have substantial social and economic benefits needed in an ever-changing world. The results show that hydrogen fuel cells can reduce greenhouse gas emissions, which are beneficial to the environment and the health and well-being of the population. Similarly, the cells can help address the rising average temperature, which can adversely affect human existence. Further, the fuel cells can ensure sustainable energy and enable countries to meet their energy needs following dwindling oil reserves which can be depleted in fifty years. Additionally, the fuel cells promote investment and development of new technologies that improve livelihoods and living standards and create employment. The fuel cells are ideal for powering trains since they take a shorter time to recharge, have more fuel efficiency, and do not require excessive capital investment like electric trains that requires powering the entire line. The fuel cells can enable societies to live productive lives and continue offering products and services needed by the current and future generations.

The findings fit into the broader literature indicating that hydrogen fuel cells promote the creation and investment in services that conserve social capital. The cells promote environmental justice, ensure resource security, improve health, create employment opportunities and enable technological development, thus improving living standards, promoting social cohesion, and contributing to fuel security (Fereidounizadeh, 2021; Shang, 2014). The findings from this study show that hydrogen fuel cells have numerous social benefits that can solve current global problems arising from energy and natural resource scarcity. The results are critical since they align with the sustainability model and different theories, like the theory of ecological carrying capacity and green economics.

5.1.3 DRAWBACKS OF HYDROGEN FUEL CELLS

5.1.3.1 *COST*

Cost is one of the major factors affecting the competitiveness of hydrogen fuel cells. It affects the entire hydrogen economy from production, storage, distribution, and usage. The findings from this study show the high cost of producing the proton exchange membrane (Cigolotti et al., 2021) and the electricity cost of producing hydrogen (Perez et al., 2021). Baba et al. (2021), Li et al. (2022), Nasser et al. (2022), Qudrat-Ullah, 2022, and Wulf and Kaltschmitt (2018) noted that production cost continues to hamper the competitiveness of hydrogen fuel cells as an alternative to non-renewable energy sources. Other costs affecting hydrogen fuel cell competitiveness include operation, maintenance, and electrolyser capital. For example, Gallo and Marinelli (2022) found out that truck drivers in China are unwilling to buy fuel cell-powered vehicles because of the high price compared to conventional fuel sources like diesel. These findings align with the literature reviewed, where the European Commission (2017) argued that the cost of fuel cells should be competitive compared with other energy sources like batteries. However, hydrogen fuel cells are complicated, translating to high costs, as observed by Dodds et al. in the literature review. The findings in this study also agree with Maestre, Ortiz, and Ortiz (2021) argument in the literature review that polymer electrolyte membranes used in hydrogen fuel cells are costly, accounting for half of the fuel cell cost. Other researchers in the literature reviewed with similar conclusions include (Wang et al., 2020 and Sapkota et al. (2020). Maestre, Ortiz, and Ortiz (2021) and Baroutaji et al. (2019) argued that the initial cost is high and thus likely to affect the competitiveness of hydrogen fuel cells. This study shows that it is possible to enhance the competitiveness of hydrogen fuel cells by addressing cost-related issues in the hydrogen economy.

5.1.3.2 *STORAGE*

Findings from this study identified storage as a major hindrance in the hydrogen economy. Storage issues arise from safety and energy density concerns which require hydrogen to be stored in pressurised tanks of adequate strength, making the hydrogen economy less economical. Further, storage at low temperatures affects daily usage. Storage is associated with daily losses through boiling, yet still maintaining hydrogen at low temperatures requires refrigeration which can be problematic. These findings align with the literature reviewed by Lindorfer et al. (2019), Hwang and Varma (2014), and Ajanovic and Haas (2021), showing storage challenges in portable and non-portable devices which affect the cost, volumes, weight, efficiency, and safety. Storage affects the competitiveness of hydrogen fuel cells and thus requires more research to identify new technologies that can address this issue.

5.1.3.3 PERFORMANCE AND COMPLEXITY OF HYDROGEN FUEL CELLS

Findings from this study show that hydrogen fuel cells are structurally complex. This is further complicated by the production of quality hydrogen, cost-related issues, and storage. Proton exchange membranes require high-quality hydrogen and a high-power load to be efficient. Despite having a high expected lifetime, fast refuelling, high tolerance to low temperature, and ability to share hydrogen infrastructure, the performance of hydrogen fuel cells is affected by the complexity, cost, and storage issue. These findings align with the literature reviewed by Yilmaz and Ispirli (2015), Wilberforce et al. (2017), Greene, Ogden, and Lin (2020), Kundu and Dutta (2016), Baroutaji et al. (2019), Isorna Llerena et al. (2019), Beurey et al. (2021) and Alves et al. (2013) on the performance of hydrogen fuel cells and showed significant performance related issues associated with the complexity of the fuel cells and other issues in the hydrogen economy. Yilmaz and Ispirli (2015) argued that the performance of fuel cells is affected by pressure, temperature, electrode conductivity, membrane thickness, and oxygen and hydrogen input pressure. Similarly, carbon monoxide poisoning, and hydrogen oxidation reactions damage the performance of fuel cells. Other impurities like ammonium can also affect cell performance. Du et al., 2021). Isorna Llerena et al. (2019) and Ezquerra Silva (2019) stressed the importance of quality hydrogen, noting that any impurities affect the performance of hydrogen fuel cells and increase production costs. However, Du et al. (2021) argued that new technologies that produce pure hydrogen or incorporate purification processes could address the challenge. However, such technologies translate to additional costs. Isorna Llerena et al. (2019) observed that impurities like ammonia affect the performance of hydrogen fuel cells and introducing pure hydrogen after the contamination or poisoning cannot revert the situation. Similarly, the cells require 100% hydration to function optimally. However, this can be problematic at higher and typical atmospheric temperatures. Such challenges affect the competitive advantage of hydrogen fuel cells.

5.2 CONCLUSION

Fuel cells can create a competitive advantage if countries harness the capability of the hydrogen economy. Production, storage, distribution, and use of hydrogen must ensure increased usage of fuel cells at an affordable cost relative to conventional energy sources like fossil fuel. Analysis of the data from this study show the great potential of hydrogen fuels to address greenhouse gas emissions, boost economic growth, and promote socio-benefits. For example, shows that fuel cells can enable countries to meet their energy needs, thus realising economic growth and stability and reducing overreliance on fossil fuels which is susceptible to fluctuations occasioned by demand and supply. Similarly, fuel cells can enable countries to Capitalise on their speciality areas, thus promoting cohesion and reducing rivalry. Further, it can address demand and supply issues caused by political instability, external factors like pandemics and geopolitical concerns since nations can use locally available materials like wind, solar, natural gas, or fossil fuels to produce hydrogen. However, there is a need to address current challenges that affect the hydrogen economy. For example, transportation, storage, and initial production costs pose challenges that affect the competitiveness of hydrogen fuel cells. Despite the high fuel efficiency and ability to use larger storage devices in heavy commercial vehicles and trains, hydrogen fuel cells remain uneconomical compared to non-renewable energy sources like fossil fuel and natural gas. However, the economic, environmental, and social benefits associated with hydrogen fuel cells continue to drive investment and research on the hydrogen economy, which is likely to address the current challenges and make hydrogen fuel cells more competitive in the future.

5.3 RECOMMENDATIONS

The competitiveness of hydrogen fuel cells is affected by different factors that impact the hydrogen economy ranging from cost, storage, initial cost, quality of hydrogen gas, and performance of the fuel cells. However, there is significant progress toward making hydrogen competitive compared to conventional energy sources. For instance, the data shows that cost continues to decline while storage capacity increases. Similarly, the data analysis shows that economies of scale can make the hydrogen economy more competitive since there is a significant decline in the production cost as more oxygen is produced. Based on these findings, it is critical for nations to formulate additional policies and frameworks to promote hydrogen consumption. Similarly, countries and business should invest in hydrogen economy strategic plans that can streamline the production, distribution, storage, and use of hydrogen. Additionally, governments need to support research and development of new technologies to address cost-related issues that hamper investment in the sector. Likewise, different stakeholders must develop cost-effective, lightweight, and robust storage that will promote the uptake of hydrogen fuel cells. Countries should encourage knowledge-sharing resource pulling and investment in bulk hydrogen production facilities amongst the business operators to reduce the production cost, share risks and build competency. It is necessary to incorporate different purification technologies to safeguard fuel cells from impurities like ammonia that can poison them and affect their performance, however there are inroads being made into green ammonia. Lastly, further research should be conducted to determine the most appropriate storage and distribution infrastructure to enhance hydrogen fuel cells' competitive advantage. Similarly, additional studies can provide new insight into technologies that can promote the usage of hydrogen fuel cells by vehicles, which are the major contributors to greenhouse gases.

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APPENDIX

EXAMINATION OF TAUGHT MASTER'S DEGREE DISSERTATION:

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Surname/Family Name **JONES**
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Declaration/Statements page

DECLARATION

APPENDIX A CANDIDATURE FORM

This work has not previously been accepted in substance for any degree and is not being concurrently submitted in candidature for any degree.

Date: 3rd of January 2023

STATEMENT 1

This work is the result of my own investigations, except where otherwise stated.

Other sources are acknowledged by footnotes giving explicit references. A bibliography is appended.

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I hereby give consent for my work, if accepted, to be available for photocopying and for inter-library loan, and for the title and summary to be made available to outside organisations.

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