

WALES'S CURRENT ABILITY TO USE HYDROGEN AS A PRIMARY PORTABLE FUEL

by

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DEDICATION

I would like to dedicate this paper to my beautiful wife who's support, and endless patience made this study possible.

ACKNOWLEDGMENTS

I would like to express my sincere gratitude to Mr. Nathan Gunter and Dr. James Monks for their invaluable support and guidance throughout the course of my research on hydrogen. Their expertise, insightful discussions, and unwavering commitment have greatly enriched the quality of this work.

I am truly fortunate to have had the privilege of working alongside such accomplished individuals. Their collaborative spirit and genuine interest in advancing our collective understanding has left an indelible mark on this research endeavour.

ABSTRACT

While challenges and uncertainties surround the energy sector hydrogen While challenges and uncertainties surround the energy sector hydrogen technology, it holds potential for addressing a significant portion of Wales's transport power demands. The findings underscore the importance of continued research, infrastructure, and regulatory support, to facilitate the successful adoption of hydrogen technology in Wales.

This paper underscores the complexity of choosing the appropriate hydrogen production method and storage, emphasizing the need for a balanced approach that considers environmental, cost and scalability. The alignment of government policies with industrial goals, show the collaborative effort towards the transition of a hydrogen-based, sustainable-fuel future.

Wales stands at the precipice of a hydrogen revolution. This is supported by ambitious projects, strategic infrastructure plans and government backing, indicating a determined push towards a sustainable, hydrogen powered future. The success of hydrogen hinges on collaborative efforts, continued investments and a comprehensive approach to solving the challenges faced by hydrogen production, infrastructure and customer adoption.

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LIST OF ABBREVIATIONS

ICE	Internal Combustion Engine
H2ICE	Hydrogen Internal Combustion Engine
LNG	Liquid Natural Gas
HFC	Hydrogen Fuel Cell
CCT	Carbon Capture Technology
PEM	Polymer Electrolyte Membrane
HOR	Hydrogen Oxygen Reaction
ORR	Oxygen Reduction Reaction
PEMFCs	Proton Exchange Membrane Fuel Cells
NO _x	Nitrogen Dioxide / Nitric Oxide
CO ₂	Carbon dioxide
SMR	Steam Methane Reforming
H ₂	Hydrogen
SSS	Solid State Solution
HV	High Voltage
OSWT	Off-Shore Wind Turbine
LOHC	Liquid Organic Hydrogen Carriers
WHP	Welsh Hydrogen Pathway
H2BRID	Hydrogen Business Research and Innovation for Decarbonization

FF	Fossil Fuel
H&S	Health and Safety
LF	Legislative Framework
UK	United Kingdom
EU	European Union

CHAPTER ONE: INTRODUCTION

1.1. Aims and Objectives

The principle aim of this paper is to conduct a comprehensive analysis of hydrogen feasibility in portable application in Wales. As part of this review, the paper will explore technology, demand, production, infrastructure and government support. This study will provide insight into the challenges and opportunities for hydrogen adoption in Wales, acting as a foundation for further research and strategic decision-making in the field of sustainable energy and hydrogen.

1.2. Justification

This study holds relevance and importance for several reasons. Justification for its undertaking are:

1.2.1. Transition to sustainable energy

The global community have now identified the importance of moving towards low-carbon and sustainable fuel because of climate change. Hydrogen is seen as a clean energy carrier and has gained attention as a fuel alternative. Understanding its potential to support the transition to renewable energy source is crucial.

1.2.2. Regional Impact

Focusing on Wales provides a regional dimension to the study. This allows for insight specific to the region and can potentially highlight unique opportunities and challenges the area may face. Understanding Wales's capacity, knowledge and short falls

in supporting renewable fuel such as hydrogen, is vital to ensure future development take these into consideration.

1.2.3. Transport Sector Impact

This study will focus on portable applications, particularly those in the transport sectors. This area aligns with the global focus on de-carbonising transport. Due to the rising concerns and environmental effects of traditional fuels, exploring hydrogens viability in transport such as vehicles, buses, maritime etc is vital for a sustainable transport solution.

1.2.4. Policy and Investment Landscape

Assessing governmental policies and support for hydrogen initiatives, shed light on the broader policy landscape and the level of commitment towards hydrogen development. Understanding the financial support and programs to attract external investment, aids in gauging the potential success of hydrogen projects.

1.2.5. Technological Advancements

This study will investigate multiple hydrogen technologies in reference to production, storage and applications, all contributing to an insight into the technology landscape. Understanding the current technology and areas for development is vital in the strategic development of hydrogen in Wales.

1.2.6. Economic Implications

By estimating the potential demand for hydrogen in Wales and considering multiple production methods, this study can provide economic perspective. This will

assist with further research into cost, scalability and the environment of different hydrogen routes available.

1.2.7. Infrastructure and education needs

Identification of infrastructure gaps and the need of supporting education, emphasise the practical challenges of adopting hydrogen technology. These findings provide actionable insight by policy makers, industrial stakeholders and educational institutions, to address these gaps and support the smooth adoption of a hydrogen-based solution.

1.3. Methodology

The research methodology will employ a systematic and iterative approach using both quantitative and qualitative analyses. Key points of methodology include:

- Literature Review
- Data Collection
- Sector-Specific Analysis
- Hydrogen Production Technologies review
- Demand Estimation
- Policy and Support Analysis
- Case Studies
- Infrastructure and Education Assessments

CHAPTER TWO: BACKGROUND

2.1 Energy for the Welsh Economy

Prior to the first industrial revolution, Wales was sparsely populated with the majority of people in aquicultural based living. However, the start of the first industrial revolution in the 18th century saw the introduction of machinery that was powered by steam turbines and water (Ashwani Sharma, 2020). As power demands increased throughout the second industrial revolution, demand on power production increased. Wales prospered as a result of this demand due to the vast deposits of coal that was now accessible with the support of mechanization (Minchinton, 1990). This boom in the industry fell sharply in the third industrial revolution as cheaper sources of coal from overseas became available, resulting in a substantial reduction in demand of Welsh coal (Minchinton, 1990). As Wales transition through the fourth industrial revolution, power generation continues to be key to supporting development. Wales benefits from multiple natural resources to support power generation such as tidal, solar and nuclear, whilst improving existing fossil fuel systems to capture the carbon produced (Michael Grubb, 2006). While progress is being made towards a new green power supply Wales has the opportunity to again be a key influencer.

2.2 The Rise of Hydrogen

Towards the end of the 20th century, the true impact of using fossil fuels as a primary fuel source became apparent (Kovac, 2021). With growing environmental and social pressure, focus on finding an alternative portable power source have been substantial. Hydrogen has been hailed as one possible solution. Whilst current mass manufactured hydrogen is produced from removing carbon from natural gas via Gasification (Energy, 2019), known as grey and blue hydrogen, hydrogen can also be produced using renewable sources, known as green hydrogen. The multiple sources of hydrogen allow for a gradual transition to renewable sources, whilst the use of hydrogen fuels can be implemented as soon as the technology is available (Kovac, 2021). Due to the versatile nature of hydrogen, it can be adapted to a wide range of power needs currently supported via fossil fuels. This is due, in part, to hydrogens high energy density offering 120MJ/KG, compared with Petrol at 45.8MJ/Kg (Andreas Zuttel, 2010)

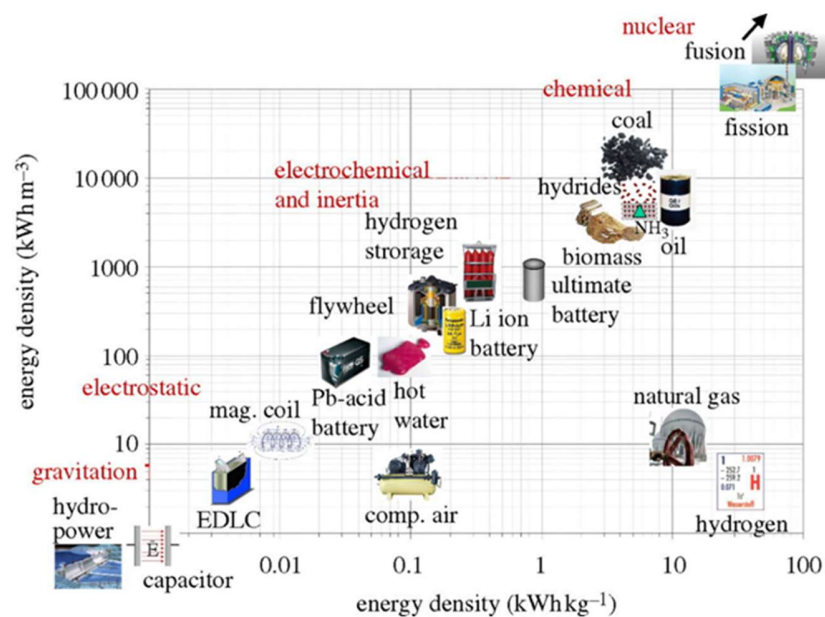


Image 1: source: (Andreas Zuttel, 2010)

2.3 Pressure to Change

There have been multiple factors driving the development of portable hydrogen power alternatives. These include:

Environmental concerns: Fossil fuel-based power generation has come under substantial pressure to be replaced by green forms of power to mitigate the historic environmental damage (Smith, 2016).

Energy security and the reliance on foreign nations to meet power needs have been a substantial driver towards a fuel alternative. Moving to locally produced and a more diverse power production system such as renewables, reduces the dependency on fossil fuel imports (Jones, 2018).

Government policies and regulations are forcing the adoption of sustainable power sources to achieve committed renewable targets. In addition to “pushing” renewable energy sources via policies, governments are also “pulling” development in renewable power, via the use of grants and support of renewable programs (Green, 2016)

These factors have resulted in substantial technological advancements within renewable power sources, often offering improvements on power delivery when compared with traditional fossil fuels. The focus on renewables have also resulted in a substantial reduction in research within fossil fuel usage, allowing renewable technology to make gains on traditional fuels (Innovations, 2020)

CHAPTER THREE: Wales Portable Power Needs

3.1 Properties of Typical Fuels

Currently, portable applications are made up of 4 primary fuel types.

3.1.1 Petrol

Petrol is manufactured from the raw material crude oil. Crude oil is refined via a process of distillation to separate the desired chemical composites. Petrol is made up of hydrocarbons, the chemical composite varies batch to batch of manufacture however, as a typical example, petrol's chemical composite is C_nH_{2n+2} (Smith, 2013).

Petrol is seen as a high energy, dense and compact fuel that has made it a household product within portable applications. Petrol offers energy release of 43-47KJ/gram, and when used within internal combustion engines, an efficiency of 20-40% returned (Green, 2016).

If drawing from reasonable assumptions:

- Typical energy density of 45Kj/g
- Typical internal combustion engine efficiency of 30% when burning petrol

From this an estimate of the usable energy within the current technology of:

$$45 * 0.30 = 13.5Kj/g$$

3.1.2 Diesel

As per petrol, diesel is derived from crude oil via the process of distillation. Diesel is also made up of hydrocarbons that vary from batch to batch however, a typical example of the chemical composite is 44 – 48Kj/gram, and when used with an internal combustion engine, returns an efficiency of 35-50% (Green, 2016).

Drawing from the following assumptions:

- Typical energy density of 46Kj/g
- Typical internal combustion engine efficiency when burning diesel 42.5%

It's estimated that the usable energy with the current technology is:

$$46 * 0.425 = 19.55 \text{ kj/g}$$

3.1.4 Battery

Battery electric offers a very efficient form of energy recovery when compared with diesel and petrol, boasting power recovery of 70-90%. This direct form of power also benefits from zero emissions being released as a result of the batteries used. The use of a battery propulsion system has additional benefits of near silent operation and reduced heat waste, whilst providing additional efficiencies via energy recovery when under breaking.

However, the limitations of this technology exclude the possibility of it replacing internal combustion applications in its entirety. Batteries have a limited range available; this is partly limited by the physical weight and size of the batteries that have to be transported as well as the application they serve. Batteries in service have also shown a finite usage and have a diminishing return over life until the units must be replaced, often at a considerable expense (Smith, 2016).

Batteries energy density varies from technology to technology however, current battery technologies will not be considered in this report for replacement. This is due to the considerable technology growth that is supporting these applications. Additionally, it is

expected that battery technology will replace a portion of Internal combustion engine applications (Smith, 2016).

3.1.4 Natural Gas

Natural gas is mostly composed of methane. This is typically produced when organic matter is buried under the Earth's surface over millions of years while under extreme pressure and temperature (Speight, 2007).

Natural gas benefits from a very high energy density, typically 46.35 Kj/g (+/- 15%) (Hein, 2014). Natural gas is typically used in heating applications for domestic and industrial environments, boilers using this technology would achieve an efficiency of circa 90% (Defu Che a b, 2004).

Considering the usage efficiency, energy use can be calculated:

$$46.35 * 0.9 = 41.715 \text{ Kg/g}$$

Natural gas is predominantly used for gas fired power plants in the production of reliable and flexible electrical energy within the UK national grid (Operator, 2019). As the usage forms part of the national grid, and by its nature cannot be considered "portable", it will be exempt from this paper.

3.2 Properties of Hydrogen

In recent years, hydrogen has gained popularity within portable applications, especially for use in transport in the form of fuel cell electric vehicles. With high energy

density and green credentials, hydrogen is widely considered one of the most promising solutions for renewable fuels (Joan M Ogden, 1998).

Hydrogen has an energy density of: 120 Kj/g

When used within an internal combustion engine, hydrogen has an efficiency similar to that of petrol and diesel, this is predominately due to similar technology use between the different fuels. This efficiency is believed to be around 20-40% however, this technology is still in development and does not benefit from the same sample pool as petrol and diesel. Efficiencies within internal combustion engines designed for use with hydrogen, shows lower thermal efficiencies when compared with the alternative of hydrogen fuel cells. Hydrogen fuel cells boast an efficiency rate of circa 60% however, as per hydrogen internal combustion engines, this technology does not benefit from the same sample pool as traditional fuels (al, 2018).

Due to the higher efficiencies, hydrogen fuel cells have seen wider adoption and for this study it will be assume this is the preferred technology.

Usable energy of Hydrogen = $120 * 0.60 = 72\text{kJ/g}$

3.3 Portable Applications Hydrogen can Support

3.3.1 Passenger Vehicles

Personal transport is a massive consumer of hydrocarbon fuels from non-renewable sources, and in turn contributes towards air pollution and environmental derogation. In a study entitled "Transportation and its Contribution to Climate Change" (Smith, 2016), the importance of the transportation sector in reducing climate change is reviewed. This

highlights the need for alternative solutions and technologies to reduce the environmental impact of personal transport.

An alternative to internal combustion engine technologies, such as Hydrogen fuel cells, renewable power sources can be used to power passenger vehicles. These technologies offer a route to carbon neutral transport, addressing the need for change whilst maintaining a circular economy (Johnson, 2022).

3.3.2 Public Transport

Hydrogen fuel cells have been identified as a potential alternative for usage within public transport systems, such as buses and trains. The implementation of renewable power on public transport that servicing large number of passengers has the potential to offer immediate environmental impact in dense population areas where air quality is of growing concerns. The research paper “Transportation research trends in environmental issues: a literature review of methodology and key subjects” (Lam, 2016) highlights the role of hydrogen within the public transport sector in reducing carbon outputs and moving public transport to renewable power.

3.3.3 Personal Mobility

The use of renewable power has revolutionised personal mobility, none more so than the humble bicycle (Luqi Wang, 2018). The electrification of bicycles have extended the range that a bicycle would normally be used for and the speed that is achieved in any given trip. Additionally, electrification of bicycles have made their use more available to

people with limited physical abilities. Hydrogen fuel cells offer the possibility to improve the technology already in use, via increased range, reduced weight and ease of refuelling. This technology is also considered a solution to reducing the number of cars used for urban travel and improve efficiency of the current transport network (Luqi Wang, 2018).

In addition to bicycles, alternative personal transport methods have arisen including electric scooters, hoverboards and skateboards. These unique personal transport methods offer an alternative to traditional transport. Much like bicycles, hydrogen offers technological advantages in these emerging transport methods. These advantages are explored in the article “Advancements in Hydrogen-Powered Personal Mobility” (Smith, 2020).

3.3.4 Maritime

Maritime applications are typically energy dense and require a high volume of power for prolonged use. The use of hydrogen in fuel cells or hydrogen internal combustion, allow for the replacement of traditional fuels and a clean energy solution for the marine industry (Smith, 2020).

3.3.5 Aviation

Aviation continues to offer unique challenges with a requirement of high-power output, along with stringent weight and space limitations. Hydrogen fuel offers such characteristics, and in some respects improvements on traditional aviation fuels (Yusaf, 2022).

3.3.6 Domestic Heating

Hydrogen can be used to supplement hydrogen via blending hydrogen gas with natural gas supplies, or as an alternative combustion system with the support of new technology (Defu Che a b, 2004). However, most heating applications in the UK can be supported by mains supplied gas and/or electrical heating technology such as heat pumps. Because of this, it will not be considered within this study of portable hydrogen applications.

3.3.7 Off Grid Power

Hydrogen offers great potential for sustainable off grid power(Lunghi, 2016). Current off grid power suffers from disposable batteries, and renewable power is often limited in the power storage capacity and weather dependent. Hydrogen by contrast can be manufactured off site and shipped as needed, offering high energy capacity whilst maintaining its green credentials (Lunghi, 2016).

3.4 Personal Transport Needs

Currently within the UK, there are an estimated 32.988 million cars registered (Transport, 2023). This is made up of:

- Petrol – 19.243 million
- Diesel – 11.498 million
- Electric – 2.247 million

Data correct as of 31st December 2022 (Transport, 2023)

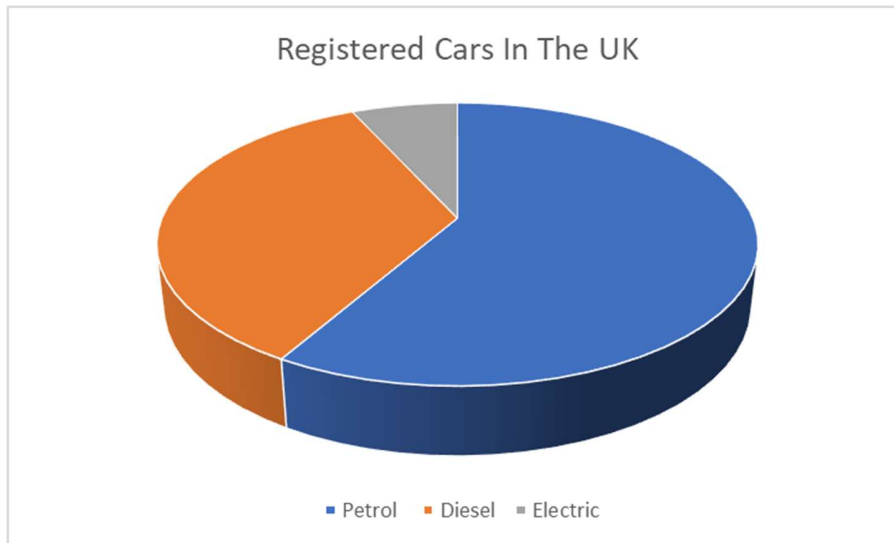


Image 2 – Registered Cars in the UK

As the transport data doesn't include a breakdown by British nation, an alternative method must be used to calculate the proportion of cars that are used in Wales.

The metrics considered for splitting the vehicles were GDP per capita, Population and Energy use.

Of these metrics, it was decided to split the values via population. This was decided as typically cars in the UK are assigned to an individual or families. Whilst no measure offered a perfect split, the metric of population is considered to be the closest available.

The UK population as a whole is 67,026,000 with Wales population being 3,105,000 (Statistics, 2022).

	Population mid-2011	Population mid-2021	Median age mid-2011	Median age mid-2021	Population density (pop per sq. km) mid-2021
UK	63,285,000	67,026,000	39.6	40.7	276
England	53,107,000	56,536,000	39.4	40.5	434
Wales	3,064,000	3,105,000	41.5	43.1	150
Northern Ireland	1,814,000	1,905,000	37.4	39.8	141
Scotland	5,300,000	5,480,000	41.3	42.2	70

Source: Office for National Statistics, National Records of Scotland, Northern Ireland Statistics and Research Agency - Population estimates

Image 3

Using the population statistics, it's possible to assign the proportion of car's used in Wales. One such study by Thompson and Collins (2012) in the Journal of Research Methods demonstrates the application of stratified random sampling in situations where base data is lacking

$$(3.105 / 67.026) \times 100 = 4.6\%$$

This allocation shows 4.6% assignment of vehicles for usage in Wales.

Using this allocation of cars based upon the population the cars registered in Wales are:

- $(19.243 \text{ million} \times 0.046) = 885,000$ petrol cars (rounded)
- $(11.498 \text{ million} \times 0.046) = 529,000$ diesel cars (rounded)
- $(2.247 \text{ million} \times 0.046) = 103,000$ Electric cars (rounded)

Cars that are already using electric technology are going to be omitted from any calculations. As hydrogen technology works in support of electric application, it is reasonable to conclude that those applications are already using battery technology, and some of the internal combustion engine applications will continue or be replaced with battery technology.

Currently, hydrogen fuel for personal transport is still in its infancy, lacking infrastructure and product offering for it to be widely adopted. However, should these points be rectified, it is estimated that hydrogen vehicles could account for 20-60% of vehicles used. The wide potential usage range is again down to the early stages of the technology and limited infrastructure (Robinius, 2018).

For this study the mid-point will be used, but readers are reminded of the potential +/-25% change from nominal.

Using hydrogen adoption from petrol and diesel, the number of cars that could be replaced are:

$$\text{Petrol} - 885,000 \times 0.40 = 354,000$$

$$\text{Diesel} - 529,000 \times 0.40 = 211,600$$

$$\text{Total cars} = 565,600$$

The study will proceed on the assumption that 565,600 cars within Wales will be supported via hydrogen technology.

3.5 Public Transport Needs

3.5.1 Buses

Within Wales, buses have already benefited from hydrogen fuel cells in pilot programs designed to cut emissions within cities.

The volume of buses has gradually fallen over the past 10 years with 2021 showing the lowest number of users and a small improvement (however still on a falling trend line) in 2022. It is worth considering that there may be some discrepancy allowance needed because of the COVID 19 pandemic (Government, 2023).

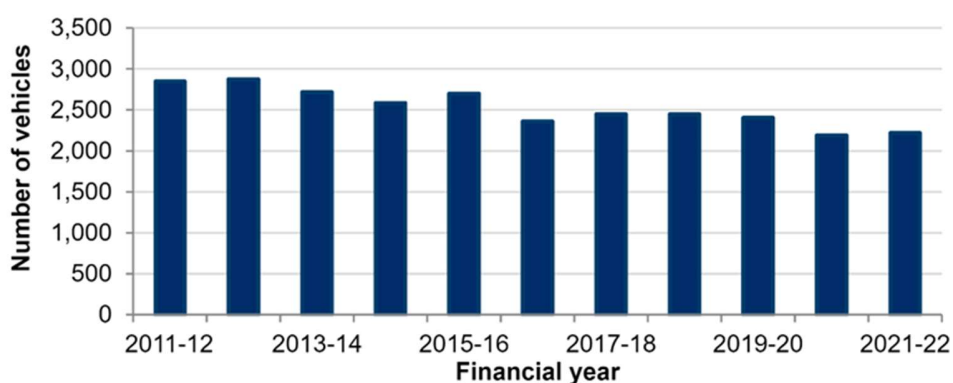


Image 4

From the latest information available, it shows that there are circa 2,215 buses operational in Wales.

Given the high energy density required, long periods of operation and consistent mileage, pure battery technology doesn't lend itself well to supporting bus application. To date, the Welsh government have planned bus electrification via hydrogen in Swansea and Bridgend starting early 2025 (Government, 2023).

Given the unique application requirements of public bus transport, hydrogen is the most supported energy alternative to the current diesel used. Whilst it is possible for

hydrogen to service 90+% of the bus system in Wales, biofuels also have the potential to support renewable power in public services (Stevens, 2020).

For the benefit of this review, its assumed that a 50% adoption rate of hydrogen power within the public bus sector.

$$2,215 \times 0.5 = 1,108 \text{ Buses (Rounded)}$$

For this review 1,108 buses in service in Wales will be used.

3.5.2 Personal Mobility

Batteries are likely to continue being used in personal mobility applications such as push bikes and scooters instead of hydrogen. Within small applications such as push bikes or scooters, batteries can offer improved energy density when you take into consideration the supporting system needed to process hydrogen into electrical energy, including fuel cell, tank, control valves, power regulators etc. (A. S. Brouwer, 2016). Batteries also have a current infrastructure for portable applications, offering charging and rent as you ride schemes within urban areas (van den Bossche, 2019). Considering hydrogen in this arena, the opportunity to refuel is limited and often outside the range of these devices needing to be serviced. This is further compounded by limited consumer options due to end user preference for established technology (Kurzke, 2019). Additionally, the cost of implementing hydrogen fuel cells are considerably more than battery alternatives already typically in service. This would also push users towards existing technology of battery power instead of the hydrogen alternative (Axsen, 2011).

Safety is also a consideration when reviewing hydrogen within personal mobility applications. Battery technology have a considerable historic usage for personal applications, such as mobile phones and personal transport, giving the user confidence in the battery's abilities whilst understanding and limiting any negative effects (van den Bossche, 2019). By contrast, hydrogen has seldom seen any usage within public applications, with concerns raised on having a highly explosive gas in close proximity to the user (Pearson, 2018).

Within the area of personal transport, batteries would appear to already satisfy the end user needs. Given the unsupported infrastructure, lack of user knowledge of the technology and inflated cost, it is unlikely that hydrogen is going to be supported within the personal transport sector. For the purpose of this review, personal transport applications will not be included as a potential hydrogen use.

3.5.3 Maritime Fuel

Hydrogen for use in maritime applications present several challenges. One of these are, hydrogen when in its gas form, often has a lower energy density than that of traditional hydrocarbon fuels (dependent on pressures). The energy density can be improved when they are stored in its liquid form (Baek, 2021). Handling of hydrogen in suitable energy density-like high pressures or at cryogenic temperatures, present complex logistical challenges and would require a specialist infrastructure solution (Ishii, 2021).

To further hinder the adoption of hydrogen in Marine environments, existing maritime regulations and standards are designed to facilitate conventional fuels such as diesel and heavy fuel oil. For hydrogen to be used in this arena, considerable changes to the marine

regulations would be needed to ensure safe and compliant hydrogen systems (Livanos, 2020). To change the maritime regulations relating to fuel, requires the collaboration between multiple countries and industry stakeholders, making this an extremely complex situation.

As with many applications, hydrogen infrastructure is underdeveloped, and refueling opportunities are often limited. Marine time would also need considerable scaling up of production and availability of hydrogen for marine fuel (Liu, 2021). Whilst Wales have the ability to change local legislation and supporting local infrastructure, this may have little to no impact on the fuels used within marine applications in Wales. Due to the nature of marine transport, most of the commercial traffic within Welsh waters start or end outside of Wales. Without the supporting infrastructure in the source/destination and legislation within each country the vessel passes through, the hydrogen vessel cannot be used. For this reason, maritime application will not be considered within our study.

3.5.4 Off Grid Applications

Hydrogen can be stored and used as a primary or redundancy during high power needs, or when renewable, local power generation is not able to meet load demand, such as night power during winter when solar power is the primary generation. Hydrogen can provide reliable and scalable off-grid power, ensuring a stable power supply without a connection to the national grid (O'Malley, 2014).

In addition to the typical usage of hydrogen fuel cells, off-grid applications can generate power through familiar technologies, such as internal combustion engines or gas turbines.

The established technology is already refined and offer high energy efficiencies while being engineered for reliability and longevity (Wu, 2013).

Within the UK, there is an estimated 4.4 million households that are not connected to the national Gas grid and rely on locally stored hydrocarbon fuels to heat their homes. 19% of homes in Wales are not connected to the national gas grid. (Parliament, 2024). Within Wales there is an estimated 1,472,400 homes (Government, 2022).

Homes not connected in Wales: $1,472,400 * 0.19 = 279,756$ homes.

Households within the UK typically use and estimated 11,500 kWh of gas per year (Ofgem, 2023).

Total gas off grid energy needs: $11,500 * 279,756 = 3,217,194,000$ kWh

Of these homes, many are connected to the electrical national grid. For these homes alternative heating sources are available, most noticeably heat pumps. Heat pumps offer a more mature and refined technology for users, with this in mind heat pumps also offer a wider consumer option. Heat pumps also offer a lower running cost for home heating when compared with hydrogen options (Smith, 2019). Given these factors, most of the homes that are able, would probably opt to use heat pumps. Whilst there is no crossover correlation between these homes for our study, its assumed 12% of the off-gas grid homes will use hydrogen fuel.

Total hydrogen / gas adoption demand = $3,217,194,000 * 0.12 = 386,063,280$ kWh

3.6 Calculating Total Portable Power Needs

3.6.1 Petrol

Typically used in light automotive applications, the application needs as calculated in “Properties of fuel – Petrol” and “Personal transport needs” documented earlier within this paper can be used.

Usable energy density – 13.5 Kj/g

Hydrogen supported cars – 354,000

The fuel efficiency of petrol cars can vary in modern cars, typically between 40-60mpg. Contributing factors include, engine size, car shape, car weight, driving style, vehicle militance, type of roads used, etc. (Transport, 2021). With this consideration, it is assuming the typical MPG lies between the given range at 50mpg.

Domestic cars in the UK are estimated to have an average annual mileage of between 7,600 and 8,300 miles. This range includes a wide variety of vehicle types and applications, from small cars used in cities to motorway cruisers used for business (Transport, 2023). With the above consideration, the average mileage considered will be 7,950 miles / year.

Based on the above, the typical cars fuel usage will be:

$7950 \text{ (miles)} / 50 \text{ (MPG)} = 159 \text{ gallons} = 722.8 \text{ litres}$

Petrol = 750 grams / l

Petrol usage = 542,100 grams per year.

Energy used = $13.5 * 542,100 = 7,318,250 \text{ Kj}$

Total energy needs of Welsh cars = $7,318,250 * 354,000 = 2,590,695,900,000 \text{ Kj} = 2,590,695.9 \text{ Gj}$

Usable Hydrogen energy density = 72 Kj/g

Amount of hydrogen needed to replace petrol portable applications:

$2,590,695,900,000 / 72 = 35,981,887,500 \text{ g} = 35,981.89 \text{ Tonne (rounded)}$

From this its conclude that within the scenario proposed, Wales would need 35,982 tonnes (rounded) of hydrogen to replace portable petrol fuels.

3.6.2 Diesel

Diesel fuels have multiple applications, this includes light vehicles, public transport, heavy goods vehicles and rail.

For this calculation the values obtained in the earlier sections of the research to support the estimation of diesel fuels used will be considered.

Usable energy density – 19.55 Kj/g

Light vehicles (cars) – 211,600

Public transport (Buses) – 1,108

As with petrol cars, diesel cars efficiencies are dependent upon multiple factors, car size, weight, maintenance, driving style, roads used etc. On average, diesel cars in the UK have a fuel efficiency ranging from 45-70mpg (Transport, 2021). As there are many influencing factors that affect fuel economy, for this exercise the mid-point of 60 mpg would be used.

As per the review in Petrol cars, average domestic car milage is 7,950 mile / year.

Based upon the above:

$$7950 \text{ (miles)} / 60 \text{ (mpg)} = 132.5 \text{ gallons} = 602.36 \text{ litres (rounded)}$$

$$602 \text{ (litres)} * 211,600 \text{ (cars)} = 127,383,200 \text{ litres / year}$$

From the above the cars in Wales will use 127,383,200 litres of diesel a year.

Public transport vehicles tend to be much larger and heavier in size, with additional loads to transport and the vehicle needing to use side-roads requiring changing speeds, fuel consumption is considerably higher than that of light vehicles. Even with this, actual fuel consumption varies from bus to bus with the same factors seen in cars (driving style, weight etc.). Buses used in public transport have a typical mile per gallon usage of 4-9 mpg (Yue, 2009). For the purpose of this study, the midpoint of this value of 6.5 mpg will be used.

Buses in typical service cover 160 miles per day, 5 days a day, 50 weeks a year.

Based on this. It's assumed a typical bus in Wales would travel circa 40,000 miles a year.

Using the details above the fuel usage can be calculated as:

$$40000 \text{ (miles)} / 6.5 \text{ (MPG)} = 6,153.85 \text{ gallons} = 27,976 \text{ litres (rounded)}$$

$$27976 \text{ (litres)} * 1108 \text{ (buses)} = 30,997,408 \text{ litres / year}$$

From the above its concluded that public transport in Wales will use 30,997,408 litres of diesel a year.

Total diesel usage – 158,380,608 litres / year (Cars + public transport)

Diesel = 850 g/l

Total diesel usage = $850 * 158,380,608 = 134,323,516,800 \text{ g}$

Diesel usage in usable joules (j)= $19.55 * 134,323,516,800 = 2,631,889,753,440 \text{ Kj}$

= $2,631,889.75344 \text{ Gj}$

Usable hydrogen energy density = 72 Kj/g

Amount of hydrogen needed to replace diesel portable applications:

$2,631,889,753,440 / 72 = 36,554,024,353 \text{ g} = 36,554.023 \text{ tonnes (rounded)}$

From this its conclude that within the scenario proposed, Wales would need 365,540 tonnes (rounded) of hydrogen to replace portable petrol fuels.

Total hydrogen demand = $36,554 \text{ (diesel)} + 35,982 \text{ (petrol)} = 72, 536 \text{ tonnes}$

From the above, to support hydrogen as a portable fuel in Wales, hydrogen supply and infrastructure would need to provide over 72,000 tonnes of hydrogen to these portable applications per year.

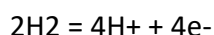
CHAPTER FOUR: Hydrogen Portable Technology

4.1 Hydrogen Fuel Cells

Hydrogen fuel cells have shown promise for a potential solution to producing electrical power on demand, whilst minimising the effects to the environment when used in collaboration with renewable hydrogen generation methods . The fuel cells work via an electro-chemical reaction between the hydrogen gas supplied and oxygen present in the atmosphere, to generate electrical power and boasting its main byproduct of water. The fuel cells system works via multiple steps, starting with the hydrogen gas fuel being supplied to the fuel cells anode. Oxygen, typically in the form of atmosphere, is introduced on the cathode side of the fuel cell (Johnson 2022). As the reaction takes place, electrons are passed through the fuel cell producing the electrical current desired via the output and the resulting byproducts, mostly water, is then expelled out of the fuel cell via a drain. A working knowledge of hydrogen fuel cells is vital to appreciate the potential for this technology, to support portable applications as a cleaner alternative to the fossil fuels currently being used.

The operation of a hydrogen fuel cell starts with the hydrogen gas being supplied into the anode section. The Anode is typically made from a catalyst material that supports the separation of the hydrogen into its component of protons(H^+) and electrons(e^-) with the introduction of oxygen typically from atmosphere. This

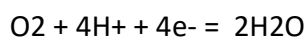
electrochemical reaction is known as hydrogen oxidation reaction (HOR) and is expressed as:



The catalyst supports these reactions allowing electrons from the hydrogen atom to be extracted, and produce an electrical current required (Wolf, 2013).

Protons generated at the anode then pass through the electrolyte, this is normally a polymer electrolyte membrane (PEM) within proton exchange membrane fuel cells (PEMFCs). During this process electrons are forced into an external circuit creating a flow of electricity. This electrical power is then applied directly to the electrical load and consumed as needed. The movement of the hydrogens, protons and electrons is the fundamental mechanism within the fuel cell that generates the electrical current (Salvatore, 2016).

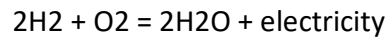
As the protons move through the electrolyte solution, they reach the cathode section of the fuel cell, this is where the oxygen is introduced into the system. The reaction on the cathode side of the fuel cell is supported with another catalyst that is used to ensure the oxygen reacts with the electrons and protons. This reaction, known as oxygen reduction reaction (ORR) is expressed as:



This reaction combines the oxygen with the protons and electrons that have passed through the electrolyte to form water. Having water as the only substance released because of the energy generation, is a key feature of the hydrogen fuel cell,

and is the primary driver behind using this technology as a clean, green alternative to traditional fuels and technology (Wolf, 2013).

The hydrogen fuel cells complete reaction is represented as:



Hydrogen fuel cells have several benefits over traditional hydrocarbon combustion-based power sources. Hydrogen fuel cells benefit from higher efficiencies, low/no greenhouse gas emissions and a reduction in fossil fuels. The only byproduct of the electrochemical reaction is the water generated from the reaction and heat, making it a clean form of power generation for portable power applications (Rao Anish, 2017).

One of the main uses of hydrogen fuel cells is for portable applications such as automotive. The hydrogen fuel cells can be coupled together with an electric drive chain providing clean, silent travel with the ability to refuel in a few minutes. In fuel cell cars, a fuel cell stack generates the electrical power, this is then used to directly power the electrical motors which in turn moves the car. Whilst hydrogen fuel cells production within automotive remain expensive, research is actively seeking manufacturing methods to reduce the capital cost and improve the output efficiency (Detlef, 2016).

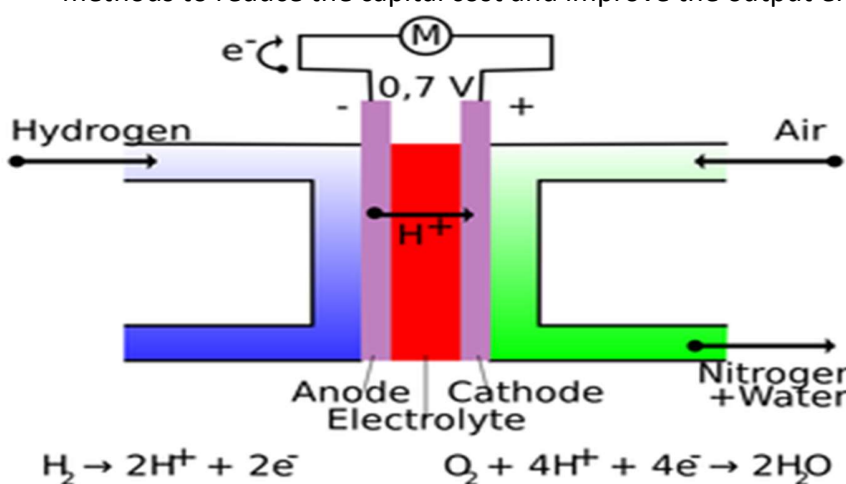


Image 5: Hydrogen electrochemical reaction, source: commons.wikimedia.org /wiki/File:Fuel_cell_

4.2 Hydrogen Internal Combustion Engines

Hydrogen internal combustion engines (H₂ICEs) is an alternative technology that uses hydrogen fuel to power an internal combustion engine, using similar principles as internal combustion engines used with petrol and diesel. Hydrogen engines has several stages of operation, this includes:

- Hydrogen injected into the combustion chamber
- Air fed into the combustion chamber
- Ignition of the fuel/air mix
- Release of energy used to produce power output

Hydrogen internal combustion systems has the potential to support portable power using the portable power technology already utilized.

First the hydrogen gas is injected into the engine's combustion chamber. The gas is regulated via an injector to ensure a precise dose, producing a controlled and well-distributed hydrogen gas within the combustion chamber, whilst maintaining the hydrogen to air mixture. This system is already well established within traditional hydrocarbon internal combustion engines, reducing the unknown variables within the system. Hydrogen injection is vital for the regulation of supply and optimizing the combustion cycle within an engine, without this, hydrogen use within internal combustion engines would not be efficient or practical (Hui, 2017).

To release the energy stored within the hydrogen, an internal combustion engine relies on an exothermal reaction between the hydrogen supply and oxygen. This reaction is initiated via a controlled and timed spark within the ignition chamber. Yet again, the

system of ignition has already been used within conventional hydrocarbon internal combustion engines and this technology reads directly across. The reaction between hydrogen and oxygen via combustion produces water vapor as the main byproduct. The release of energy in the reaction benefits from almost zero emissions released into the atmosphere, the reduction in emissions supports the goals of environmental impact and makes this technology a potential alternative to traditional hydrocarbon engines (Sorokes, 2012).

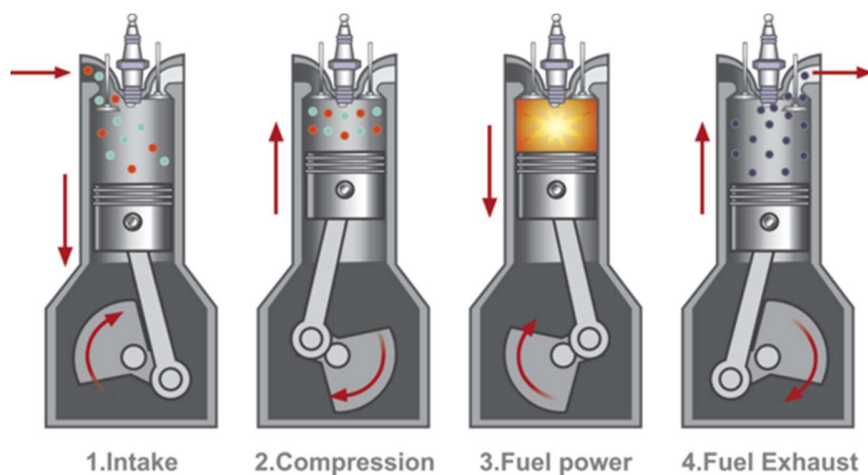


Image 6: ICE stages, Source: <https://www.airbus.com/en/newsroom/stories/2020-11-hydrogen-combustion-explained>

The hydrogen internal combustion engine operates the same energy capture principles as a traditional internal combustion engine. High pressure gases generated by the combustion of the hydrogen, drive a piston down the combustion cylinder converting the pressure into mechanical force. This mechanical force is converted into rotational motion via a mechanical interface known as a cam shaft. The alignment between traditional hydrocarbon engines and hydrogen engines presents the opportunity for existing hydrocarbon burning engines to be retrofitted and made suitable for operation

with hydrogen. This integration would offer substantial benefits in the implementation and adoption, offering the user a stepping-stone into hydrogen technology before making substantial changes. Any conversion would need to address key differences in the fuel behaviours such as different valve timing, optimized compression and combustion/fuel burn rates (Sorokes, 2012).

Whilst hydrogen internal combustion engines seem like a perfect solution to bridge existing technologies and emerging technologies, the systems are not without its drawbacks. While the storage of hydrogen for transport remains an issue for all hydrogen technology, hydrogen engines have issues with producing outputs harmful to the environment. As previously stated, hydrogen engines mostly produce water vapour as a byproduct however, in addition to the water vapour, nitrite salts more commonly known as NO_x are produced. NO_x is a known contributing factor towards environmental issues such as acid rain and have been linked to respiratory issues within humans. While the production of NO_x is not desirable, it is worth noting that the use of petrol and diesel internal combustion engines produce considerable CO₂ that is released into the atmosphere, whereas hydrogen engines do not (Sorokes, 2012).

	Reduction in climate impact			Scalability	Net Impact
	Direct CO ₂	NO _x	Water vapour & contrails		
H2-electric					
H2 combustion					
Sustainable aviation fuels					
Battery electric					
Hybrid-electric					

 Comprehensive
  Moderate
  Limited

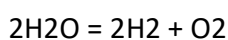
Image 7: renewable fuel impact, Source: <https://zeroavia.com/>

4.3 Different Classifications of Hydrogen

Hydrogen can be produced using different methods however, these methods are not necessarily equal depending on your ultimate goals. There are 3 main types of hydrogen production in use today, these are grey, blue and green hydrogen.

4.3.1 Green Hydrogen

The production of green hydrogen is achieved via electrolysis, this is where water is split using electricity to produce hydrogen and oxygen. To qualify as green hydrogen the electrical power supplied to the process would have to have been generated via a renewable power source, such as wind, solar or hydro power. This method of hydrogen production is considered renewable and environmentally friendly, as it doesn't release any contaminant into the environment. The process of electrolysis can be shown as:



(Michael, 2014)

The manufacture of green hydrogen requires a continuous supply of renewable energy, this typically takes the form of wind, solar and hydropower. The availability of such power sources dictates the practicality and scalability of green hydrogen production. To support the generation of green power, key infrastructures are required for large scale production. Such infrastructure to consider would be power demand and source, a suitable water source, hydrogen storage and/or distribution system and supporting technical knowledge. Continued investment in the electrolysis process and

industrialisation would improve efficiency and support the reduction of indirect emissions (J Bockris, 2000).

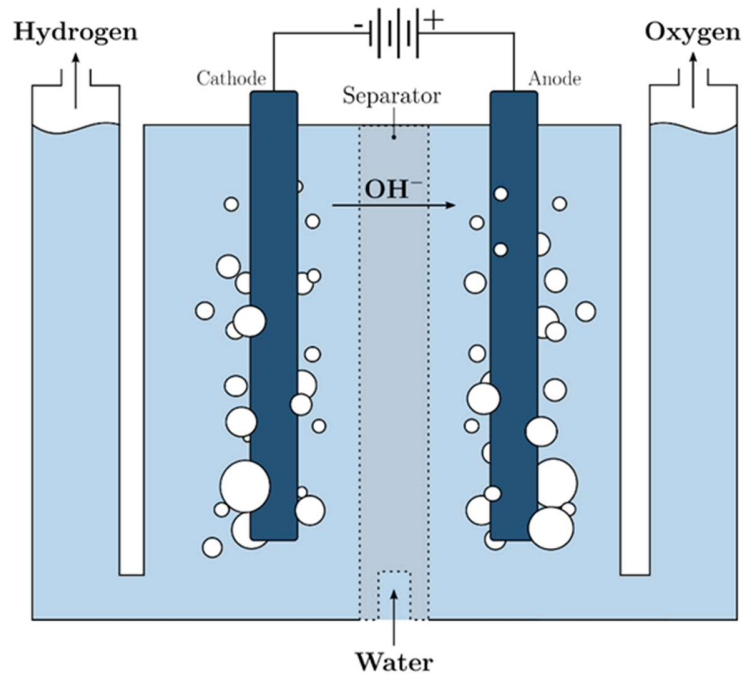


Image 8: Electrolyze, Source: (Vidas, 2021)

Whilst green hydrogen is seen as being the most environmentally friendly method of hydrogen production, it is also the most expensive, with higher costs driven by renewable power and the high energy demand of the electrolysis process. The set-up cost for an electrolysis production plant and renewable power infrastructure to support hydrogen production, is considerably more than any other hydrogen production method and effectively increases the cost to produce the hydrogen. As technological and industrial scalability is developed, it's expected that these costs and efficiencies would be reduced, in turn, reducing the production of green hydrogen (Wojciech, 2015).

Scaling green hydrogen for high-capacity output is dependent on the ability to supply renewable power to the proposed electrolysis plant. As social and governing demand for renewable power increases, greater infrastructure is invested to support renewable power projects. This investment reduces the issue of renewable power supply for countries, such as Wales, who have established and reliable power networks (Michael, 2014).

4.3.2 Grey Hydrogen

Grey hydrogen is the most common form of hydrogen production. Grey hydrogen is manufactured via processing fossil fuels, predominately natural gas, using a production method called steam methane reforming (SMR). This process produces hydrogen by removing the carbon and then releasing it into the atmosphere, in the form of carbon dioxide as a byproduct.

Steam methane reforming is an established technology used for hydrogen production on an industrial scale. The main input for grey hydrogen production is methane. This is typically supplied in the form of natural gas that is readily available. The current natural gas infrastructure allows for a consistent supply of methane, allowing for hydrogen production in multiple locations as needed (J Bockris, 2000).

The production of hydrogen using steam methane reforming has substantial environmental impact, due to the release of carbon dioxide into the atmosphere. The release of carbon dioxide is typically at a rate of 9 – 12 Kg for every 1Kg of hydrogen produced. For this reason, grey hydrogen is considered a heavy pollutant with high

levels of carbon dioxide being released into the atmosphere, contributing to climate change and the associated environmental damage (Wojciech, 2015).

Gray hydrogen continues to be popular despite the environmental impact. This is due, in part, to grey hydrogen being cheaper to produce than the alternative options available. Being a well-established process that uses technology and infrastructures already in place to support the petrochemical industry, is the primary reason why grey hydrogen's cost is so much lower than the other options available (Wojciech, 2015).

Grey hydrogen is already established as a high-capacity production method. As a mature and established production method, the grey hydrogen has been scaled for high-volume supply as demanded by industrial and commercial needs. This scaling has refined the production process further and driven down the hydrogen manufacturing cost. This low-cost method of hydrogen production is seen by most as un-sustainable due to its environmental impact and that alternative production methods must be developed (J Bockris, 2000).

4.3.3 Blue Hydrogen

Blue hydrogen is seen as a transitional method of hydrogen production. Blue hydrogen looks to reduce the effects of grey hydrogen production via the use of carbon capture techniques, reducing the carbon dioxide released into the atmosphere during the steam methane reforming.

Blue hydrogen uses the existing infrastructure needed for grey hydrogen production, including the steam methane reforming technology. Blue hydrogen sees the introduction of carbon capture and storage, preventing the release of carbon dioxide

into the atmosphere. For the carbon capture system to be effective, the captured carbon needs a permanent storage method to prevent its release into the atmosphere. For a site to implement blue hydrogen, suitable geological storage is essential (Haijun, 2003).

Blue hydrogen offers improved environmental properties over grey hydrogen however, the process of blue hydrogen production still releases carbon dioxide into the atmosphere. The released carbon dioxide in blue hydrogen is substantially less than that of grey hydrogen due to the implementation of carbon capture technology. The effectiveness of the carbon capture system varies from site to site, this means that not all blue hydrogen production is as environmentally friendly as each other. With this in mind, high-efficient carbon capture systems can produce blue hydrogen that releases low-carbons and offers a viable alternative to grey hydrogen whilst alternative hydrogen technology is developed (Haijun, 2003).

Blue hydrogen production is typically higher than grey hydrogen due to the additional processing needed for carbon capture and storage. The installation of carbon capture and storage infrastructure requires considerable investment, adding to the operational cost of hydrogen production. Whilst blue hydrogen is more expensive than grey hydrogen, it offers an immediate partial solution to the carbon dioxide normally released in grey hydrogen production (Wojciech, 2015).

The ability to scale-up blue hydrogen production is limited by the carbon captures needed for a geological layout suitable to support the storage of carbon dioxide indefinitely. As customers demand for low carbon supply of hydrogen increases, carbon

capture technology continues to be developed, offering various solutions depending on the local resources for storage. As blue hydrogen lends itself to being retro fitted to existing grey hydrogen facilities, the ability to scale up production is impressive and aligns with global targets of carbon reduction (Haijun, 2003).

4.4 Storage and Logistics

4.4.1 Gas Hydrogen

Compressed hydrogen is a well-established method of storage and is widely used within hydrogen application. This technology works by compressing hydrogen gas to pressures typically in the range of 350-700 bar and keeping in a special design container normally in the form of cylinders or tanks. The compression of the hydrogen gas increases the amount of gas stored in any given volume. The technology used to achieve this is mature and is regularly industrialised (Mantripragada, 2007).

Compressed hydrogen offers a simple and established system of hydrogen storage. As this technology is mature, the set-up cost is considerably lower than alternative methods of hydrogen storage available. The infrastructure for compressed hydrogen storage is also widely used by applications in the hydrogen industry, making compressed storage compatible with most existing hydrogen systems, particularly in portable applications (Mantripragada, 2007). The modular design of the cylinders used for compressed hydrogen means the system can be scaled for applications as needed and is already implemented in industrial hydrogen supply and refuelling (Mantripragada, 2007).

Gas hydrogen can be transported via the use of pipeline transport. This method of handling hydrogen can accommodate high volumes of hydrogen gas over long distances. Dedicated hydrogen pipelines utilise the pipelines similar to natural gas systems already in use. By using this established system of gas transport utilised by the Petrochem

industry, hydrogen benefits from the stability and reliability of a refined transport technology (Brown, 2013).

Using the pipeline storage to transport gas hydrogen allows for an efficient method for supplying high quantities of hydrogen. The maturity of the technology allows for an established infrastructure and reliable performance (Brown, 2013). However, pipelines used for transportation of hydrogen can suffer from hydrogen embrittlement, adding to maintenance and inspection costs and an increased risk of pipeline failure. Additionally, investment in building a hydrogen gas pipeline represents a substantial financial investment (Brown, 2013).

As an alternative to a dedicated hydrogen gas pipeline, hydrogen can be transported in a blended hydrogen / natural gas mix. This system of hydrogen supply is seen as a transitional technology to reduce the negative effects of natural gas usage, without the need to change any of the supported technology. Blending hydrogen into natural gas pipelines allow the use of existing natural gas pipelines and natural gas infrastructure by injecting a calculated amount of hydrogen gas into the system. This technique typically only inserts a small % of hydrogen into the natural gas mix to limit the degradation of the pipeline infrastructure, and to limit any safety concerns regarding usage technology downstream of the supply (Hughes, 2019).

The blending of hydrogen into a natural gas supply, requires very little set up costs and can be scaled up due to the already established natural gas pipeline system. This introduction helps reduce the environmental impact of natural gas usage, when renewable hydrogen (Green or blue hydrogen) is injected, without the need for

infrastructure or end user changes (Hughes, 2019). Introducing hydrogen into the natural gas system needs to be done with care, too much concentration of hydrogen can damage the pipeline. In addition, consideration needs to be given with regards to the combustion characteristics, as the end user might not be aware of any supply changes and its suitability within the technology the gas mix is consumed. Finally, this form of blending hydrogen gas into natural gas does not remove the negative environmental impacts but instead reduces it, hence why this application is seen as a transition application and not the final solution (Hughes, 2019).

Hydrogen gas can also be transported under pressure, typically in high-pressure tube trailers. Tube trailers typically consist of multiple gas cylinders mounted on the trailers in pressures between 350 – 700 bar. This type of transport is normally used for medium to short distance transportation, such as facilitating distribution points or refuelling stations (Forsberg, 2013).

High pressure tube trailers provide flexibility and mobility options to supply hydrogen point-to-point. This method of transport allows for hydrogen to be transported on the existing road network, without the need of investment in a dedicated hydrogen gas pipeline. Compressed gas tube trailers are limited by the amount of hydrogen gas that could be transported; this makes this transport ill-suited for high consumption hydrogen gas (Forsberg, 2013).

4.4.2 Liquid Hydrogen

As the name suggests, liquid hydrogen storage involves storing the hydrogen in its liquid form. To achieve this, the hydrogen must be cooled to cryogenic temperatures below -250 degrees Celsius where it changes from a gas into a liquid. Liquid hydrogen is stored in a container that is specially made to insulate to reduce thermal transfer and ensure the hydrogen remains below its evaporation temperature (Browman, 1991).

Hydrogen stored as in its liquid form benefits from higher energy density meaning a large amount of hydrogen can be stored in a comparatively small space. This reduced fuel volume makes it perfect for applications that have limited space, such as aerospace (Browman, 1991).

The process of reducing the hydrogens temperature to convert it into its liquid form, requires large amounts of energy and specialist technology. This energy needed to reduce the hydrogens temperature effectively reduces the overall efficiency of the hydrogen storage. In addition, the equipment needed to reduce the hydrogens temperature below -250 degrees Celsius is specialized and represent considerable investment when compared to compressed hydrogen storage options (Browman, 1991).

Transporting liquid hydrogen requires a cryogenic suitable tank and technologies to ensure the hydrogen remains in its liquid state. Whilst the transport needs of liquid hydrogen require specialist technology, it can be adapted to multiple transport methods including, but not limited to, rail, ships, trucks, aircrafts etc. This transport methods lends itself to remote applications or international transport where hydrogen gas pipelines are not available (Beller, 2015)

Liquid hydrogen allows for high density hydrogen transport. This high-density hydrogen transport is perfectly suited for large quantity shipments of hydrogen over medium to long distances, without the need for a pipeline infrastructure. However, keeping hydrogen in its liquid form requires the consumption of energy, typically in the form of consuming the gas being transported. This usage of the hydrogen during transport reduces the efficiency of the process (Beller, 2015).

4.4.3 Metal Hydride Storage

This method of hydrogen storage involves using metal alloys that are able to absorb hydrogen for storage and then release the gas on demand. The hydrogen is absorbed into the metal via a chemical reaction and when needed, is released by applying heat to the storage media (Bogdanovic, 2016).

The use of metal hydride storage provides a compact, solid-state solution without the need for continual energy output whilst in storage, such as liquid hydrogen storage. The release of hydrogen is self-regulating via the application of heat, allowing for a controlled release of hydrogen gas without specialist equipment (Bogdanovic, 2016).

However, the release of the hydrogen is limited via the chemical reaction and might not be able to supply enough hydrogen in high volume usage applications. The introduction to a metal media into storage increases the storage weight and drops the hydrogen storage capacity by volume and mass when compared to other hydrogen storage systems (Bogdanovic, 2016).

Transporting hydrogen in metal hydride often requires the use of a custom designed container. The design is dependent upon the metal used for the storage however, typical factors that need to be considered are temperature, humidity, exposure to reactive elements and electrical isolation (Bogdanovic, 2016).

The transport of metal hydride allows for hydrogen to be transported in a solid state and compact form. Whilst the containers used for the metal hydride are bespoke, they are often modular allowing for scalability. However, controlling the environment is key to ensuring the hydrogen remains suitable for use after transport. These transport containers add considerable cost and complexity when compared to alternative transport technology (Bogdanovic, 2016).

4.4.4 Chemical Hydrogen Storage

Storing hydrogen via chemical is done by combining hydrogen to a chemical compound, such as ammonia or liquid organic hydrogen carriers (LOHC), to store and release hydrogen (Sordakis, 2018).

Chemical hydrogen storage provides high energy density by volume. This liquid form of hydrogen storage allows for transport using traditional liquid carriers used in traditional hydrocarbon fuel transport (Sordakis, 2018).

Chemical hydrogen storage is much more difficult to release when needed. In order to release the hydrogen from the chemical compound, a catalyst or specific release conditions must be met. This release process adds complexity and cost to the storage process (Sordakis, 2018).

Hydrogen stored within chemical compounds are able to utilise similar transport technologies as used in the transport of chemical acids and alcohols. The system of storage changes according to the chemicals used as the storage media however, storage tankers are typically used. Transporting hydrogen in a chemical allows for high density and liquid transport at room temperatures however, the use of chemical compounds adds complexity in the consideration of transport vessel suitability and health and safety concerns unique to the chemical compound used for the hydrogen storage (Sordakis, 2018).

CHAPTER FIVE: UK AND WALES GOVERNMENT POLICES

5.1 Renewable Targets

The UK government have outlined its targets for energy generation with a focus on cleaner power generation. The UK's Net Zero Strategy outlines the UK governments plans to meet its goal of 95% electrical power generation from a low carbon source by 2030 (Committee, 2023). As part of this ambitious target, the UK government is planning on increasing the offshore wind generation capacity to 40 GW by 2030 as well as support the development and implementation of other renewable technologies (Committee, 2023). The UK government outlines its methods to support growth of renewable energy, including the investment in Carbon capture usage and storage and investment in hydrogen technology within its ten-point plan, for a green industrial revolution (Committee, 2023).

In addition to the renewable power goals outlined above, the UK government have also committed to phase out and decommission coal fired power stations by 2024 and to install 600,000 heat pumps by 2028 (Committee, 2023). The UK government have also committed to investing in research and development in innovation technology within renewable power generation (Committee, 2023).

The Welsh government has set similar ambitious targets for renewable energy generation. The Welsh Government set the goal of meeting 70% of the electrical power needs via renewable sources by 2030 (Government, 2023). To date, Wales have

achieved 90% of its 1GW of energy capacity of energy capacity to be locally owned by 2030, producing an estimated 1.9GWh of electrical power in 2021 (Government, 2023). The Welsh government have shown forward thinking in their renewable power targets by revising the commitments made to reflect the progress to date, with the new goal of 100% of Wales electrical power generation needs coming from renewable sources by 2035, with 1.5GW of the renewable power coming from locally owned projects (Government, 2023).

In support of these goals, the Welsh Government have been investing in several renewable projects. For example, the Welsh government has proposed a roadmap for Wales to meet the target of 100% of its electrical needs using renewable power sources by 2035 (Government, 2023). The Welsh government have also assigned investment to review potential new offshore wind power projects and new supporting projects that will support a consistent power supply via smart control and energy storage and release (Committee, 2023).

5.2 Position on Hydrogen Fuel

The UK Government have made its position on hydrogen well-known via introduction of multiple initiatives to support the development of hydrogen technology and applications. The UK Government published the UK Hydrogen Strategy in August 2021, that demonstrated the government's commitment to support hydrogen on an industrial level with the goal of increasing hydrogen support through the 2020's. The government's position forms a strong foundation for the hydrogen industry to build on,

as businesses and individuals are ever conscious of the impact on their energy use (Government, 2021).

The UK's goal for hydrogen production is for 10GW of production by 2030. To provide scale, this amount of hydrogen could generate enough energy to power 3 million homes. To help reach this target, the UK government have pledged £240 million in a Net Zero Hydrogen Fund to support the development and implementation of blue and green hydrogen production sites (Government, 2023). Additionally, the UK government have confirmed investment to support the infrastructure needed for offshore wind generation to support 5GW of wind production by 2030. This power generation will help support the production of green hydrogen (Government, 2023).

In a similar way, the Welsh government have shown equally strong commitments to supporting the development of hydrogen power. The consultation paper "Hydrogen in Wales – A Pathway and next steps for developing the hydrogen energy sector in Wales" issued in 2021, have generated considerable interest by Welsh businesses and individuals with 79 responses (Government, 2022). The consultation was generated to gather feedback from businesses affected by the proposal and support the Welsh Government in supporting the hydrogen energy sector.

The Welsh governments commitment to have at least 1.5GW of renewable power locally owned by 2035, this target will support the governments long-term goals to produce hydrogen from renewables, to support areas less suited to electrification such as transport, shipping and parts of industry (Government, 2021).

To support the development of hydrogen usage in Wales, the Welsh government have invested in several initiatives and projects. One such project commissioned, Element Energy to publish a pathway for Wales. Key objectives of this report were the collection of evidence, based off projects and expertise in Wales relating to the hydrogen and supporting technology, and an exploration strategy that have the potential to benefit Wales in meeting its renewable goals (Government, 2022).

The Welsh government have also looked to further support hydrogen development by developing a complimentary supporting service, Welsh Hydrogen Business research and Innovation for Decarbonization (H2BRID), to support businesses that are developing solutions in support of the Welsh Hydrogen pathway (Government, 2021).

5.3 Current Hydrogen Programs

5.3.1 H2 Teesside

The H2Teesside project, is a large-scale project to produce low-carbon hydrogen. Based in the UK, the Teesside site will become the largest of its type in Europe. The project is a development by BP Alternative Energy Investments and is located in the Northeast of England. This site will have an initial production capacity of 80MW of green hydrogen however, the site has the potential to have a high output of 500MW by 2030. This site would produce 10% of the UK government's hydrogen target of 10GW (Grubnic, 2021).

The project is expected to also provide regeneration to the area with an initial surge of 660 jobs during construction, and then 100 new jobs to support ongoing operations. The hydrogen produced is expected to support hydrogen transport and decarbonisation of local domestic heating systems supporting local improvements in air quality (Grubnic, 2021).

The site is supported by the UK Hydrogen Business Model/ Net Zero Hydrogen Fund, this fund has a total value of £240 million. This fund is in place to support projects exactly like this that has a focus on low carbon energy solutions (Grubnic, 2021) (Rashad, 2023)

5.3.2 H2H Saltend

This project has the substantial goal of generating 600MW of blue hydrogen with a low-carbon hydrogen production facility with a 95-carbon capture rate. The project has been taken on by Equinor, and when complete will be the first of its kind in the UK (Matthey, 2023). The project will be undertaken in Hull within the Saltend Chemical Park and is part of a wider project to make the area net zero by 2040 (Equinor, 2023).

The site will produce hydrogen via natural gas with the released CO₂ being captured and stored offshore. The hydrogen produced will be used to replace fossil fuels in industrial applications, as well as being blended into the Saltend Power Station to reduce its carbon output (Equinor, 2023).

5.3.3 The West Wales Hydrogen Project – Phase 1

The West Wales Hydrogen Project – Phase 1 is establishing a low-carbon hydrogen production facility in West Wales. The project is managed and funded by a group made up of industry leaders and is part of a wider goal of promoting the use of hydrogen at scale to supply applications including transport, industry and heating (Grubnic, 2021).

The initiatives have been supported by the UK and Welsh Government, both of whom are actively supporting projects of this type. This project represents a substantial investment and commitment to building a low-carbon infrastructure in the UK (Grubnic, 2021).

CHAPTER SIX: IMPLEMENTATION

6.1 Hydrogen Production in Wales

6.1.1 Natural Resources

Wales possesses an extensive range of natural resources that can be utilised in the hydrogen production.

One of the most abundant resources Wales possess is wind. Wales's global position allows for consistent production of offshore and coastline wind energy that is harnessed via the use of wind turbines. This method of power generation is typically used to support electrical use in the national grid however, during times when power generation is greater than demand, the excess power could be used to support hydrogen generation (Hughes, 2015).

Wales is infamous for being wet and windy and this can help produce renewable power. It is possible to harness the water courses and rivers to utilise hydropower in substantial quantities. The consistent weather patterns and geology allows for much more predictable power production than wind and could support the production of hydrogen (Aggidis, 2018),

Wales does not benefit from as much direct sunlight as some of its European neighbours however, solar energy is still a renewable source of power generation that could be harnessed. By strategically placing solar panels in areas with an unhindered

south-facing sky, energy production can produce enough power to support hydrogen generation (Dubey, 2018),

Whilst Wales isn't known for geothermal activity such as volcanoes, there is still a potential to harness geothermal power generation. Geothermal energy recovery via techniques such as heat pumps is possible however, requires further research and development before it becomes a viable power generation technique (Busby, 2015).

Wales boasts a substantial coastline and strong tidal currents making it well suited to tidal power generation. The Severn estuary has one of the highest tidal ranges in the world, making it an excellent candidate for tidal power generation. The Severn estuary has the potential to produce a large contribution to Wales's energy needs, as well as the potential to support hydrogen production (Evans, 2018). The exploitation of the tides around the Welsh coastline is supported further by the development of tidal energy technology using innovative methods of power capture to increase yield and reduce cost associated to tidal energy (Jones, 2020).

6.1.2 Existing Industrial Infrastructure

Wales benefits from key port infrastructure, such as Milford Haven and Port Talbot, that would allow for global distribution for hydrogen exports. Ports are key in the energy infrastructure supporting the import and export of energy goods. Using established port system would accelerate the development of hydrogen energy supporting the import of materials for hydrogen production and the export of hydrogen to other regions, extending the influence of energy production in Wales (Scott, 2021).

Wales benefit from a skilled workforce in relation to research and technical capabilities that are needed for hydrogen technology development and implementation. The UK as a whole have a tendency to have industrial knowledge in clusters according to the area's industrial needs. Wales have experience within the Petrochem and heavy industry, with training, these skills can be adapted to support hydrogen production and infrastructure (Thomas, 2018).

Wales also have the potential to support transitional forms of hydrogen manufacturing, such as blue hydrogen, by using its current and redundant industrial hubs. Repurposing industrial hubs into natural gas processing and carbon capture systems, Wales would be able to support the early adoption of hydrogen technology, while renewable options continue to be developed (Thomas, 2018). The geology around Welsh coastlines would also allow for permanent carbon capture storage, further supporting blue hydrogen production in Wales (Wilkinson, 2019).

6.1.3 Government Support

Within Wales there is substantial support for the development of renewable technologies. This is reflected by the initiatives and policies that have been passed in recent years. Renewable technology is dependent upon supportive government policy and framework to attract the investment, vital to renewable power projects. With a clear and positive legislation enacted by the Welsh government, renewable projects such as hydrogen are not only possible, but encouraged (Jenkins, 2020).

6.2 Hydrogen Production in Capacity

6.2.1 Blue Hydrogen

The amount of hydrogen produced from natural gas via steam methane reforming (SMR) have multiple variables that can affect performance. The yield of hydrogen from natural gas can be affected by the concentration of methane within the natural gas and the efficiency of technology used within the SMR process (Kumar, 2019). Considering the use of modern methods of steam methane reforming, a yield of 75-80% from methane natural gas is expected (Liu, 2018). From Liu's study to produce 1kg of hydrogen, 1.2-1.5kg of natural gas would be needed.

Based on the estimated portable power needs in section "Calculating Total Portable Power Needs", Wales would need to produce 72,000 tons of hydrogen to support hydrogen as a main portable power source.

Taking the mid-point of yield as an average. 1.35 Kg of natural gas is needed to produce 1kg of hydrogen. The volume of natural gas needed:

$72,000 \text{ (hydrogen in tons)} \times 1.35 \text{ (natural gas conversion rate)} = 97,200 \text{ tonnes of natural gas.}$

Natural gas conversion,

1 tonne = 1333 cubic metres

1 cubic metre = 10.55 KWh *

*Note, this value can change according to the calorific value of the gas, in this calculation the nominal value has been used however, this can be +/- 5% from what has been stated.

$97,200 \text{ (natural gas needed in tonnes)} \times 1333 = 129,567,600 \text{ cubic metres of natural gas}$

$129,567,600 \times 10.55 = 1,366,938,180 \text{ KWh of natural gas}$

1.367 TWh (rounded) of natural gas needed.

The UK demand on natural gas is currently at circa 800 TWh a year, so this increase of gas consumption would represent a minimal change of 0.171% when compared to the yearly variance of gas consumption (Heaton, 2023).

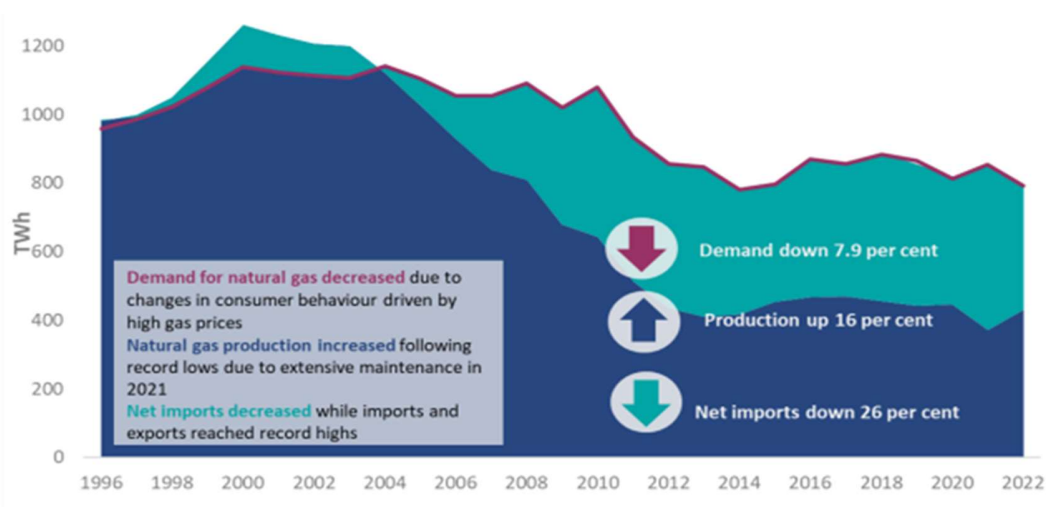


Image 9: Supply and demand for natural gas, source: (Heaton, 2023)

The supply of hydrogen would need production in the range of 300-400 tonnes per day to meet portable power application needs within Wales (based on a 5-day week production and 50 weeks a year operation). Whilst this scale of hydrogen production would be considered large even by industrial standards, several production facilities already are in service producing hydrogen gas in quantities similar to this. The following graph shows several hydrogen production facilities that are able to supply hydrogen on the scale of 100-1,300 tonnes per day.

FACILITY	H ₂ PRODUCTION CAPACITY	H ₂ PRODUCTION PROCESS	HYDROGEN USE	OPERATIONAL COMMENCEMENT
Enid Fertiliser	200 tonnes per day of H ₂ in syngas	Methane reformation	Fertiliser production	1982
Great Plains Synfuel	1,300 tonnes per day of H ₂ in syngas	Coal gasification	Synthetic natural gas production	2000
Air Products	500 tonnes H ₂ per day	Methane reformation	Petroleum refining	2013
Coffeyville	200 tonnes H ₂ per day	Petroleum coke gasification	Fertiliser production	2013
Quest	900 tonnes H ₂ per day	Methane reformation	Bitumen upgrading (synthetic oil production)	2015
Alberta Carbon Trunk Line - Sturgeon	240 tonnes H ₂ per day	Asphaltene residue gasification	Bitumen upgrading (synthetic oil production)	2020
Alberta Carbon Trunk Line - Nutrien	800 tonnes H ₂ per day	Methane reformation	Fertiliser production	2020
Sinopec Qilu	100 tonnes H ₂ per day (estimated)	Coal/Coke gasification	Fertiliser production	Expected 2021

Image 10: Hydrogen production from fossil fuels, source: (Zapantis, 2021)

6.2.2 Green Hydrogen

As previously explored in “Different classifications of Hydrogen”, Green hydrogen is manufactured via electrolysis using renewable power generation.

The Welsh government have commissioned a study into hydrogen production in Wales, with the view of understanding the best way to support renewable hydrogen production. The report entitled “Hydrogen Development in Wales: Baseline Report”, provides a comprehensive overview of the ongoing hydrogen projects in Wales, new potential energy generation projects and the supporting skills in the area including academic research (Michael, et al., 2020). The report stresses the importance for development of

initiatives and policies within Wales to capitalize on the new emerging market within the power sector.

In addition, research have been conducted in support of hydrogen development. One noteworthy example, “An Examination of the Feasibility of Producing Green Hydrogen”, explores the potential for offshore wind power to support renewable hydrogen via electrolysis (Griffiths, 2021).

To understand the renewable power needs to support the electrolysis process used in the manufacture of green hydrogen, first it’s vital to understand the efficiency of the process typically used in industrial volume production.

To start with, an assessment of the power needed for 1Kg of hydrogen production, then scale up the calculation to Wales’s portable application needs.

A perfect electrolysis system will consume 39.4kWh of electricity in the production of 1 Kg hydrogen gas however, this does not take into consideration losses within the system.

With the use of modern technology for electrolysis within large-scale hydrogen production, losses are introduced, increasing the power needed to produce 1Kg of hydrogen. Real world production of 1Kg of hydrogen produces figures closer to 50kWh of power (Bossel & Eliasson, 2003).

With the above in mind, 1 tonne of hydrogen would require 50,000kWh of electrical power.

Knowing that portable applications need 72,000 tonnes of hydrogen a year, the total electrical power needed:

$$50 \text{ (MWh)} \times 72,000 = 3,600,000 \text{ MWh} = 3.6 \text{ TWh}$$

To support the portable power needs using green hydrogen, Wales would need to produce 3.6TWh per year.

In terms of scale, the UK consumes approximately 800 TWh of electrical power per year (Operator, 2019).

Production of hydrogen would require 300-400 tonnes a day to support portable hydrogen applications within Wales. This scale of green hydrogen production is already in operation, thus can be implemented on an industrial scale ranging from 2.4 – 4800 tonnes of hydrogen per day (Zapantis, 2021).

FACILITY	H ₂ PRODUCTION CAPACITY	H ₂ PRODUCTION PROCESS	OPERATIONAL COMMENCEMENT
Fukushima	2.4 tonnes H ₂ per day	10MW electrolyzers powered by 20MW solar PV	2019
Neom	650 tonnes H ₂ per day	4GW wind and solar PV powered electrolyzers	Expected after 2025
AREH	4800 tonnes H ₂ per day	23GW wind and solar PV powered electrolyzers	Possible after 2028

Image 11, Green hydrogen production facilities. Source: (Zapantis, 2021)

Reviewing the report “Energy Generation and Use in Wales”, it shows the installation of 43MW of renewable electricity production projects in the year 2022, increasing Wales renewable power production capacity to 3,550MW (Regen, 2023). The report also shows that renewables account for 27% of all electrical energy produced. As Wales produces more electrical power than it consumes, the renewable power generation accounts for 59% of all electrical energy consumed in Wales (Regen, 2023). It is estimated that 70% of the renewable energy produced in Wales is done so via wind power generation, with the remaining 30% generated via photovoltaic solar power

(Regen, 2023). It is noted that tidal power generation is underutilised within these numbers and could offer a powerful and reliable form of power generation.

Given the renewable capacity in Wales is 3,550MW, the power in kWh produced in a year is 3,550,000,000 kWh or 3.55 TWh

If Wales is to make green hydrogen into a primary portable power source, then the power generated would need to be more than doubled, this does not include the additional renewable power generation needed to meet the Welsh governments target of 70% renewable by 2030 (Regen, 2023).

Total renewable energy needed to meet the Welsh governments energy targets and manufacture the hydrogen needed for portable applications based on consumption data today would be:

3,550 MW = 59% of Wales electrical power consumption.

70% renewable power generation = $(3550/59) * 70 = 4,212$ MW (rounded) = 4.212 TWh per year

Power needed for hydrogen generation = 3.6TWh per year

Total renewable power needed = 7.812TWh per year

To meet Wales's renewable target and meet the power needs for portable hydrogen production, the Renewable power generation in Wales would need to increase 120% to 7.812 TWh.

6.3 Hydrogen Infrastructure Investment

Investment in hydrogen infrastructure within Wales is key to hydrogens adoption as a mainstream fuel. Key investment areas include refuelling, production and a distribution network. The hydrogen infrastructure development initiative by H2 Wales, outlines the strategic roadmap to hydrogen use in Wales (Wales, 2023). The Welsh government have also committed to supporting commercial projects and job opportunities in the field of hydrogen, with the view of attracting investment in manufacturing and assembly plants supporting hydrogen in Wales (Government, 2021). The Welsh government have outlined the path towards renewable power, including the construction of a 10 MW renewable hydrogen production facility due to start construction in 2024 and completion due 2030 (Government, 2021). Whilst this site would not have the capacity to support a full switch to hydrogen fuels completely, it would allow for the understanding of how the facilities work and the refinement of the technology for greater capacity sites in the future.

Currently in Wales, portable power applications are supported by a network of refuelling stations dispensing petrol and diesel to the end user as needed. It is estimated that there are 1,000 refuelling stations in service across Wales, by contrast Wales have less than 10 hydrogen refuelling stations currently in service (Regen, 2023). The hydrogen fuel stations that are in service across Wales are typically dedicated to specific projects researching the viability of hydrogen fuel, such as that used for Mid and West Wales Fire Service or the University of South Wales Baglan Hydrogen Refuelling Station (Michael, et al., 2020).

For hydrogen to be adopted as a main portable fuel in areas such as transportation, substantial investment would be needed to increase the availability of hydrogen refuelling. Refuelling can be supported with innovations such as NanoSUN's hydrogen refuelling station. These portable solutions provide refuelling on-site as needed, in support of portable applications such as off-highway, domestic vehicles and heavy goods vehicles (Regen, 2023). This style of refuelling solution allows for rapid deployment and implementation whilst remaining low cost.

6.4 Support for Consumer Adoption

Support for consumer adoption is an important aspect of hydrogens success as a mainstream fuel source. Using tools that instil confidence in the technology, increase public awareness of hydrogen fuel and how it can be used as a sustainable alternative to the traditional fuels used today (Zero, 2023).

Public awareness campaigns are able to support the adoption of hydrogen fuels. This is done by educating the general public about the benefits hydrogen can bring. Campaigns can inform its target audience about the environmental impacts and economic and social advantages of hydrogen power in any given sector. By raising awareness of hydrogen technology with regards to renewable sources, storage and its use within technologies such as cars, the public can become better informed on how hydrogen can support environmental and energy security goals. Awareness campaigns can also engage important technology stakeholders, such as industry and academia (Michael, et al., 2020).

Demonstration projects can aid the adoption of hydrogen fuel by demonstrating the benefits and practical applications of hydrogen technology. These projects show how hydrogen have real world applications across multiple sectors, such as transportation, industry and energy production. By demonstrating hydrogen technology in practical applications and settings, the technology builds confidence by its audience. Additionally, demonstrating projects can highlight what supporting infrastructure or legislation might be needed to allow unhindered adoption of the technology (Department for Business, 2022). In a recent trial, Wales & West Utilities showed how they could develop refuelling in areas that are currently unsupported. This study showed how hydrogen can be used to support homes and businesses in the region via a hydrogen fleet of vehicles (Peachey, 2024).

Consumer incentives can influence users' decision to adopt hydrogen technology. Research have shown that factors such as purchase price, knowledge, refuelling time, refuelling station density and policy incentives, influence the adoption of hydrogen fuel (Government, 2022). The Welsh government have proposed using public funds to subsidise for the early adoption of hydrogen power to encourage investment and to help the technology to become common place (Government, 2022).

The development of hydrogen-ready products would support the adoption of hydrogen technology, this can be achieved by several methods. The Welsh government have already actively engaged with businesses that are in or could be supported by hydrogen fuel. The consultation "Hydrogen in Wales – A Pathway and Next Steps for Developing the Hydrogen Energy Sector in Wales", confirmed that local businesses and the public are

in support of hydrogen and expect the government to be more ambitious in its hydrogen goals (Government, 2022).

CHAPTER SEVEN: HYDROGEN LIMITATIONS

7.1 Cancelled Hydrogen Projects

Cancellation of hydrogen projects can have significant implications for the development of hydrogen energy. Cancelled projects can happen for several reasons such as loss of public or government support, environmental concerns, escalation of project cost, withdrawal of investor support and underpinned technology not practical. The cancellation of projects highlights the need to address project challenges such as cost and delays in regulatory framework (Burgess, 2024).

7.1.1 HyBont Project

HyBont project was a development by Marubeni Europower. The project was planned to be based in Bridgend, Wales within the Brynmenyn Industrial estate. The site was designed to be powered in part by a local solar farm and on shore wind farm, making it an ideal candidate for green hydrogen production (HyBont, 2023). The HyBont project had ambitious goals that aligned with the Welsh government objectives of transitioning to a low carbon powered economy. By producing green hydrogen from the renewable power sources in the area, the project aimed to reduce the carbon released in transport, heating and local industry power applications. In addition to supporting local low carbon objectives, the site would create new job

opportunities and attract investment for further projects in the hydrogen sector (HyBont, 2023).

The successful completion of the HyBont project would have resulted in increased hydrogen capacity in Wales, contributing to the Wales and wider UK Government goals, as well as creating a technology centre to support the growth of a hydrogen ecosystem. The technology used in the project would have helped the furtherment of industrial scale technological development, as well as expanding the technical understanding of hydrogen technology in the location (HyBont, 2023).

The cancellation of the HyBont project has potentially set back the development of green hydrogen production in Wales, as well as the lost hydrogen production capacity. The cancellation of the project might also hinder any investors' confidence in future projects that are similar. The project cancellation also leaves local businesses and domiciles with little option but to use the existing fuels available that are typically higher in carbon emissions (HyBont, 2023).

Whilst no specific reason has been publicised for the cancellation of the project, it is speculated that the changing cost estimations and timing were a contributory factor in the cancellation decision (HyBont, 2023).

7.1.2. Project Cavendish

Project Cavendish was a proposal to manufacture low carbon released hydrogen on the Thames estuary, UK. In the original proposal, the plans were due to be in service

early 2027 and was meant to capture and store 1.2 million tonnes of CO₂ annually from the production of blue hydrogen. With the view to have a capacity of hydrogen production of 1.75GW by 2030, increasing carbon capture to 3 million tonnes per year. The project was a collaboration between Arup, VPI, National Grid Ventures, Shell, SSE Thermal and Uniper (Burgess, 2021).

The cancellation of project Cavendish has impacted the UK's goals towards net zero, as the capacity for low carbon hydrogen has been impacted considerably. The project was projected to generate 100's of jobs and support 1000's on indirect jobs, but this economic prospect was removed when the project was cancelled (Burgess, 2021).

As per the HyBont project, the reason for the project cancellation was not provided, but again it is speculated that an escalation in cost is one of the contributing reasons behind the project's failure (Burgess, 2021).

7.2 Green Power Shortfall

The UK already have established green power generation projects and continue to develop this form of power generation however, the production of green energy is in support of the power demands from the national grid, with little consideration to the additional needs of hydrogen production (Zero, 2023).

Despite the established projects for green energy production, the UK still needs to scale-up green energy production. However, this itself has limitations due to the need to scale-up the infrastructure limitations to support the higher energy demand. If the UK is going to make green hydrogen, then the demand would need circa 300% more green

electrical capacity than currently available, not accounting for the green electrical power needs of the electrical grid. This shortfall shows the need for substantial investment in infrastructure, power generation and hydrogen processing to support hydrogen usage in the UK (Zero, 2023).

7.3 Efficiency Losses

The process of converting electrical energy into hydrogen have several stages, each have inefficiencies and result in power losses. One of the main technologies for hydrogen is via electrolysis, where water is split into its component parts of oxygen and hydrogen. This process typically operates with an efficiency of 60-70% when using modern technologies. Some improvements can be made using PEM electrolysis however, losses still exist due to cell voltage needs and activation overpotential, making this power storage 70-80% efficient (Carmo, 2013).

In addition to the losses in the hydrogen production, the produced hydrogen gas needs to be compressed for practical storage and logistical usage. The compression of hydrogen consumes energy in the physical compression of the gas and some losses due to leakage, this loss is circa 5-15%. The source of the electric used also impacts on the efficiency and carbon natural credential of the process, with renewable energy supporting low carbon hydrogen production best (Azarabadi, 2021).

Whilst modern technology continues to improve efficiencies in processes, inherent losses persist. Continued research would be vital to maximise hydrogen production and

reduce electrical power needs, reducing the overall cost of hydrogen production in the future.

7.4 Safety Concerns

7.4.1 Safety and Feasibility Testing

Safety and feasibility testing is a vital requirement of any technology that is to be adopted, ensuring it is safe, reliable and economically viable. This is the case for hydrogen-based technology. Hydrogen energy presents its own unique safety concerns that need to be addressed before it can be safely used in applications. These concerns include the gas being colourless and odourless and with a low/high ignition range by concentration mix. This risk needs to be managed via safety systems such as leak detection and gas purity monitoring (Buttner, 2022).

Feasibility studies for hydrogen programs often face technical challenges, this is due in part to multiple forms of hydrogen production methods and even different technologies that are used within the same hydrogen production processes. (Leon, 2023). Each hydrogen production method has its own technical challenges that needs to be addressed, to ensure the safe and efficient production and use of hydrogen. Safety procedures are necessary for each hydrogen production and usage technology, to ensure the wellbeing of all users of the technology. Some of the considerations needed are due to hydrogen properties as a fuel, requiring strict measures in handling, storage and usage (Leon, 2023).

Economic challenges in feasibility testing include substantial costs that can hinder the project development. This is in part due to the unknown factor of validating new technologies, often needing substantial time under test to confirm its safe operation and instil confidence in the users. This extended expenditure of testing hydrogen technology can hamper the technologies cost competitiveness, seen as a key economical consideration to hydrogens wider adoption (Leon, 2023).

7.4.2 Distribution and Storage Barriers

As per safety and feasibility testing, distribution and storage of hydrogen raises safety concerns centered around hydrogens highly flammable nature, with a wide range of flammable ignition concentration when mixed with air. The increased susceptibility to ignition, increases the risk of accidental fire. This detection of which is further hampered by hydrogen burning without a visible flame (Amiri, 2023).

Another consideration for safe storage of hydrogen is its potential to damage materials used in the handling of hydrogen. When hydrogen is in contact with certain materials, it can lead to embrittlement, increasing the risk of leaking or structural failure. High pressure hydrogen storage and transport have additional risks due to the potential of failure, due to rapid decompression having an explosive reaction when materials fail (Copco, 2021).

These concerns are often addressed by consideration, from conception and material selection to safety systems and checks to ensure the equipment remains fit for service. Some materials commonly used in hydrogen storage are stainless steel and metal hydrides, to limit the material damage and leaks in service. Additionally, systems can utilise pressure sensors to monitor the system to aid leak detection (Copco, 2021).

In addition to the safe selection of systems and materials, it is important to mitigate any safety concerns with regards to human error. With consideration to this it is vitally important that personnel and users of the technology are properly trained in its use and operation to prevent any dangerous scenarios. By implementing these safety protocols, the risk associated with hydrogen storage and distribution can be managed, making this potentially hazardous fuel effectively managed and safe for application (Mantripragada, 2007).

7.4.3 Market Structures Issues

One of the key issues with the Market Structure in the UK is regarding the supply uncertainty of low carbon hydrogen. Currently, the UK have no commercially available low carbon production, leading to uncertainties about how hydrogen would be supplied in the future (Department for Business, 2021). The proportion of hydrogen supply depends upon the technology used, this can be influenced by cost, performance, time etc. However, most technologies have not been commercially demonstrated in the UK, adding to the uncertainty surrounding the future in hydrogen supply (Department for Business, 2021).

In addition to this, the infrastructure in the UK have hindered the adoption of hydrogen on a larger scale. The current hydrogen system in the UK has around 70% its captive production where hydrogen is produced and used on site. Only 10% of produced hydrogen in the UK is available for sale to other users. This distribution limitations highlight the need for infrastructure development, to enable efficient distribution and storage from production to the end user (Department for Business, 2021).

7.5 Legislation

7.5.1 Policy and Regulatory Uncertainty

Within the UK, hydrogen fuel faces considerable limitations due to policy and regulatory uncertainty that can impede hydrogen fuel's widespread adoption. One of the challenges faced by hydrogen fuel is the cost when compared with fuels currently in use that are typically hydrocarbon based. The higher cost presents a financial barrier to its wider adoption, making it less competitive than current energy options (Simakov, 2023).

The outcome of not having policy and regulatory uncertainty on hydrogen technology results in resistance in technology adoption in the UK. This has led to a decrease in attracting external investments in the hydrogen industry, impacting on the UKs competitiveness on a global scale. Additionally, uncertainties are hindering potentially lucrative export opportunities for hydrogen, limiting hydrogen fuel growth potential in the international sector and lack of support in adoption within the private, domestic market (Department for Business, 2021).

Consideration of the impact upon the users is a critical consideration that must be made. Reducing the disruption and cost for domestic applications are vital to ensure the successful adoption of hydrogen fuel technology. The lack of policy and regulatory clarity for low carbon hydrogen hinders the technology research and development needed to improve the technology to reduce the cost to the user. This hindrance directly affects the confidence in the market, reduces demand and the economic viability of hydrogen fuel (Department for Business, 2021).

7.5.2 Legislative Framework Gaps

Legislative framework gaps in the UK hinders the development and adoption of hydrogen technology, this is due to several points. Noticeably there is a lack of specific legislation dedicated to hydrogen, forcing projects to navigate an unclear legislative landscape and seek compliance in laws ill-suited to hydrogen fuel, such as the Gas Act 1986 which is regulated as part of the UK gas market (Majumder-Russell, 2023). This generic approach to regulations creates uncertainty and has resulted in gaps that need to be addressed if hydrogen is expected to flourish.

Looking further afield to Wales's European neighbours, the European government have developed and produced the EC79 standard that provides regulatory clarity for hydrogen applications, in particular hydrogen in portable applications. Whilst the UK and Welsh governments don't specifically have a like for like document for EC79, it is evident that the UK government is taking steps to regulate and support the development in use of hydrogen, including setting standards for low-carbon hydrogen

production and providing funding for projects that align with this (Rotar , et al., 2023).

It is important to consider that whilst the UK is embracing hydrogen into its legislative frameworks, this legislation needs to interface with the legislation being implemented by our trade parties such as the European union.

CHAPTER EIGHT: CONCLUSION

8.1 Conclusion

In conclusion, this study aimed to assess the feasibility of adopting hydrogen fuel as a primary fuel source for portable applications in Wales. The analysis started with addressing various application needs where hydrogen could be utilised, compared with the current systems of power distribution such as petrol, diesel and electric in various vehicles across UK. Given the lack of information available, specifically for Wales's automotives statistics, a novel approach was used using population metrics and was devised leading to an estimated 4.6% allocation of vehicles in Wales from the overall statistics in the UK.

The review continues to evaluate hydrogen in public transport requirements, focusing on buses, trains and personal mobility. Buses were well suited to hydrogen technology and were estimated to have an adoption rate of 50%. Trains and personal transport equipment were excluded from the review as they can potentially be supported by better technologies already in use. The review continued with Maritime applications however, obstacles relating to hydrogen storage and regulations made initial adoption unlikely within the foreseeable future.

Following a review of the current fuel demands and with consideration to the efficiencies of the technologies used, calculations were performed to estimate the potential demand for hydrogen in a given scenario. This concluded that Wales would require over 72,000 tonnes of hydrogen per year to replace the applications previously outlined.

Following a review of Welsh demands, focus was then moved to reviewed technologies that can best utilise hydrogen technologies for portable applications, in particular hydrogen fuel cells and hydrogen internal combustion engines. Hydrogen fuel cells, known for their efficiency and minimal emissions, were identified as a promising solution for portable fuel applications, especially for automotive applications. Hydrogen internal combustion engines were also considered as an alternative and transitional technology, offering potential integration with existing infrastructure, but presented challenges relating to NOx emissions.

Following the review of hydrogen technology, production of hydrogen in support was then considered. Depending on the technologies used to produce the hydrogen, a different classification is given, each with distinctive processes and considerations. The main categories reviewed within this paper are green, grey and blue hydrogen, highlighting the environmental implications, cost and scalability.

Green hydrogen is produced via electrolysis and using renewable energy sources is noted as being the most environmentally friendly form of hydrogen production however, the investment and production cost are considerably higher than alternative forms of hydrogen production available. This is further hindered by the challenges of having a continuous and consistent supply of renewable energy.

Grey hydrogen is derived from fossil fuels via steam methane reforming and is most widely adopted due to the cost-effectiveness. Despite being an established process with high production capacity, the environmental impact by the release of carbon dioxide is of concern. From the evidence collected it can be concluded that alternative methods of hydrogen production need to be explored if hydrogen is going to be adopted as a mainstream fuel source.

Blue hydrogen has been presented as a transition solution to grey hydrogen production. Using the same manufacturing methods of grey hydrogen, blue hydrogen introduces a carbon capture technique to reduce the environmental impact of production. While offering improvements on carbon release, this process incurs higher cost due to the additional processing, but offers the possibility of scalability using existing infrastructure.

In addition to the production of hydrogen, this paper explored the ability to store and transport hydrogen vital to the distribution network needed to support end users of

hydrogen technology. Whilst several methods of hydrogen storage were explored, each hydrogen storage had its advantages and disadvantages. If a successful hydrogen network is going to be utilised, then not one system of storage and distribution would be needed, but a mix of each of these technologies unique to the application scenario.

Hydrogen technology is supported in the UK and Wales by policies that have been passed by the government. The policies that have been put in place highlight the government's commitment to renewable energy targets that hydrogen has a key role in realising these objectives. The UK governments hydrogen strategy and substantial financial support, including the net zero hydrogen fund, shows the dedication of the government to hydrogens development. Similarly, the Welsh government have set ambitious goals and investment in hydrogen related programs, such as the hydrogen business research and innovation for decarbonization (H2BRID). These programs and support show forward-thinking and dedication to hydrogen development and implementation.

In support of the hydrogen technology development, The UK have several projects to demonstrate hydrogen principles, this shows a promising trajectory towards a sustainable low-carbon energy future. Projects such as H2 Teesside will have significant production capacity and have benefited from support from the UK Hydrogen Business model/ Net Zero Hydrogen Fund, showing how the UK's development funds can support

new hydrogen developments. By way of another example, this can also be seen in the H2H Saltend that is aiming to generate 600MW of blue hydrogen a year.

Specifically in Wales, examples such as the West Wales Hydrogen Project can be seen. These projects benefit from support from both the UK and Welsh government, demonstrating a collaborative effort towards developing hydrogen / renewable technology. These projects demonstrate the ability of new technology, whilst encouraging external investment in similar projects.

Digging further into Wales's potential to support hydrogen technology, the landscape lends itself to a rich range of natural resources that could be supported by existing industrial infrastructure. The potential of blue and green hydrogen production, along with renewable energy capacity, demonstrates the vast scale of challenges and opportunities for Wales to become a significant influence in the hydrogen landscape.

The hydrogen infrastructure and investment outlined within this study, in particular the initiatives by H2 Wales and the commitment of the Welsh government to a 10MW renewable hydrogen production facility, sets a strategic roadmap for hydrogen adoption in the area. Challenges such as a limited number of hydrogen refuelling stations and limited infrastructure, highlight the need for substantial investment to accelerate the adoption of hydrogen as a mainstream fuel.

In addition to infrastructure investment, education of the technology must be undertaken to support adoption. This could be achieved through public awareness campaigns, demonstration projects and incentives that would help instil trust in the new technology. The Welsh government have taken a proactive approach with engagement of businesses and the public, as seen in the “Hydrogen in Wales – A Pathway and Next Steps” consultation. This shows a system of cooperation between the new hydrogen technology and its users.

However, as with many emerging technologies, hydrogen have many hurdles and limitations and it must be navigated before it could be successfully adopted. The cancellation of hydrogen development projects such as the HyBont and Project Cavendish, underlines the complexities and uncertainties that are involved with hydrogen developments, highlighting the complexities and uncertainties associated with hydrogen projects. To limit the risks of these projects’ key aspects of cost estimates, timing and regulatory framework, need to be considered if more projects are going to be successful in showcasing hydrogens potential. In addition to this, developments in green power generation and processing into hydrogen need to be developed further to improve efficiency and be cost effective for industrialisation. Safety considerations in all aspects of hydrogen usage need to be reviewed and addressed to ensure safe operation. A key part of this would be the implementation of stringent protocols, material selection and training, to ensure hydrogen usage is done in a safe manner.

Market structure issues highlighted uncertainties regarding the supply and distribution of low carbon hydrogen, necessitating significant development. Legislative challenges such as policies, regulatory uncertainty and legislative framework gaps, pose challenges to the widespread adoption of hydrogen technology. Addressing these challenges require a collaborative and constructive approach from governments, industries and research institutions, to provide the necessary support, standards and framework for hydrogen to reach its potential as a mainstream fuel.

8.2 Limitations and Further Research

8.2.1 Data Availability and Specificity

Whilst there is a range of data available, the review faced challenges in some cases, most notably data specifically to Wales automotive and industrial sectors. The use of population metrics for vehicles estimations introduces a level of assumption, potentially impacting on the accuracy of the findings.

8.2.2 Exclusion of Certain Sectors

The decision was made to exclude certain sectors from the review as current technologies already provide adequate renewable power supports however, should these technologies not be adopted, or changes of offerings be made, this could impact the accuracy of the study's results.

8.2.3 Assumptions in Demand Estimations

Estimations of hydrogen demand were based on assumptions regarding the adoption rates of hydrogen technologies in various applications. These assumptions are based on literature reviews however, introduce a level of uncertainty to the overall results.

8.2.4 Environmental Impacts Assessment

The assessment considers the environmental impact of key technology however, greater study and considerations must be made prior to technology implementation. Consideration towards factors such as water usage, land footprint, native species displacement, could benefit from a detailed study.

8.2.5 Policy Dynamics and Future Changes

Government policies and financial support from an integral part of this study and are subject to change over time and government charges. As government priorities change and time passes, the policies used to support this study may become obsolete and updated government policies would need to be checked.

8.2.6 Projects Cancellations and Uncertainties

The study provides some examples of programs that are in development in support of hydrogen technology however, there are also examples of projects being cancelled prior to completion. It needs to be considered that the status of the examples provided may change over time and its actual status will need to be confirmed by an independent study.

8.2.7 Technological advancements

Whilst the study includes a technology assessment, it cannot foresee the development of new supporting technologies that may make those mentioned in this report redundant.

8.2.8 Regional Infrastructures Challenges

Whilst the study addresses the need for substantial investment in hydrogen infrastructure, it doesn't delve deeply into the specific challenges faced by Wales. Further research would be needed to support the specific infrastructure investments needed.

8.2.9 Snapshot in Time

The study uses a fixed point in time for a review of hydrogen consumption and needs. As with many emerging technologies, the landscape of need is changing, including technology efficiencies, adoption rates policies change and public opinions. Changes in these factors would need to be considered.

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