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3YP Green Hydrogen Public Mobility Project

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1 Introduction

An effective public transport system is one of the vital components of a thriving city. It allows for ease of mobility for the people, both for leisure and work-related purposes. However, in order to meet global, national and city-specific targets for reducing emissions, the public transport system in Oxford needs swift, major adjustment. In this report, a proposed solution to this problem will be presented. A link to a repository containing the modelling for this project is available at the top of the list of references.

1.1 Project Outline and Scope

The main objectives of the project are as follows:

1. To design a net zero public transport system for Oxford City using green gas
2. To consider an Oxfordshire-based generation and distribution site for the green gas production
3. To consider additional benefits, through integration with the wider energy system

The scope of this project includes buses operating within Oxford, whether they operate solely within Oxford or connect to other cities. The bus companies included in this scope are Stagecoach Oxfordshire (SC), the Oxford Bus Company (OBC) and Thames Travel (TT). City Sightseeing Tours is not being included in this project due to their plans to operate a fully electric fleet, which they have already begun to develop [1.1]. In addition to this, they only cover approximately 25,000 bus kilometres each year, whilst the three companies being considered cover over 33,000,000 bus kilometres annually in total. The modelling by which these figures were obtained will be presented in more detail in Section 4. Trains are not included in the scope of this project, and nor are taxis, though this project yields some relevant results that could be applied to similar projects in those areas.

1.2 Project Motivation

When the Paris Agreement was adopted by 196 parties in late 2015, and then brought into force in November 2016, the signatories took upon themselves responsibility to ensure that the global rise in temperature above pre-industrial levels remains well below 2°C, preferably below 1.5°C [1.2, 1.3]. As a signatory, the UK has since been updating previous targets, and adding new measures to reduce their carbon emissions. In 2019, the UK committed to achieving net zero harmful emissions by 2050, improving on its original aim declared in the Climate Change Act of 2008 for an 80% reduction in carbon emissions by 2050, from a 1990 baseline [1.4]. From 2008, the Government has been committed to setting carbon budgets [1.5]. These are legally binding caps on carbon emissions over a period of five years, which help guide the UK toward its 2050 target. These are put together by the Climate Change Committee more than a decade ahead of the relevant timeframe, to provide enough time to prepare policies and investments for the most economically beneficial route to the target [1.5]. Amongst the policy measures taken so far are carbon pricing, low-carbon energy support, improvement of energy efficiency and increased spending on international climate action [1.5].

On top of the aims of the UK government to reduce carbon emissions, the Oxford City Council has targets of its own to accelerate the process of becoming a zero emissions city. In 2019, there was an Oxford Citizens' Assembly on Climate Change. The main relevant findings published in the report were [1.6]:

- A majority felt that Oxford should aim to achieve net zero earlier than 2050
- Increased public transport and fewer cars were seen as a central part of achieving net zero
- The burden of change appeared to be put on individuals, so the Council needed to better communicate a shared vision and strategy to achieving net zero

In response to this, the Council proposed to do the following among other measures [1.7]:

- Set a Climate Emergency Budget which commits a total of £19 million to address the climate emergency, on top of £84 million of ongoing investment to tackle the climate emergency in Oxfordshire
- Cut transport emissions and boost renewable energy installation
- Hold a Zero Carbon Oxford summit involving the organisations responsible for most of the emissions in the city to develop a shared plan to tackle the carbon problem
- Establish a Zero Carbon Oxford Partnership and influence partners to do more

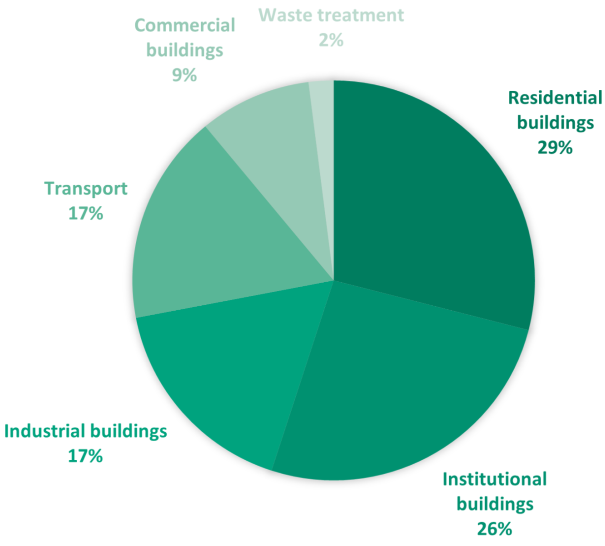
- Create new carbon budgets for the city to step down to zero emissions

In December 2020, the council announced that it had achieved its target of a 40% reduction in carbon emissions from a 2005 baseline, as well as joining the UK100's aim of achieving net zero harmful emissions by 2045 [1.8].

In February 2021, some of these aims were improved, whilst others were expanded upon, at the Zero Carbon Oxford summit [1.9]. At the summit, leaders of major organisations in Oxford signed the Zero Carbon Oxford Charter to give their support to achieving net zero by 2040, an entire decade before the UK's legally binding date to achieve this as a country. As well as advancing the date by which the city will have zero emissions, the summit marked the creation of the Zero Carbon Oxford Partnership. The partnership provides a collaborative approach to achieving the ambitious targets for carbon reduction, enabling greater sharing of methods and insights between partners, attracting greater financial support for innovative projects to achieve the city's aims, as well as engaging citizens and communities in shared action. Furthermore, the partnership will allow for more coordinated lobbying of the UK government, which should allow the city to develop the means to achieve their aims, whether through improved policy or greater funding.

Fig 1.1 shows a chart of the sources of Oxford's carbon emissions. As shown, the transport sector in Oxford is responsible for 17% of the city's carbon emissions [1.10]. Of the remainder, the vast majority is taken up by various building-related emissions, and a small amount (less than 2%) is associated with waste treatment [1.10].

Although the aim is to have the city as a whole net zero by 2040, the Council has set a separate aspiration for all buses within the city to be zero emissions capable by 2035 [1.11]. This lines up with the plans to improve the current low emissions zone to a zero emissions zone which covers the entire city by 2035 [1.11].



< Fig 1.1 : Sources of carbon emissions in Oxford [1.10] >

1.3 Overview of Oxford's bus network

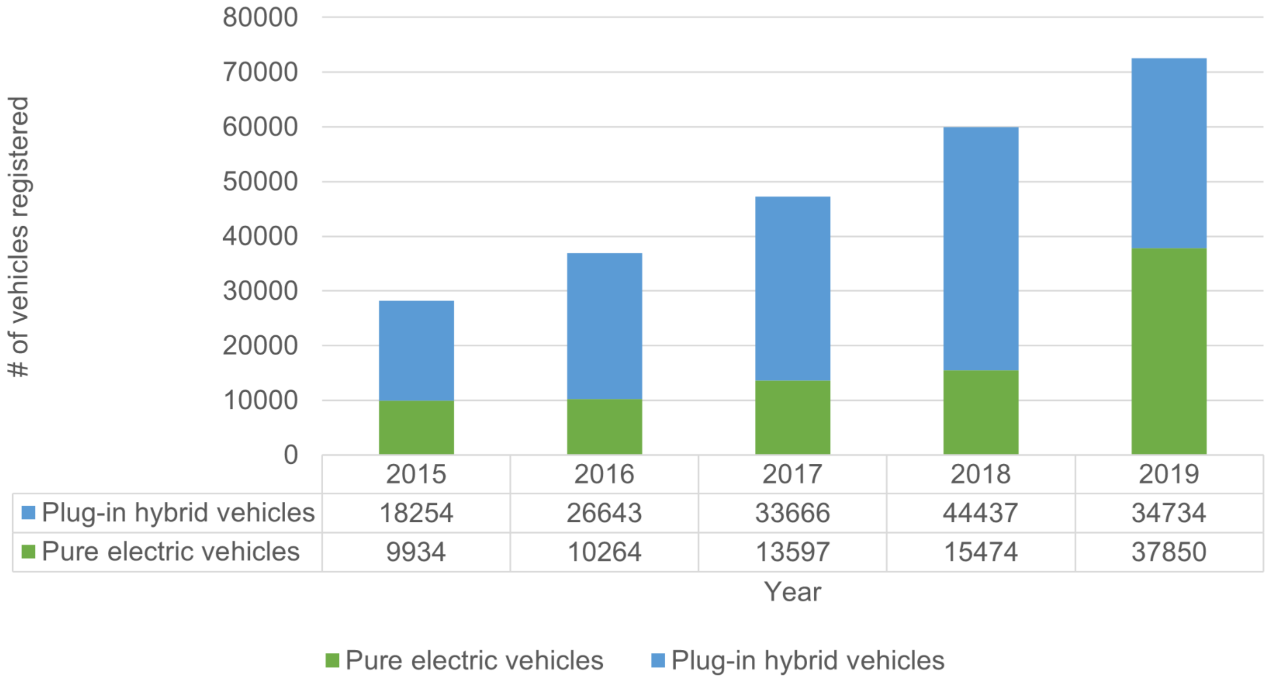
As mentioned previously, the three bus operators in the project scope are Stagecoach Oxfordshire, the Oxford Bus Company, and Thames Travel. The latter two are both subsidiaries of the Oxford Bus Group, and therefore share management. On top of this, Stagecoach and the Oxford Bus Company share certain routes under a shared ticketing scheme.

The Oxford Bus Company operates out of their depot in Cowley, Thames Travel operates out of one in Didcot, and Stagecoach Oxfordshire operates from a depot in Cowley and another one in Witney. The Oxford Bus Company currently has a fleet of 148 buses and coaches, while Thames Travel has 83, and Stagecoach Oxfordshire has 168, giving a total of 399 buses within the scope of the project [1.12, 1.13, 1.14].

The Oxford Bus Company runs services including BROOKESbus, the airline, Park & Ride, and city routes [1.15]. A number of the city routes are shared evenly between the Oxford Bus Company and Stagecoach Oxfordshire. In addition to this, Stagecoach Oxfordshire runs services which link the city to various locations in Oxfordshire, as well as the well-established Oxford Tube service, which runs between Oxford and London [1.16]. Thames Travel runs services connecting Oxford to local areas which surround it, as well as to some further locations including Henley-on-Thames and Reading [1.17].

1.4 Limitation of battery electric vehicles

An obvious solution to reducing the emissions caused by the Oxford bus network may seem to be a transition to battery electric vehicles (BEVs). Indeed, the purchase of battery and hybrid electric vehicles in the UK has been rapidly growing in the last five years, as shown by Fig. 1.2 below.



	2015	2016	2017	2018	2019
Plug-in hybrid vehicles	18254	26643	33666	44437	34734
Pure electric vehicles	9934	10264	13597	15474	37850

< Fig. 1.2: Registration of new hybrid and battery electric vehicles in the UK from 2015 - 2019 [1.18, 1.19, 1.20, 1.21, 1.22] >

City Sightseeing Tours, a member of the Oxford Bus Group has already begun to develop and operate a fully electric fleet [1.1]. However, although BEVs are seeing a massive increase in popularity, they still suffer from issues such as low range and long recharging time which are key vehicle metrics for a bus network. Fuel cell (FC) buses surpass BEVs on these key vehicle considerations. This is less of a problem for City Sightseeing Tours as their services are bound to the city centre with very low mileage and hence they have no need for long range buses. Other services, especially those travelling outside the city centre serving places such as Heathrow airport, need buses that have the extra range that FC buses can provide.

Despite the growth of BEVs, they are not desirable for Oxford's public transport system for the following reasons. A starting point is to first examine the fuel sources for each vehicle. A summary of the key properties is provided in Table 1.1 below.

Fuel	Gravimetric Energy Density ($MJ\ kg^{-1}$)	Volumetric Energy Density ($MJ\ L^{-1}$)
Hydrogen	120 [1.23]	2.80 (at 27°C, 350 bar) [1.23]
Ammonia	18.8 [1.24]	15.6 (liquid) [1.25]
Lithium-Ion Batteries	0.36 – 0.95 [1.26]	0.93 – 2.41 [1.26]
Diesel	44 [1.23]	38.6 [1.27]

< Table 1.1: Gravimetric and volumetric energy density of various fuel types >

It is clear that whilst batteries and green gas have a similar volumetric energy density, both hydrogen and ammonia have significantly greater gravimetric energy densities. This is important as it contributes significantly to the overall efficiency and range of the vehicle due to the much lower mass of fuel required for the same energy output. Range is the major advantage of FC buses over BEVs and typical values are ~ 240 km for BEVs [1.28] and ~ 320 to 430 km for FC buses [1.29].

Another key vehicle consideration is the refuelling/recharging time. FC buses have the advantage here as it takes only minutes to refuel an FC bus. For example, the Wrightbus H2Bus can take as little as 7 minutes to refuel [1.29, 1.30]. This is in comparison to, for example, the Tesla Model S, a BEV which takes 1.25 hours to fully recharge when using a supercharger, the fastest method of charging. BEVs can take several hours to charge and this down time directly translates to financial loss for the bus operators. Many of the public BEV chargers located across the country are connected to the national grid and so by using these chargers there is a contribution to carbon emissions. Green gas powered vehicles can be completely net zero.

Finally, the costs of these vehicles can also be compared. Both BEVs and FC buses can use exactly the same electric drivetrain system and will only differ on the methods used to power the drivetrain. For a FC bus the main capital costs will be the fuel cell and the hydrogen storage, whereas in a BEV the capital cost will be for large-capacity lithium-ion batteries. Due to the high cost of modern, high-density lithium ion batteries and the fact that quite a large number of batteries are required to give the BEV a decent range (again this is due to the very low gravimetric energy density of lithium-ion batteries) BEVs lose out to FC buses in this criteria. The cost of a FC bus capable of the ranges mentioned previously is ~ £356,000 [1.31] whereas a BEV with a lower range will cost ~ £554,000 [1.28].

The major vehicle metrics have been summarised in Table 1.2 below.

	BEVs	**FC Buses**
Gravimetric Energy Density ($MJ\ kg^{-1}$)	0.36 – 0.95	18.8 – 120
Range (km)	240	320 – 430
Refuelling Time	Hours	Minutes
Cost (£)	554,000	356,000

< Table 1.2: Summary of the major vehicle metrics between BEVs and FC Buses >

It is also important to look at the wider environmental impact caused by both vehicle technologies. While BEVs may seem to be carbon free, there are many other secondary sources of emissions to consider such as transport, manufacture and mining. Many of these secondary emissions, namely manufacture and transport, will be mirrored in a green gas based system. The major source of damage to the environment, caused primarily by BEVs, is the impact on wildlife and local ecosystems due to the mining and processing of metal ores. While a green gas based system is certainly not battery free as batteries are used onboard FC buses, it does contain fewer batteries than a BEV system. Batteries onboard FC buses are also much smaller (lower capacity and therefore containing less lithium) than those used on BEVs as their main purpose is to ensure that there is a constant current through the fuel cell, not to be the primary power source [1.32, 1.33]. The idea of replacing the batteries in an FC bus with ultracapacitors is something that is already being explored, specifically, Wrightbus has been working with a company called Skeleton Technologies to replace the lithium based batteries currently used in the H2Bus with ultracapacitors which are much more environmentally friendly [1.34].

There are two primary metals used in lithium-ion batteries, they are lithium and cobalt which is found in the cathode of the batteries. The mining of these two metals is extremely harmful to the environment and has had damaging effects on the landscape and inhabitants of the countries in which they are found.

The process of lithium extraction uses a large amount of water, approximately 500,000 gallons per tonne of lithium extracted [1.35] and produces many toxic chemicals as by-products, including hydrochloric acid (HCl) [1.35]. These damage the soil and leak into nearby rivers, killing fish and any land animals that drink from the river. Many environmental incidents have occured due to the mining and processing of lithium such as, in May 2016, when environmental protestors threw dead fish onto the streets of Tagong, Tibet in opposition to China's mining operations at the Ganzizhou Rongda lithium mine which had leaked toxic chemicals into the nearby Liqi river, which is from where the dead fish had been taken [1.36]. In Chile, lithium mining operations have left pools of toxic liquids which are visible from the sky. The American photographer David Maisel has documented the devastating impact lithium mining has had on the once beautiful Chilean landscape in his work *Desolation Desert* [1.37].

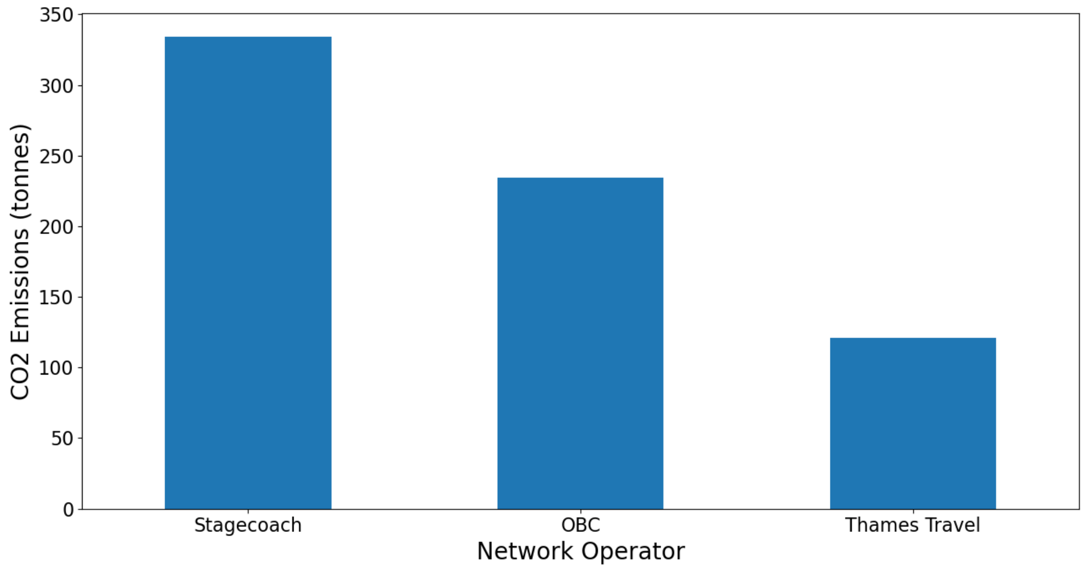
The majority of the world's cobalt ores are found in the Democratic Republic of Congo (DRC). Kinshasa, the country's capital, is a leading source of cobalt, supplying approximately 70% of the cobalt produced worldwide in 2020 [1.38]. The leading consumer of cobalt in 2020 was China, with 80% of its consumption being used by the rechargeable battery industry [1.38]. The mining of cobalt in the DRC has had a severe human toll and there have been several reports of child-labour, exploitation, dangerous working conditions and serious health problems due to the mining of cobalt [1.39]. These include thyroid and breathing problems and come as a result of workers not being provided with adequate machinery, often having to resort to mining with hand tools which results in exposure to dangerous chemicals [1.39]. The bigger concern, however, is the link to birth defects in children whose parents worked in a cobalt mine. Children in the DRC are being born with a condition known as *holoprosencephaly* which is usually fatal. This is being investigated by doctors at the University of Lubumbashi, a large centre for cobalt mining in the DRC [1.39].

Overall, the FC bus outperforms the BEV in the most important vehicle considerations of range, refuelling time and cost. This point is reinforced later by the results of the route modelling (Section 4.1) which shows that buses with a significant range are required to maintain coverage that the current bus network requires. The environmental impact of battery technology is much greater than first meets the eye and hence, it is vital that the system design minimises the need for battery technology and is able to take advantage of other forms of energy storage such as ultracapacitors. Hence, it is for these reasons that a green gas based system is the way forward and most likely to achieve a successful net zero transport system.

1.5 Current environmental impact

The current environmental impact of the transport network in Oxford is considerable and it is worth estimating the emissions caused in order to quantifiably measure the change that switching to a net zero system will have. In order to estimate the emissions it was necessary to gain a thorough understanding of the current bus network. This was achieved by creating a model of the current network using Google Maps [1.40] and the online timetables of the network operators [1.15, 1.16, 1.17]. The modelling is discussed in much detail in Section 4.1, here only the results of the emissions aspect of the route modelling will be presented.

The results of the route modelling came to a total of 35,867 tonnes of CO_2 released annually by the bus network in Oxfordshire, which contributes to the 17% of the city's emissions caused by the transport sector [1.10]. This value can be down into the individual contributions of the three networks operators identified in the project scope. These are Stagecoach Oxfordshire, the Oxford Bus Company and Thames Travel. Fig 1.3 shows the breakdown of weekly CO_2 emissions by the network operators.



< Fig 1.3: Estimate of the weekly CO_2 emissions by each network operator >

Stagecoach contributes most to the emissions of the bus network, around 330 tonnes weekly.

It is important to note the impact of the COVID-19 pandemic on the timetables of the networks. When doing the research for the route modelling it was noticed that the value obtained for the distance travelled yearly using 2020 timetables was significantly lower (around half) than the value published by the bus companies for the total distance travelled in 2019 [1.41, 1.42]. It was obvious that this was due to a downsizing of operations caused by the national restrictions put in place to combat the spread of the coronavirus. As such, the results were adjusted to better reflect the operation in a normal year. This modelling was also used to estimate the total annual hydrogen demand, which is a key metric of the system, hence it was doubly important that the figures were reflective of what is expected in a normal year.

2 Evaluation of green gases

In order to choose an appropriate source of power for the system, it was necessary to review the options and compare them with each other. This section of the report aims to explore the technical aspects of two different potential fuels for the public transport network; these are hydrogen and ammonia. This section will aim to evaluate and compare the performance, production and storage of these fuels, providing technical information where necessary, in order to make an informed choice for the system.

2.1 Hydrogen

This subsection will give a brief overview on the performance of hydrogen as a fuel, its different methods of production, the environmental impact of these processes and finally, the different methods of hydrogen storage.

2.1.1 Hydrogen as a fuel

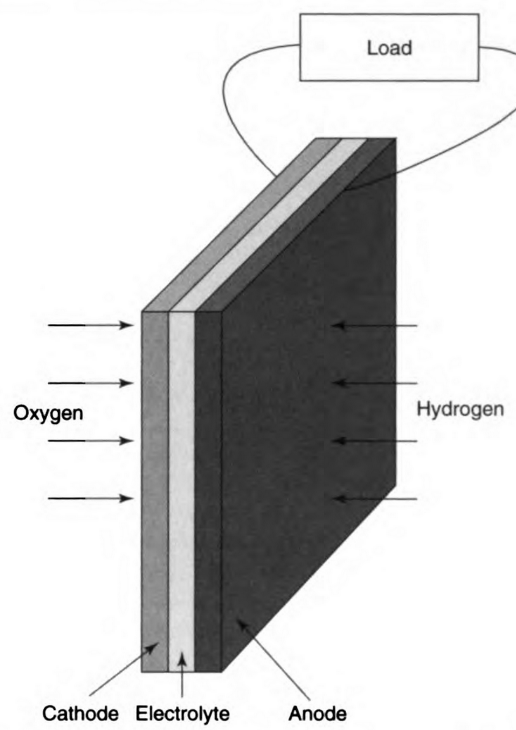
Hydrogen is a highly flammable, colourless gas that exists as a diatomic H_2 molecule. It has an atomic weight of 1.008 kg $kmol^{-1}$ [2.1], making it the lightest element on the periodic table. It is also the universe's most abundant element. It has a mass density of 0.090 kg m^{-3} (at 0°C, 1 atm) [2.1] and a gravimetric energy density of 120 MJ kg^{-1} [1.23], making it much more energy dense than modern lithium ion batteries (0.36 - 0.95 MJ kg^{-1} [1.26]).

Electricity is produced from hydrogen by an electrochemical device known as a fuel cell. This converts the chemical energy stored within hydrogen directly into electricity via electrochemical reactions known as reduction and oxidation (redox) reactions which take place at the electrodes. There are many different types of fuel cells which mainly differ by type of electrolyte they use and their size. The most common of these are:

1. Alkaline fuel cells (AFCs) in which the mobile ion is OH^- and the electrolyte used is potassium hydroxide (KOH). They operate at temperatures between 50 and 250°C and have aerospace applications, having been used on both Apollo and Space Shuttle spacecraft [2.2, 2.3].

2. Polymer Electrolyte Membrane/Proton Exchange Membrane fuel cells (PEMFCs) conduct protons (H^+ ions) through a membrane which forms the electrolyte. They have an operating temperature between 30 and 100°C [2.2, 2.3].
3. Solid Oxide Fuel Cells (SOFCs) conduct oxygen O^{2-} ions via an electrolyte made of a solid, nonporous metal oxide. An example of this is yttrium stabilised zirconium (YSZ) which consists of zirconium dioxide (ZrO_2) stabilised with yttrium oxide (Y_2O_3). They have an operating temperature range of 500 - 1000°C and are used in large-scale commercial applications [2.2, 2.3].

Fuel cells are appropriate for transport applications as they have no moving parts, operate quietly and have a modular design [2.4]. Being modular means that the fuel cell can be scaled up or down depending on the application, giving them more flexibility to operate within different parameters and use cases. PEMFCs, having the lowest operating temperature, is the favoured fuel cell type for transport applications and hence, the rest of this section will focus on them. Fig. 2.1 shows the basic operation of a fuel cell and the arrangement of the two electrodes (anode and cathode) and the electrolyte.



< Fig. 2.1: Basic operation of a fuel cell [2.3] >

The first PEMFC was developed in the 1960s by General Electric for use by NASA on their Gemini spacecraft as an auxiliary power source [2.2, 2.5], there have obviously been significant advances in the technology since then but the basic principles of operation remain the same. At the anode, hydrogen is continuously fed in and is oxidised to form H^+ ions and electrons as shown in equation 2.1 below [2.2],

$$H_2 \rightarrow 2H^+ + 2e^- \tag{2.1}$$

At the cathode, oxygen is fed in and reduced as shown below [2.2],

$$\tfrac{1}{2}O_2 + 2H^+ + 2e^- \rightarrow H_2O \tag{2.2}$$

Combining these two half equations gives the following overall equation for the fuel cell,

$$H_2 + \tfrac{1}{2}O_2 \rightarrow H_2O \tag{2.3}$$

Note that this equation is identical to the equation for the combustion of hydrogen in air and so it must be an exothermic reaction, meaning it will have a negative change in enthalpy ΔH and will release heat.

2.1.2 Fuel cell efficiency

An important metric to understand is the efficiency of fuel cells as this will play a key role in designing the system requirements later on, specifically the hydrogen demand of the system. Hence, it is important to look at fuel cell efficiency and compare this with the efficiency of a modern internal combustion engine.

The maximum theoretical efficiency of a PEMFC is ~ 83% [2.2] which is much greater than the efficiency of a modern internal combustion engine. This is expected as fuel cells have no moving parts and subsequently have no mechanical friction losses which is a major source of loss in an internal combustion engine. The irreversible energy losses in a fuel cell can be summarised as follows:

1. Activation losses: These are due to the speed of the reactions taking place at each electrode. These reactions are not instantaneous, in fact they are rather slow, and so a proportion of the voltage is lost in order to drive the reactions to completion [2.3].

2. Concentration losses: As the fuel is used, the concentration of reactants on the surface of the electrodes will reduce and this will affect the cell potential [2.3].
3. Ohmic losses: This is perhaps the most obvious form of voltage drop. There is a resistance to the flow of electrons through the electrodes and there is a resistance to the flow of ions through the electrolyte [2.3].

Modern PEMFCs are manufactured in a way that reduces these losses to increase the fuel cell efficiency. This involves increasing the roughness of the electrodes to give them a higher surface area, using electrodes with high electrical conductivity σ, such as platinum, although this may increase cost and finally by trying to make the electrolyte layer as thin as possible to reduce the ionic resistance [2.3]. Fuel cell efficiencies are ever increasing with new advances in materials science and chemistry, the current standard value is around 60% [2.6].

The fuel cell process produces only water and heat as by-products and is completely carbon free if pure, green hydrogen is used [2.7]. This is an important distinction to make as not all hydrogen is classed as green hydrogen and thus would not adhere to the project aim of being net zero, this will be discussed further in Section 2.1.3.

2.1.3 Hydrogen Production

Not all hydrogen that is produced is suitable for this project and so, it is important to understand the different methods of production and their environmental impact. The current most common method of hydrogen production is a process known as *steam methane reformation*. This is a chemical reaction between the simplest hydrocarbon, methane (CH_4) and steam. It is a highly endothermic (ΔH = +206 kJ/mol) and reversible reaction with the following chemical equation [2.8],

$$CH_4 + H_2O \rightleftharpoons CO + 3H_2 \tag{2.4}$$

Additional hydrogen can be produced by the water-gas shift reaction which is an exothermic (ΔH = -40.6 kJ/mol), reversible reaction between carbon monoxide and water [2.9], equation 2.5 shows the water-gas shift reaction,

$$CO + H_2O \rightleftharpoons CO_2 + H_2 \tag{2.5}$$

Therefore the overall equation for this process can be written as follows,

$$CH_4 + 2H_2O \rightleftharpoons CO_2 + 4H_2 \tag{2.6}$$

The reaction has an overall enthalpy change of ΔH = +165.4 kJ mol^{-1}, which means that it is an endothermic process and takes in heat. Hydrogen produced in this way is known as grey hydrogen which is not net zero and therefore, unsuitable for the project. The carbon emissions caused by this process can be quantified from the overall chemical equation. Taking the molecular weights (Mr) of hydrogen (H_2) and carbon dioxide (CO_2) to be 2.016 kg kmol^{-1} and 44.009 kg kmol^{-1} respectively [2.1] and using the equation $moles = \frac{mass}{Mr}$ it is possible to calculate that there will be 5.46 kg of carbon dioxide released per kg of hydrogen produced. This is a "best case" scenario and due to real-world inefficiencies, there will likely be a greater emission of carbon dioxide than this calculation suggests. In actuality grey hydrogen emits roughly 9.3 kg of CO_2 per kg of hydrogen produced, which translates to approximately 0.28 kg of CO_2 per kWh of energy [2.10]. Hydrogen is also produced through the gasification of coal, hydrogen produced this way is known as brown hydrogen. Brown hydrogen is the least clean form of hydrogen production.

If a system is implemented to capture and store the carbon dioxide waste, then the hydrogen produced is known as blue hydrogen. Blue hydrogen is much cleaner than grey hydrogen but due to the limitations with current carbon capture technology and the fact that such a system could never capture 100% of the carbon emissions, it is incorrect to call blue hydrogen a net zero fuel. It is therefore unsuitable for this project. However, it can be viewed as a potential transition fuel as it makes use of the most common hydrogen production method which is the steam methane reformation process described above.

Green hydrogen is hydrogen that is produced by electrolysis of water powered by renewable energy [2.11] and is the only form of hydrogen production capable of achieving the net zero goal of this project. Electrolysis is the reverse of a fuel cell reaction and hence, it is a non-spontaneous reaction that requires energy to take place thereby consuming electricity. Just like fuel cells, electrolysers are electrochemical devices and are classified by the type of electrolyte they use and their size, the most common are:

1. Alkaline electrolysers which use a solution of KOH or NaOH as the electrolyte and have a typical operating temperature range of 80 - 200°C [2.12].
2. PEM electrolysers which use an acidic electrolyte allowing for the transfer of protons (H^+ ions) from the anode to the cathode. Their operating temperature range is 25 - 80°C [2.12].
3. Solid oxide electrolysers use a solid metal oxide electrolyte which conducts oxygen ions. The most commonly used metal oxide is zirconium dioxide (ZrO_2) which is doped with around 8% yttrium trioxide (Y_2O_3) or scandium trioxide (Sc_2O_3). The doping produces crystallographic defects, allowing oxygen ions to pass through [2.12]. Solid oxide electrolysers operate at extremely high temperatures in the range 900 - 1000°C [2.13].

It is important to understand the different types of electrolyser and their operating parameters when designing the system so that an informed choice could be made about what type of electrolyser is needed. Further comparison, the choice of electrolyser and modelling of its operation is detailed in Section 6.2 and 6.3 respectively.

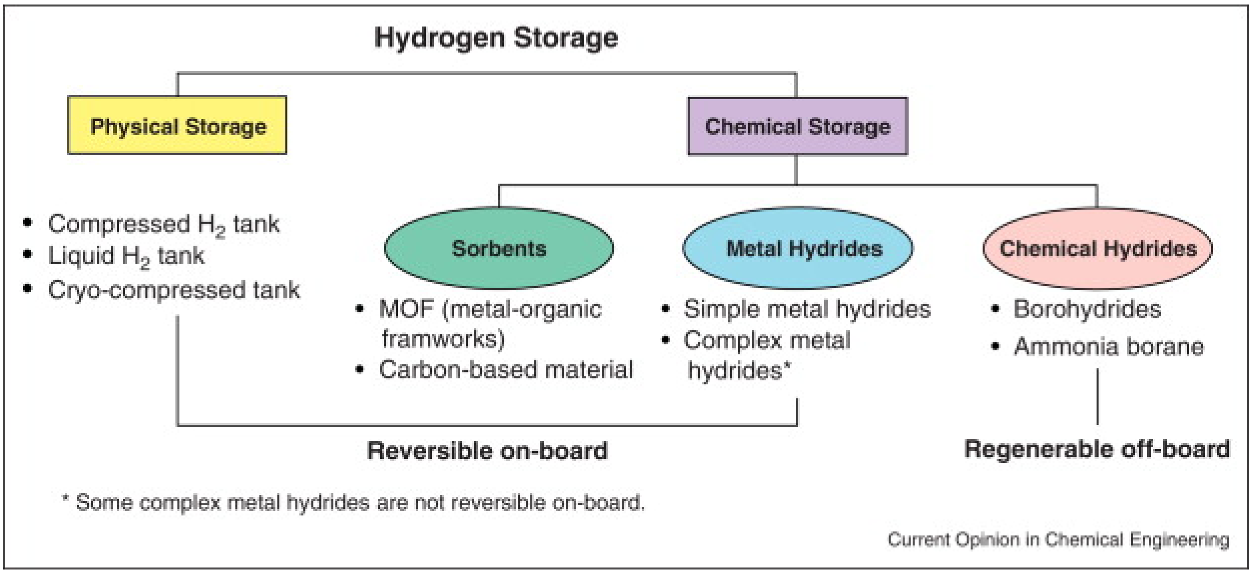
The overall water splitting reaction that occurs in an electrolyser is,

$$H_2O \rightarrow H_2 + \tfrac{1}{2}O_2 \qquad (2.7)$$

The exact half equations that take place at the anode and cathode differ depending on the type of electrolyser, specifically they depend on what ion the electrolyte is able to conduct. This overall equation is the reverse of the fuel cell equation and so input energy is required to make this reaction happen. This must be provided by a green, renewable electricity source in order to meet the project goal of being net zero.

2.1.4 Hydrogen storage

Hydrogen can be stored in a variety of ways and this section will give a brief, qualitative overview of the most common storage methods currently in use. Fig 2.2 breaks down the different classifications of hydrogen storage methods.



< Fig. 2.2: Classification of hydrogen storage methods [1.23] >

Hydrogen can be stored in elemental form in two ways, either as a compressed gas or as a liquid. Storage as a compressed gas is the most common of the two being utilised by several existing hydrogen buses such as the Wrightbus H2Bus [1.29] and the Mercedes-Benz EvoBus [2.14]. The pressure used in onboard storage for buses is 350 bar whereas 700 bar is commonly used for passenger cars such as the Toyota Mirai [2.15]. Storage as a gas is the simplest storage method. However, it has a low volumetric energy density and is inefficient due to the energy consumed by the compression process itself [2.6]. To combat the low volumetric energy density, hydrogen can be stored as a liquid. This, however, comes with other problems including having to maintain the hydrogen at a temperature of −253°C at ambient pressure [2.6], which requires specialist tanks. The liquefaction process is also very energy intensive and hence this is an inefficient storage method [2.6].

Hydrogen can also be stored in the form of another compound. The two main methods being metal and chemical/organic hydrides. These storage methods are more useful as long term, back-up storage in case of a system failure, such as an electrolyser breaking down. Metal hydrides are by far the safest form of hydrogen storage as they are stable solids which will not immediately combust upon ignition. However, they do have issues which need to be considered, mainly their weight and the fact that there are multiple conversion steps required throughout the process which reduces the overall efficiency [2.6, 2.16]. The most popular metals being considered for this type of storage are aluminium (Al) and magnesium (Mg) due to their low weight and cost [2.16].

Hydrogen can also be stored as a liquid organic chemical such as ammonia (NH_3), methanol (CH_3OH) or methanoic acid (HCOOH). These chemicals are widely used in other markets and the infrastructure for their transport and distribution is already in place making them an attractive option [2.16]. They are all light organic liquids with a high weight percentage of hydrogen, especially when compared to metal hydrides [2.16]. However, they also have drawbacks which include a loss of efficiency due to the extra conversion steps and safety issues as these are all flammable organic compounds. Of note, however, is ammonia which has a relatively high hydrogen weight percentage. The synthesis and transportation infrastructure for ammonia is already extremely mature and widespread [2.17].

Finally, the last form of hydrogen storage which is being explored by researchers is the sorbent method. This method involves the adsorption of hydrogen onto a framework surface and exploits physical, rather than chemical, bonds such as the Van Der Waals bonding between hydrogen molecules and specific materials known as metal-organic frameworks (MOFs) [1.23, 2.16]. This technology is largely still in development and furthermore, both a low temperature and high pressure are required in order to obtain a similar hydrogen storage density as existing technologies [2.16]. This could be a fantastic technology in the future. However, currently it has not reached a level of scientific maturity where it could become commercially viable.

2.2 Ammonia

2.2.1 Introduction to Ammonia

Ammonia is the second of the two emission-free fuels taken into consideration to be used as an energy source for Oxford's public transport system. This section will explain how ammonia is used as vehicle fuel, the different ways to produce ammonia and the costs of ammonia storage and distribution. Throughout Section 2.2, comparisons between ammonia and hydrogen will be made and by the end of the section, readers will understand why hydrogen is chosen as the ideal green gas.

2.2.2 Ammonia as a fuel

Ammonia Combustion

Ammonia is a colourless and pungent gas at room temperature, with each molecule consisting of a nitrogen atom and 3 hydrogen atoms. It can be used as a fuel for vehicles in two main ways: direct combustion to power an internal combustion engine (ICE) or to power fuel cells to generate electricity.

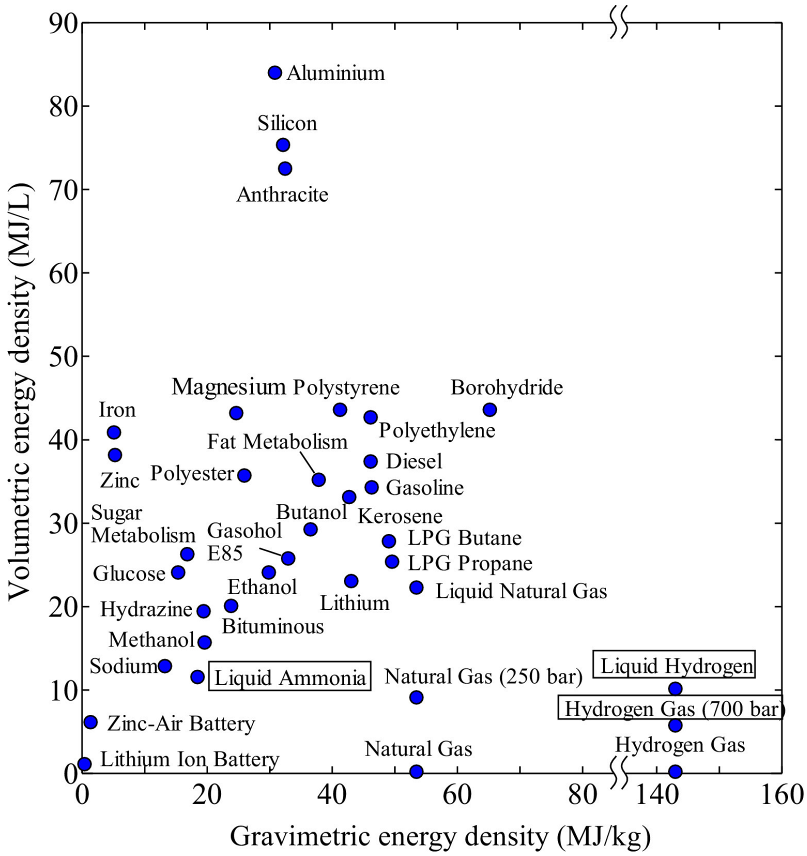
To fuel an ICE, ammonia combusts with air via the following equation:

$$NH_3 + 3O_2 \rightarrow N_2 + 6H_2O \qquad (2.8)$$

and moves pistons which provide power to the wheels. As such, ammonia-fuelled vehicles operate similarly to existing petrol vehicles, except they only emit nitrogen and water vapour, making ammonia a zero-emission fuel. However, there are concerns with regards to NO_x pollution, which can be rectified using a selective catalyst reduction (SCR) system in NH_3 fuelled vehicles [2.18]. Ammonia has similar physical properties to propane [2.18]. Most notably, their condensation pressures at room temperature are similar at 9.90 atm or 10 bar for ammonia and 9.40 atm or 9.5 bar for propane [2.19]. Thus, with just straightforward modifications, a conventional petrol vehicle can be retrofitted to run on liquid ammonia [2.18]. The ease of storing ammonia onboard a vehicle is a strong advantage over hydrogen, which requires a storage pressure of 350 to 700 bar [2.20].

While ammonia excels in storage ease compared to hydrogen, it suffers in terms of energy density: losing to diesel and gasoline in both volumetric and gravimetric density, and losing to hydrogen in gravimetric energy density. This means that for the same desired range, a vehicle would have to carry roughly 7 times the weight of ammonia compared to hydrogen.

There are additional challenges with ammonia combustion, including high ignition temperature, low flame velocity and slow chemical kinetics, all of which will affect engine performance.

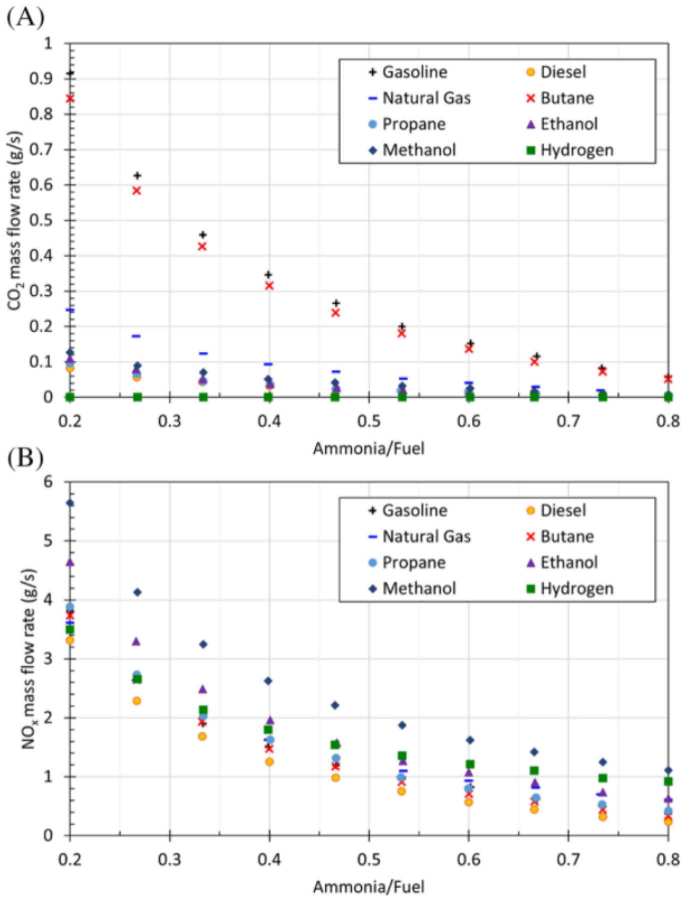


<Fig. 2.3: Gravimetric and volumetric energy density of combustible materials and batteries [2.19]>

These challenges are usually tackled by combining ammonia with traditional fuels such as diesel, gasoline or even hydrogen to make ammonia/fuel blends. However, this inevitably will result in carbon emissions for most traditional fossil fuels, and increased toxic NO_x emissions for all ammonia fuel blends (see Fig. 2.4).

Ammonia Fuel Cells

Ammonia fuel cells generally work on the principle of converting the chemical energy of ammonia into electricity through redox reactions. They are split into direct and indirect fuel cells, with the latter involving thermal decomposition of ammonia into hydrogen before utilising said hydrogen for energy, and the former directly using ammonia as an energy source. This report will focus on direct ammonia fuel cells since this eliminates the need for onboard storage of hydrogen and decomposition process of ammonia, thereby reducing costs and increasing efficiency [2.22].



< Fig. 2.4: (A) CO2 and (B) NO_x emissions for different ammonia fuel blends [2.21] >

Direct ammonia fuel cells can be categorised into solid oxide fuel cells (SOFC), alkaline fuel cells or microbial ammonia fuel cells [2.22]. SOFCs are generally deemed to be the most ideal type of direct ammonia fuel cells due to its high efficiency and it is the most studied ammonia-fed fuel cell technology [2.22, 2.23]. Thus, this section will focus on ammonia SOFCs.

In ammonia SOFCs, ammonia is cracked into hydrogen at high temperatures,

$$2\ NH_3 \rightarrow N_2 + 3\ H_2 \tag{2.9}$$

and the hydrogen is then immediately utilised to generate electricity [2.22]. The conversion of hydrogen into electricity was discussed in Section 2.1.1. At high operating temperatures, the decomposition process and electricity generation process is effectively merged, negating the need for on-board storage of hydrogen [2.22].

On-board vehicular use of ammonia, however, pose significant challenges, including high operating temperature, purification requirements (of hydrogen), and high cost of on-board “cracking” of hydrogen [2.24].

2.2.3 Ammonia production

$$N_2 + 3\,H_2 \rightarrow 2\,NH_3 \qquad (2.10)$$

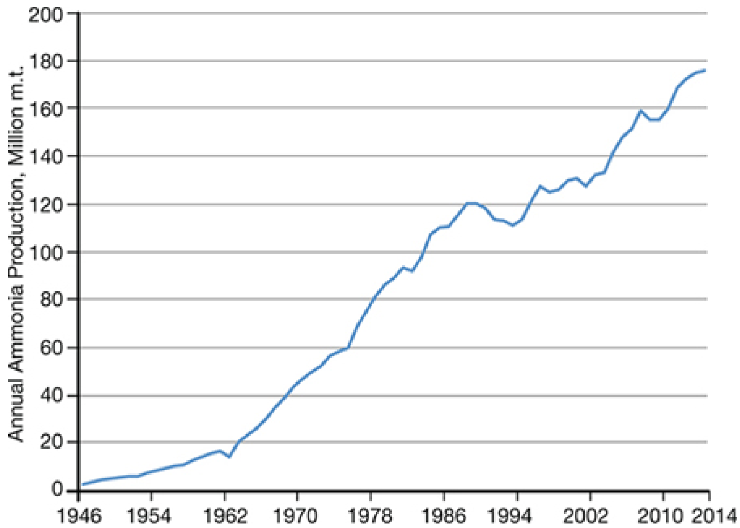
The predominant method of ammonia production today is the Haber-Bosch Process, where hydrogen is combined with nitrogen to form ammonia, using an iron-based catalyst, under high temperature ranging from 325–525°C and high pressure ranging from approximately 150–350 bar [2.22].

Due to the energy demands of maintaining high temperature, ammonia production via the Haber-Bosch process currently accounts for 1% of the world’s energy consumption and 1% of global carbon dioxide emissions [2.25]. This makes ammonia production the highest emitter of greenhouse gases in the chemical industry [2.26]. In addition to emissions from high energy demands, most commercial production of ammonia uses brown or grey hydrogen [2.19], which emits carbon dioxide in their production, as mentioned in Section 2.1.3. Despite its current environmental impacts, the Haber-Bosch process can be made clean by powering it with renewable energy and to use renewable energy to produce the green hydrogen needed for ammonia production.

2.2.4 Ammonia storage and distribution

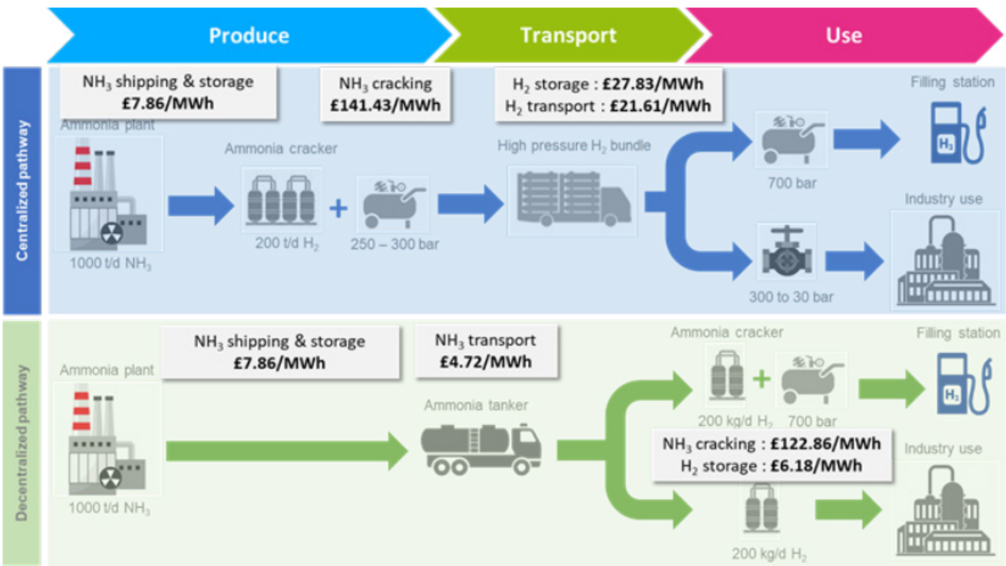
Ever since the first commercial ammonia plant started production in Germany in 1913 [2.27], demand for ammonia has increased steadily to meet demands from various industries, including agricultural, industrial and chemical.

Historically, ammonia is most commonly used as a fertiliser in the agricultural industry. It is also used as raw material for industrial purposes and as refrigerants for industrial cooling. Additionally, ammonia is a crucial ingredient for NO_x emissions removal [2.19]. As such, the infrastructure technology for ammonia storage and production is already mature and widespread, with liquid ammonia being transported around the world via various means including ship, trucks and pipelines. This compares with hydrogen, which will require new investments in infrastructure.



< Fig. 2.5: Global ammonia production [2.27] >

Due to the maturity of the industry and the physical properties of ammonia, it is much cheaper to store and transport ammonia compared to hydrogen. As can be seen from Fig. 2.6, not only is it more expensive to transport hydrogen at £27.83/MWh (compared to £4.72/MWh for ammonia), it is also more expensive to store hydrogen for transport (£21.61/MWh) compared to stationary hydrogen storage (£6.18/MWh). As such, the case of ammonia is much stronger when transportation of fuel over long distances is required. The costs indicated in Fig. 2.6 are for transportation distances of over 100 km [2.28].



< Fig. 2.6: Comparison between centralised and decentralised models of ammonia decomposition [2.28] >

2.3 Verdict on green gas

At first consideration, the obvious choice for the fuel of choice is hydrogen since there will be clear inefficiencies to produce ammonia via hydrogen, when hydrogen can be used directly to power the public transport system. The undesirability of ammonia is further worsened by the challenges of on-board ammonia storage for ammonia fuel cells, as well as the energy intensive process to manufacture ammonia.

Nevertheless, It must be considered that ammonia has two main advantages over hydrogen: first, ammonia is a suitable fuel for conventional ICE vehicles, indicating an easy transition process from majority-fossil fuel public transport system to a majority-ammonia public transport system. Secondly, ammonia storage and distribution technology is more mature and much cheaper than that of hydrogen. The cost savings are amplified for long distance distribution.

Unfortunately, these advantages are largely rendered irrelevant due to the goal of net zero emissions and local generation and distribution. For the first advantage, ammonia combustion is only effective when combined with traditional fossil fuel such as gasoline or diesel. This will inevitably create carbon emissions, which undermines the goal of net zero emissions. Additionally, NO_x emissions from ammonia combustion will be undesirable for the population of Oxford. Thus, fuelling combustion vehicles with ammonia will not be considered for this project. For the second advantage, the cost savings from ammonia storage and distribution will not be realised due to the goal of having a Oxford-based generation and distribution site, which means minimal transportation of fuel.

Amidst the criticisms of ammonia discussed so far, perhaps the most prominent flaw of ammonia-fuelled public buses is the lack of commercial technology and ongoing projects. This compares with hydrogen bus technology, with existing hydrogen-powered double decker buses by Wrightbus [2.29] already operating on the streets of Aberdeen [2.30] and soon-to-be on the streets of Birmingham [2.31] and Liverpool [2.32]. As such, this project will focus on powering Oxford's public transport with green hydrogen.

3 Bus technology and fleet requirements

It is useful to explore the bus technologies which are currently used by bus companies in Oxford. This will help define the performance targets that will be required by a net zero fleet, in order to meet or exceed the current standards. Firstly, current diesel and hybrid electric vehicles will be discussed. Secondly, fuel cell vehicle capabilities will be investigated. The reasons as to why battery electric vehicles are not considered for a net zero solution have been discussed in Section 1.4. Once vehicle technologies have been explored, the details of a future bus fleet for Oxford will be discussed. This section involves financial calculations. To convert euros or US dollars into British pounds, currency exchange rates as of February 2021 have been used. This results in a factor of 0.87 applied to convert euros to pounds [3.1] and a factor of 0.72 to convert US dollars to pounds [3.2].

3.1 Diesel bus technology

The technical aspects of modern diesel powertrains will be analysed to understand their benefits and limitations when operating Oxford bus routes.

One of the most common diesel buses used in Oxford is the Wrightbus Streetdeck [1.12]. A benefit of diesel buses is their range. An average diesel bus has a range of 690 miles [1.28] or 1,100 km [2.1]. This large range implies that bus operators do not need to schedule refuelling frequently. This is useful when operating a busy service. The range requirements for buses to operate Oxford routes will be described in further detail in Section 3.4.2.

Another benefit of diesel buses is the ease of refuelling. Diesel can be quickly transferred in liquid form from a large storage tank to the on-board fuel tank. The fuel does not need to be compressed, refrigerated or transformed into a different state. It is then essential that a net zero solution in Oxford also relies on a fast refuelling service for bus companies to keep their current service times, reduce idle time, maximise equipment availability and optimise the return on their investment. The refuelling requirements for a hydrogen fleet will be discussed in Section 3.4.3.

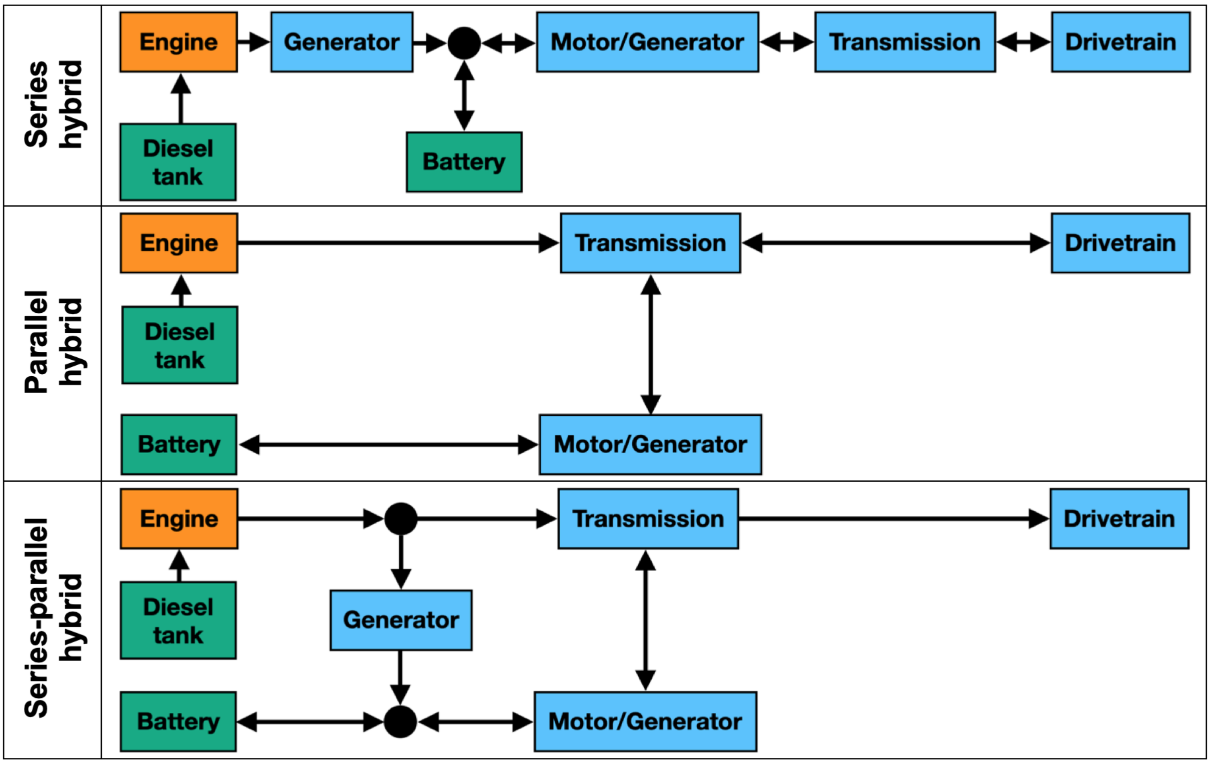
One drawback to diesel powertrains is how they must rely on pollution reducing systems to meet environmental targets [3.3]. These systems add to the total cost of the bus. Diesel engines typically produce soot as a by-product of the combustion process [3.4]. In order to avoid the formation of soot particles, current generation diesel engines run on a lean fuel mixture [3.3]. In addition to running the engine lean, diesel powertrains also feature particulate exhaust filters, which trap the soot particles which could still be produced by the engine [3.5]. The excess oxygen used to achieve the lean fuel mixture leads to the formation of a significant amount of NO_x emissions [3.3]. To reduce these NO_x emissions, a diesel exhaust fluid is injected into the exhaust gas [3.5]. Carbon emissions have been discussed in Section 1.5.

In order to meet future regulations, diesel buses will have to feature more complex pollution reducing systems, further adding to cost. Hybrid technologies are an alternative for bus companies.

3.2 Hybrid bus technology

A common short term goal for Oxford bus companies is to replace conventional diesel buses by hybrid buses [1.41, 3.6]. It would be useful to analyse what features of a hybrid bus can be carried over to a net zero solution.

Hybrid buses feature both a diesel engine and an electric motor [3.7]. They are equipped with battery packs which can be charged by the diesel engine or through regenerative braking [3.7]. There are three main types of hybrid vehicles illustrated in Fig. 3.1 below, adapted from [3.7]. The arrows represent directions of energy transfer either mechanically or electrically.



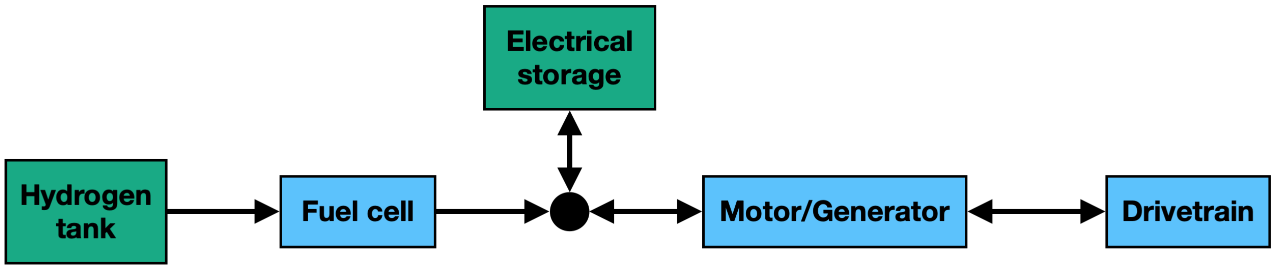
< Fig. 3.1: Various hybrid systems used on buses, adapted from [3.7] >

The series hybrid is the most popular configuration for low speed city buses [3.7]. The drivetrain is entirely driven by an electric motor. This allows the engine to operate efficiently at an optimised rpm setting regardless of the vehicle speed [3.7].

Hybrid buses provide ways to reduce emission levels by optimising the engine operating point and to improve fuel efficiency through regenerative braking. Hydrogen buses can also benefit from using electrical energy storage to optimise the power plant (fuel cell) operating point [3.8]. Regenerative braking systems are also incorporated in the design as will be discussed in the next section [3.8].

3.3 Hydrogen bus technology

A hydrogen bus uses hydrogen to generate electricity through a fuel cell [3.9]. The process of generating electricity from a fuel cell is discussed in Section 2.1.1. Hydrogen buses only emit water vapour [3.9]. Fig. 3.2 below outlines the main features of a hydrogen bus.



< Fig. 3.2: Hydrogen bus outline adapted from [3.9] >

There are many subsystems in a hydrogen bus which ensure the fuel cell runs as efficiently as possible. For example, the fuel cell system consists of a power electronics controller and a thermal system [3.8]. The power electronics controller distributes electrical power between the fuel cell, the motor and on-board electrical storage [3.8]. The fuel cell's performance is closely related to its operating temperature [3.10], hence a thermal management system controls the fuel cell temperature [3.8]. Additional subsystems also ensure the fuel cell performs well during the winter under sub-zero temperatures [3.11]. If the bus is held at sub-zero temperatures for long periods of time, a control system will purge water from all lines and fuel cell components [3.11]. This allows the bus to be stored at sub-zero temperatures without damaging the fuel cell unit. This ensures that bus companies in Oxford will be able to park their buses outside throughout the year, avoiding the need to store buses in temperature controlled depots.

Fuel cell vehicles have been developed for more than a decade [3.12]. Practical applications have demonstrated their robustness for automotive applications, making hydrogen a viable option for a net zero emission fleet. These applications include hydrogen buses currently used in France [3.13].

3.4 Oxford fleet requirements

This section will outline the performance targets and specific requirements which must be met by a hydrogen bus fleet in Oxford.

3.4.1 Bus type requirements

To determine the types of hydrogen vehicles required for Oxford, the current number of single and double deck buses in Oxford will be tallied. As mentioned in Section 1.3, 148 buses are currently owned by the Oxford Bus Company (OBC) [1.12], 83 buses are owned by Thames Travel [1.13] and 168 buses are owned by Stagecoach [1.14, 3.14]. This represents around 399 total buses in Oxford. The amounts of double deck and single deck buses operated by each company are shown below in Table 3.1. Table 3.1 also illustrates how many diesel and hybrid buses are owned by each company.

Bus company	**Number of single deck buses**	**Number of double deck buses**	**Number of diesel buses**	**Number of hybrid buses**
OBC [1.12]	48	100	67	81
Thames Travel [1.13]	39	44	81	2
Stagecoach [1.14, 3.14, 3.15, 3.16]	63	105	155	13
All companies	150	249	303	96

< Table 3.1: Types of buses operated by Oxford bus companies >

In total, 150 single deck buses and 249 double deck buses are used in Oxford.

The hydrogen storage tanks are situated on the roof of typical single and double deck hydrogen buses [3.17]. Since the passenger compartment space is not sacrificed, it can be suggested that hydrogen buses have similar passenger capacities compared to diesel buses. It will be assumed that the number of hydrogen buses required is equal to the current number of buses in Oxford bus fleets.

3.4.2 Range requirements

It is useful for bus companies to only refuel their buses once a day. This maximises the vehicle usage. Oxford buses must then have a range larger than the distance they are expected to travel per day. Using bus timetables [3.18], road distances [1.40, 2.1] and a Python model to compile the data, the total distance travelled by all OBC Park and Ride routes on a single weekday is approximately 5,812 km. These are some of the longest routes in Oxford which span outside of the city [1.40] (see Fig. 4.1). There are 19 buses operating these routes [1.12]. This results in around 306 km required by each bus to travel in a single day on average. This range requirement will be analysed in Section 3.6.1.

3.4.3 Refuelling time requirements

Most buses in Oxford typically operate between 4am and 8pm [3.18]. This leaves an 8 hour period in which refuelling can take place. Refuelling can either be conducted in the early morning or late evening. There are 148 buses [1.12] assigned to the Oxford Bus Company depot in Cowley [1.40]. This is the largest number of buses assigned to a single depot (see Table 7.1). It is then a requirement for a single depot to be able to refill 148 buses in an 8 hour period. This refuelling requirement will be analysed in Section 3.6.2.

3.4.4 Speed requirements

Hydrogen buses will have to sustain the same speeds used by current diesel buses. There are A-type roads in Oxford where buses are required to reach a speed of 60 mph [1.40, 3.19]. For instance, the S5 Park and Ride route covers 9.2 km on the A34 road [1.40, 2.1]. This speed requirement will be analysed in Section 3.6.3.

3.5 Hydrogen fleet advantages

This section will discuss the impact of moving from a diesel/hybrid fleet to a hydrogen fleet in terms of vehicle cost, maintenance and environmental concerns. Fuel costs will be discussed in Section 4.

3.5.1 Vehicle costs

The prices of diesel and hybrid buses are outlined below in Table 3.2. This table shows the price evolution as a function of time. The table also extrapolates these prices to 2040, when the net zero target is expected to be achieved. These extrapolated prices will be used to show that hydrogen buses are expected to reach a similar price to hybrid and diesel buses in the future, assuming that these buses will still be meeting environmental regulations. The extrapolation was based on a line of best fit generated with Python and the *polyfit* function. Prices are assumed to follow the same linear evolution after 2030.

Diesel			**Diesel hybrid**		
Year	Price (€) [3.9]	Price (£) [3.1]	Year	Price (€) [3.9]	Price (£) [3.1]
2020	233,000	203,000	2020	299,000	260,000
2025	238,000	207,000	2025	299,000	260,000
2030	244,000	212,000	2030	300,000	261,000
2040 (extrapolated)	255,000	222,000	2040 (extrapolated)	301,000	262,000

< Table 3.2: Comparing the price evolution of diesel and diesel hybrid buses >

Table 3.2 shows an increase in the forecasted prices of diesel buses with time. Diesel powertrains are likely to become more expensive with more pollution managing technologies to be added. The forecasted purchasing price of diesel hybrid buses appears to remain constant with time. With an increase in production volume for hybrid buses, the selling price can be expected to decrease. However, inflation can compensate for this decrease in selling price.

Table 3.3 below shows the price evolution of hydrogen buses.

Year	**Unit price of a hydrogen bus**
2010 (Winter Olympics bus) [3.12]	\$2,000,000 = £1,440,000 [3.2]
2016 [3.12]	\$1,235,000 = £889,200 [3.2]
2020 [3.20]	€450,000 = £391,500 [3.1]
2030 (estimated) [3.20]	€350,000 = £304,500 [3.1]

< Table 3.3: Price evolution of hydrogen buses >

Contrary to diesel and hybrid buses, a significant decrease in the selling price of hydrogen buses is expected with time. The selling price of hydrogen buses is expected to drop by 22% between 2020 and 2030. This is mostly due to economies of scale, as hydrogen solutions transition to industrial production [3.21]. It is only in recent years that bus companies have begun to benefit from economies of scale. Hydrogen buses were initially sold in very small volumes. Only 20 2010 Winter Olympics buses were produced for example, which led to a high £1,440,000 unit bus price [3.12, 3.2]. The relatively high purchase price of hydrogen buses can also be explained by the warranties provided for 5 to 10 years compared to 2 years for a standard diesel bus [3.9].

Hydrogen buses are therefore forecasted to reach competitive vehicle costs. Oxford bus companies will be able to transition to a hydrogen bus fleet with similar investment costs to those required to renew their current fleets with diesel/hybrid technology.

3.5.2 Maintenance costs

In order to model how much bus companies are spending on bus maintenance per year, it is useful to analyse bus maintenance costs. Section 8 will then include the maintenance costs found to estimate the annual expenditures of bus companies.

Diesel buses have an average service cost of £0.1/km [3.22]. This relatively low maintenance cost makes diesel buses appealing to bus operators. Diesel buses also have a relatively long lifetime of 15 years [3.23].

The service costs of hybrid buses are typically 4% lower than for diesel buses [3.24]. This represents a service cost of £0.09/km for an average hybrid bus. A hybrid bus typically has a lifetime of 12 years [3.25]. The maintenance and replacement of lithium ion batteries represents most of the hybrid bus maintenance process [3.25]. The battery packs need to be replaced twice during the bus lifetime [3.25].

Hydrogen buses are expected to have a service cost of €0.3/km [1.31] or £0.26/km [3.1]. This service cost is three times higher than the cost found for diesel buses. However, one can estimate the service costs of hydrogen buses to decrease over time as bus operators develop new techniques for maintenance. The expected lifetime of a hydrogen bus is 12 years [3.9].

3.5.3 Noise

Hydrogen buses have the additional benefit of generating significantly less noise than diesel buses. Table 3.4 below compares the noise levels of hydrogen and diesel buses for when the buses are stationary and moving.

Vehicle status	Diesel bus noise level [3.9]	Fuel cell bus noise level [3.9]
Stationary	80 dB	63 dB
Moving	77 dB	69 dB

< Table 3.4: Noise levels for diesel and hydrogen buses >

A reduction in noise levels represents an improvement in noise pollution in urban areas. It can be suggested that a reduction in noise will increase certain property values in Oxford, hence providing additional support to the financial effort of refitting Oxford fleets with hydrogen buses.

3.5.4 Conclusion on hydrogen fleet advantages

Hydrogen is a viable solution for a net zero bus fleet because it allows for zero CO_2 and NO_x emissions. Due to the nature of an urban bus network, the fleet can be refuelled at specified locations, minimising the hydrogen storage and refuelling infrastructure needs. Due to larger production volumes, vehicle unit prices are becoming interesting for bus companies [3.9]. One manufacturer of hydrogen buses is Wrightbus [1.31]. Wrightbus is planning to mass produce the H2Bus, a hydrogen bus available in single and double deck configurations [1.31]. This is one of the most popular buses considered by bus companies in the UK [3.26].

3.6 Fleet retrofitting

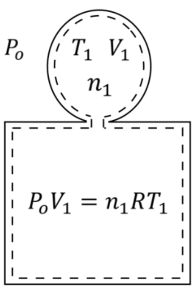
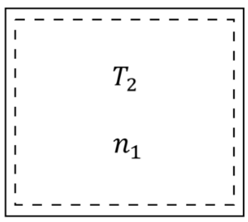
While it is possible to upgrade old diesel engines to lower their emission levels by installing pollution reducing systems [3.27], it is much too complicated and expensive to completely retrofit old diesel buses with hydrogen fuel cells and energy management systems. It is therefore necessary to eventually replace Oxford’s entire bus fleet with hydrogen-powered vehicles in order to transition to a net zero emission solution. This section will examine whether the Wrightbus H2Bus will be suitable to fulfil Oxford fleet requirements.

3.6.1 Range verification

The hydrogen buses proposed by Wrightbus have a range of 310 to 450 km [1.31] without extended range options. As mentioned in Section 3.4.2, it is a requirement in Oxford for a bus to have a range of at least 306 km. The 310 km range of the double deck H2Bus is therefore insufficient to ensure that all buses can cover their routes with some safety. Extended range options will be required for the double deck buses. This extends the range to 420 km [1.31].

3.6.2 Refuelling time verification

The refuelling times of hydrogen buses are limited due to temperatures in the on board storage tanks rising during refuelling [3.28]. Type IV hydrogen tanks are often used for hydrogen vehicle applications [3.29]. These tanks feature an inner plastic liner which must be kept under 85 ºC to prevent damage [3.28, 3.29]. The extent of the temperature increase during refuelling can be studied. Fig. 3.3 below performs a control volume analysis of refuelling a Type IV tank from an empty vacuum state to 350 bar. 350 bar is the standard pressure used to refuel a hydrogen bus [3.30].

State 1: Hydrogen entering tank	**State 2: Control volume is moved to the tank**
 . n_1 moles enter the tank of volume V_1 at temperature T_1 . P_o is the delivery pressure from the hydrogen dispenser (350 bar) . The ideal gas equation will be applied	 . Applying first law: $\Delta U = Q - W$ $n_1C_v(T_2 - T_1) = Q - P_o\Delta V$. Assuming adiabatic: $n_1C_v(T_2 - T_1) = -P_o\Delta V$ $n_1C_v(T_2 - T_1) = P_oV_1$ $n_1C_v(T_2 - T_1) = n_1RT_1$. Re-arranging: $T_2 = \gamma T_1$
Symbol definitions: n_1 = moles of hydrogen gas being fed T_1 = initial temperature from dispenser T_2 = final temperature in tank V_1 = tank volume P_o = pressure from dispenser (350 bar) R = universal gas constant	ΔU = change in internal energy ΔV = change in volume Q = heat exchanged W = work done C_v = specific heat at constant volume γ = ratio of specific heats

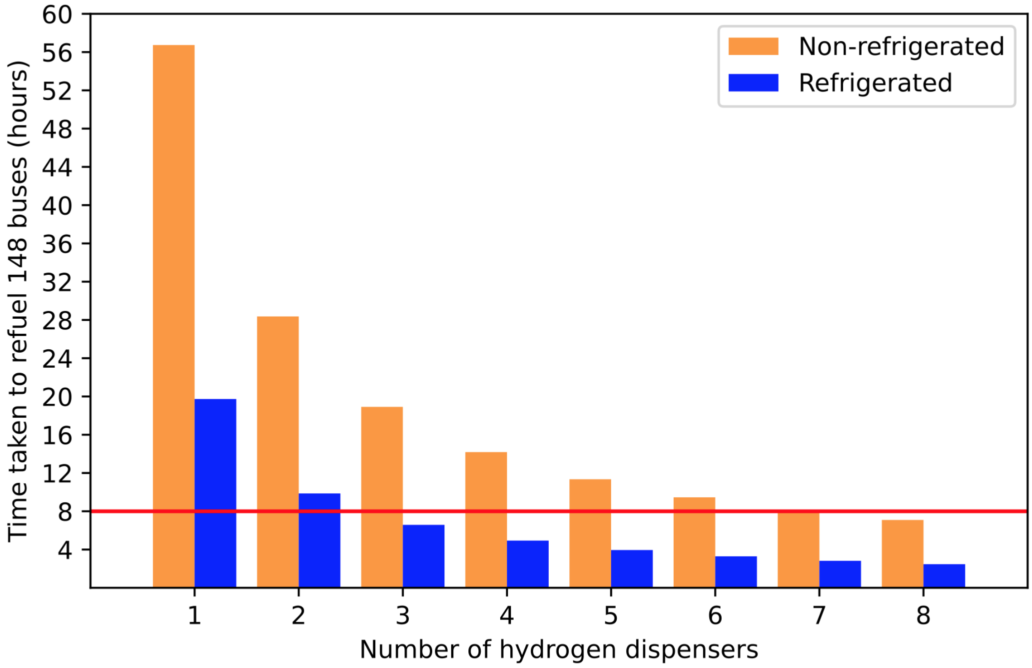
< Fig. 3.3: Control volume analysis for hydrogen entering a tank adapted from [3.31] >

The estimated final temperature is T_2 = γT_1. For hydrogen, γ = 1.41 [2.1]. Assuming a filling temperature of 25 ºC, T_2 can be calculated:

T_2 = 1.41(25+273) = 420.2 K = 147.2 ºC

This is the temperature which would be reached in the hydrogen tank if filled from an initial vacuum. This temperature is above 85 ºC and would therefore damage the tank. In practice the hydrogen tank is not filled from an empty vacuum state. However, the large pressure difference between the tank and the fuelling station dispenser outlet justifies this approximation. In order to refuel the buses quickly without damaging the tank, the hydrogen can be refrigerated before transferring it to the bus [3.28]. Refuelling with refrigeration can take 5 minutes per bus [3.17]. Refuelling without refrigeration can take up to four times longer [3.32], resulting in 20 minutes per bus. To account for a three minute time taken to move the buses to the hydrogen dispensers, the refuelling time can be approximated as 8 or 23 minutes per bus. A model was created to determine whether refrigeration is required before refuelling an Oxford bus fleet.

The model assumes that 148 buses are allocated to a single refuelling station. As mentioned in Section 3.4.3, this is the maximum number of buses assigned to a single depot in Oxford. Fig. 3.4 below shows the time taken to refill all 148 buses for different amounts of hydrogen dispensers. A red horizontal line is drawn to indicate the 8 hour refuelling period limit mentioned in Section 3.4.3.



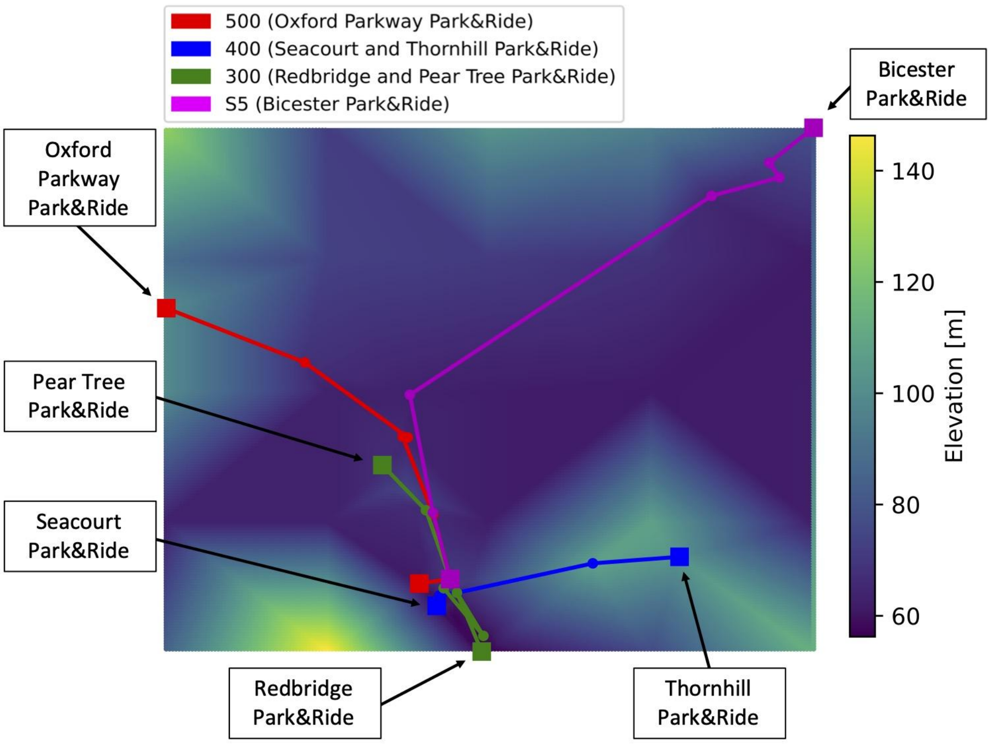
< Fig. 3.4: Number of hydrogen dispensers required for non-refrigerated and refrigerated systems >

Fig. 3.4 shows that a single dispenser is insufficient to refuel 148 buses within an 8 hour timeframe, regardless of whether refrigeration is used. Three hydrogen dispensers with refrigeration allows refuelling to take place within the 8 hour period. Without refrigeration, 8 dispensers will have to be used. This would drive the costs and space needed for the refuelling station. As a conclusion, refrigeration will be used at all hydrogen fuelling stations to minimise the cost of additional hydrogen dispensers and the space associated with the fuelling station.

3.6.3 Speed verification

The Wrightbus H2Bus cannot sustain speeds higher than 40 mph on fuel cell power alone due to limited fuel cell power output [3.26]. Additional power is provided by the electrical motor to sustain speeds of up to 60 mph [3.8, 3.26]. Supercapacitors are used to store and deliver the electrical energy during this intermediate power need [3.33]. These have a capacity of 20 kWh [3.33] or 72 MJ. The supercapacitors can be charged through regenerative braking or by the fuel cell when the vehicle is not requiring the maximum fuel cell power [1.30].

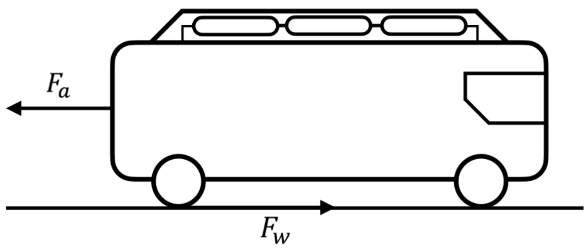
To determine whether the Wrightbus H2Bus would be able to sustain 60 mph on A-type roads in Oxford, it is necessary to first verify whether the intermediate energy storage is large enough to provide the energy required, and secondly whether this energy can be acquired through regenerative braking. This verification process will be applied to all Park and Ride routes in Oxford. Park and Ride routes have been selected for this study as they span well throughout Oxford and outside the city [1.40]. Park and Ride routes are illustrated below in Fig. 3.5. Fig. 3.5 has been constructed by using bus timetables [3.34, 3.35, 3.36, 3.37] and Google Maps [1.40]. This figure also features a superimposed topography map created with code borrowed from [3.38] in Python. Points and elevations were taken from [3.39].



< Fig. 3.5: Park and Ride routes with superimposed topography map >

Fig. 3.5 illustrates that Oxford is situated in a sink area of lower land. This is shown by the lighter yellow colours on the outside of the figure surrounding the central blue area of the map. This feature will play an important role in energy management.

To model energy management, a free body diagram will be considered as shown below in Fig. 3.6.



Symbol definitions:
F_a = air resistance (N) $= \frac{1}{2} C_D \rho A v^2$ [3.40], where:
. C_D = drag coefficient = 0.6 [3.41]
. ρ = air density = 1.225 $(\mathrm{kg\ m^{-3}})$ [2.1]
. A = frontal area $\approx 2.52 \times 4.5 = 11.34\ (\mathrm{m^2})$ [3.42] (estimated height for a double deck bus)
. v = bus speed $(\mathrm{m\ s^{-1}})$
F_w = wheel force provided by the bus (N)
M = bus mass = 11,350 (kg) [3.42]

< Fig. 3.6: Free body diagram for a bus travelling at constant speed >

The energy required by a bus to sustain a speed, v, over a distance, d, will be computed. This energy is calculated by multiplying the air resistance force, F_a, by the distance travelled, d. Wheel resistance is neglected in this model. An equation for the energy required, E_v , is shown below.

$$E_v = \left(\frac{1}{2} C_D \rho A v^2\right) d \tag{3.1}$$

The additional energy required by a bus accelerating from 40 mph to 60 mph and sustaining 60 mph over a certain distance will be computed. This amount of energy is estimated by using equation 3.1 and by adding the difference in kinetic energy, ΔKE, when accelerating from 40 mph to 60 mph:

$$\begin{aligned} \Delta E &= \Delta E_v + \Delta KE \\ &= \left(\frac{1}{2} C_D \rho A {v_2}^2 d - \frac{1}{2} C_D \rho A {v_1}^2 d\right) + \left(\frac{1}{2} M {v_2}^2 - \frac{1}{2} M {v_1}^2\right) \\ &= \frac{1}{2}\left({v_2}^2 - {v_1}^2\right)\left(C_D \rho A d + M\right) \end{aligned} \tag{3.2}$$

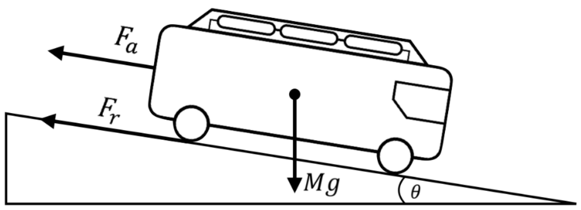
Where v_1 corresponds to 40 mph and v_2 corresponds to 60 mph. Table 3.5 below was created by applying equation 3.2 to Park and Rides in Oxford. A single bus is considered for each route.

Route	**Distance, d, required to travel at 60 mph per trip [1.40, 2.1] (km)**	**Additional energy required by intermediate power source using equation 3.2 (MJ)**
500	0	0
400	1.0	3.93
300	0.6	3.27
S5	9.2	17.6

< Table 3.5: Tabulating the additional energy required to obtain 60 mph >

Table 3.5 shows that all of the energies required are less than the 72 MJ capacity of the intermediate energy storage of the Wrightbus H2Bus. This additional capacity can be used for successive accelerations for example on high speed roads.

It will now be determined how the required energies can be generated during normal operation. Two regenerative braking scenarios will be considered. During descent, the mechanical resistance of the generator is used to provide braking power and maintain a constant speed while charging the supercapacitors. When the bus decelerates to a stop, energy can also be recovered through the generator. A free body diagram will be considered to model descent at constant speed. The free body diagram is shown below in Fig. 3.7. A similar method can be found in the literature [3.40].



$$F_r = Mg \sin\theta - F_a \quad (3.3)$$

Symbol definitions:

F_a = air resistance (N) $= \frac{1}{2} C_D \rho A v^2$ [3.40], where:

. C_D = drag coefficient = 0.6 [3.41]

. ρ = air density = $1.225\ (\mathrm{kg\ m^{-3}})$ [2.1]

. A = frontal area $\approx 2.52 \times 4.5 = 11.34\ (\mathrm{m^2})$ [3.42] (estimated height for a double deck bus)

. v = bus speed = $17.88\ (\mathrm{m\ s^{-1}})$ [2.1] (40 mph)

F_w = wheel force provided by the bus (N)

F_r = regenerative braking force (N)

M = bus mass = 11,350 (kg) [3.42]

g = acceleration of free fall (= $9.81\ (\mathrm{m\ s^{-2}})$) [2.1]

θ = inclination angle (degrees)

< Fig. 3.7: Free body diagram for a bus travelling at constant speed in descent >

From equation 3.3 in Fig. 3.7 the regenerative braking force, F_r, can be found. To calculate the inclination angle, θ, the elevations of different bus stops and road distances were used [3.39]. Regenerative braking systems can have an energy recovery efficiency as high as 70% [3.43]. This efficiency will be used in the model. F_r is multiplied by the distance travelled, d, and by the recovery efficiency to calculate the energy generated from the regenerative braking system during descents.

This method is applied to all Park and Ride routes shown in Fig. 3.5. Results are shown below in Table 3.6, using a Python script to compile the data. Regenerative braking is considered from the two scenarios explained above: energy recovered from descents at a constant 40 mph speed and the energy recovered when the bus comes to a full stop, with a recovery efficiency of 70% [3.43]. Table 3.6 also shows an estimate of how much the energy recovered represents in kilograms of hydrogen per year. This was calculated by using a hydrogen energy density of 120 MJ kg^{-1} [1.23] and a conversion efficiency of 60% [2.6] for converting hydrogen into useful work. Bus frequency data was also taken from bus timetables [3.18] to estimate how often the buses would travel per year. Outbound routes refer to bus routes going out of the city centre. RBS stands for regenerative braking system.

Route	**Energy recovered by RBS by a single bus in one trip (MJ)**	**Intermediate energy required (from Table 3.5) (MJ)**	**Yearly hydrogen saved by RBS by a single bus (kg)**
500 (outbound)	9.14	0	980
500 (inbound)	11.7	0	1,260
400 (outbound)	6.57	3.93	1,860
400 (inbound)	9.86	3.93	2,790
300 (outbound)	9.85	3.27	3,590
300 (inbound)	10.3	3.27	3,760
S5 (outbound)	8.92	17.6	2,200
S5 (inbound)	9.58	17.6	2,360

< Table 3.6: Energy recovered or hydrogen saved for all Park and Ride routes >

Table 3.6 shows that the energy recovered from regenerative braking is sufficient to provide the intermediate energy for all routes apart from for the S5. Regenerative braking alone is therefore insufficient to charge the intermediate energy storage in this case. Hence, the bus will have to charge its supercapacitors by using the fuel cell power during lower speed travel. As many roads in Oxford are limited to 20 mph [3.44], the fuel cell will be able to fulfil this role during a significant portion of the daily route. The fuel cell power is 75 kW [3.42]. If 25% of its capacity is used to recharge the energy storage, it will be able to provide the 8.68 MJ of additional energy required for the S5 outbound route in around 460 seconds.

Table 3.6 also shows that more energy is recovered on inbound routes. This can be explained by the elevation difference between the city centre and its surrounding. As shown in Fig. 3.5, the 300 and S5 routes mostly stay in regions of lower elevation. The difference between inbound and outbound energy recovery is therefore minimal. However, the 400 and 500 routes transition between regions of high and low elevation. This results in a significant difference in the energy recovered for inbound and outbound routes.

There are some limitations in the model used above. The regenerative energy recovery efficiency may drop from 70% to 16% depending on the bus driving style [3.43]. This implies that less energy may be recovered during descents and stopping. The model assumed 70% kinetic energy recovery while braking from 40 mph to zero. The buses are also likely to operate at slower speeds closer to the city centre. This would result in a lower kinetic energy recovered from stopping the bus.

In practice, when buses come to a full stop, regenerative braking systems can only slow down the bus by 0.4*g* [2.6]. Beyond 0.4*g*, in strong braking, conventional brakes activate [2.6]. However, passengers very rarely experience decelerations greater than 0.3*g* [2.6]. This implies that regenerative braking can cover all braking situations. Fully regenerative braking is also beneficial to a net zero solution as it drastically reduces the brake disc usage and wear. Disk pad wearing contributes up to 20% of air pollution associated with particles smaller than 2.5 μm in diameter [3.45].

Now that the range, refuelling time and speed capabilities of the Wrightbus H2Bus have been shown to match Oxford requirements, the financial aspects of transitioning to a hydrogen bus fleet will be explored.

3.6.4 Financing a hydrogen bus fleet

The selling prices of the Wrightbus single deck and double deck hydrogen buses are forecasted to be €375,000 and €410,000 respectively [1.31]. This converts to £326,250 and £356,700 [3.1]. As shown in Table 3.1, 150 single deck and 249 double deck hydrogen buses will need to be purchased resulting in a total investment of around £138 million. This investment would be deployed over several years. In order to propose a replacement strategy, the age distribution of the current diesel/hybrid fleet will be analysed.

In 2020, the average age of the 231 buses operated by the Oxford Bus Company and Thames Travel was 7.8 years [3.46]. The average age of the 168 Stagecoach buses was 7.5 years [3.47].

The average bus age in Oxford can then be calculated to be around 7.7 years. As mentioned in Section 3.5.2, the diesel and hybrid buses have a lifetime of 15 and 12 years respectively.

It is expected that bus companies will start by replacing their older conventional diesel buses, which may not be able to meet future emission regulations, and for which maintenance costs become more significant as they reach the end of their service life. Then, in a second step, bus companies could consider selling their mid-life buses of around 7 to 8 years of service. In order to estimate the contribution coming from the sale, it is useful to calculate the typical residual values for mid-life diesel and hybrid buses.

A diminishing value method can be used to calculate how much these buses have depreciated over time, applying a high level of depreciation at the start of the bus lifetime and a progressively lower level of depreciation towards the end of the bus lifetime [3.48]. The formula for calculating diminishing value for a bus is provided below [3.48]:

$$\text{decline in value at end of year} = \text{value at start of year} \times \frac{2}{\text{bus lifetime}} \qquad (3.4)$$

Equation 3.4 can be applied to calculate the residual value of hybrid and diesel buses. Calculations are shown below in Table 3.7. 2020 purchasing prices are used as an approximation.

Bus type	Diesel	Hybrid
Purchasing price in pounds (from Table 3.2)	203,000	260,000
Lifetime in years	15 [3.23]	12 [3.25]
Years of service	7.7	7.7
Calculated residual value in pounds	62,100	79,500

< Table 3.7: Calculating the residual values of buses in Oxford >

From Table 3.7, an average diesel bus in Oxford is expected to have a residual value of around £62,100 versus £79,500 for an average hybrid bus of a similar age. Should another bus company be interested in making an acquisition, these amounts could definitely contribute to accelerating the transition to a net zero fleet in Oxford.

Naturally, the most recent buses, including the more advanced hybrid versions, would remain in service for the longest time, to finally be considered for replacement once the older, conventional diesel vehicles are replaced. The investment timing will be further discussed in greater detail in Section 8.

4 Estimating the hydrogen demand

This section will detail the process of deriving an estimate of the annual hydrogen demand of the system and present the results of the route modelling which was done in order to understand the composition of the current bus network.

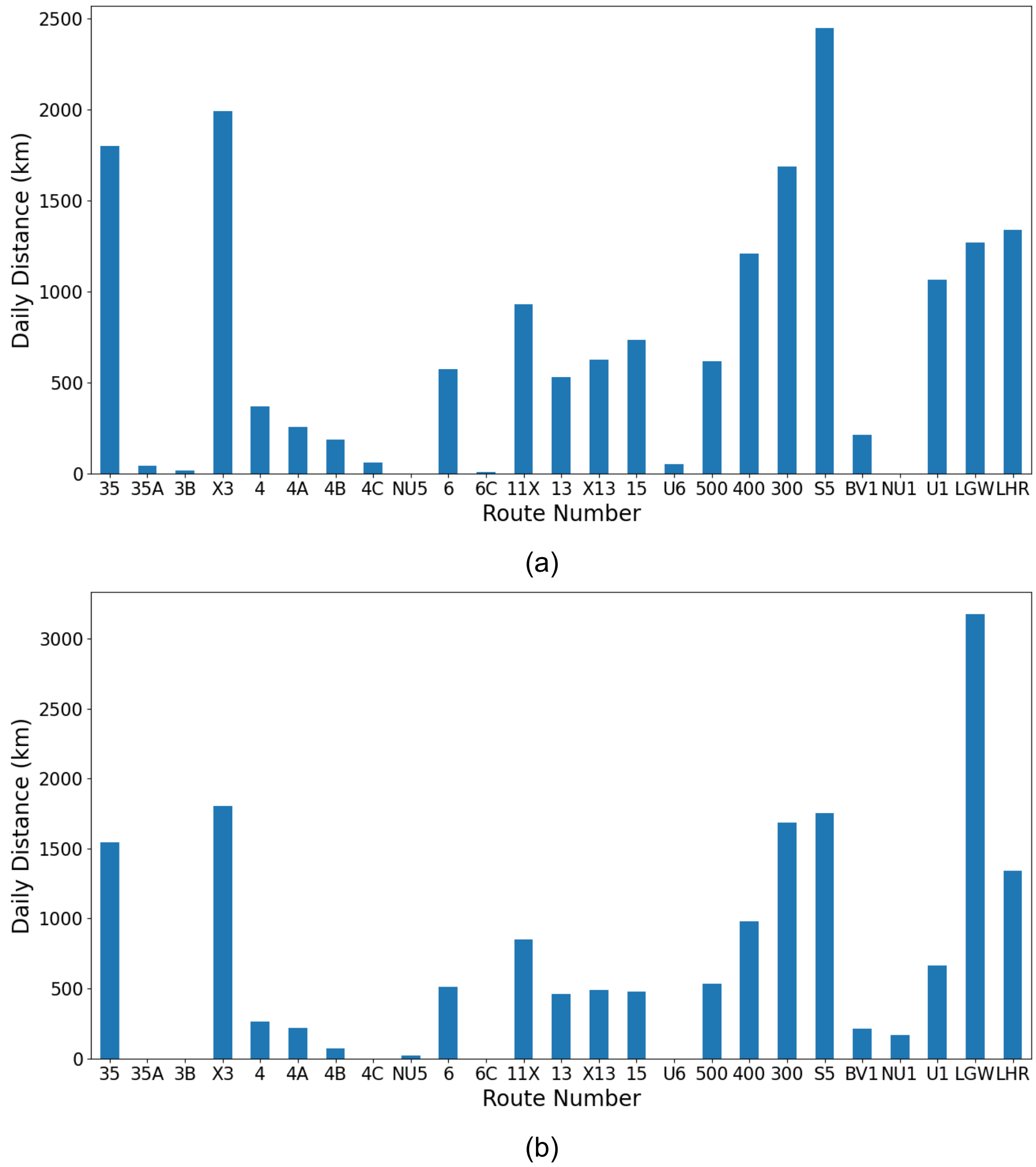
4.1 Route modelling

In order to begin estimating the annual hydrogen demand of the system, it was first necessary to have a comprehensive understanding of the current bus network. The route modelling was done in order to answer the following three questions:

1. How many different routes are provided by the three network operators identified in the project scope?
2. What is the annual distance travelled by the bus network?
3. What is the annual diesel fuel demand and the associated carbon and financial costs?

By answering these questions, it would be possible to estimate the hydrogen demand necessary to provide the same bus coverage and the costs of the current network, both environmental and financial, would be quantifiable which would justify the reasons why transitioning to a green hydrogen based transport system is required.

The first step was to identify how many bus routes fell within the scope of the project. In total, 58 routes were analysed, 25 of which are operated by OBC, 17 by Stagecoach, 8 by Thames Travel and 8 were jointly operated by OBC and Stagecoach. The next step was to use a combination of Google Maps [1.40] and the online timetables of the network operators [1.15, 1.16, 1.17] to calculate the distance travelled by the bus network annually and, perhaps more importantly, to have this data at a high resolution i.e. to have a figure for daily distance travelled on both a weekday and a weekend. The result of this analysis for OBC is shown below in Fig. 4.1. Generating similar results for Stagecoach and Thames Travel led to an estimate of the total distance travelled annually by the bus network equaling 33,542,938.2 km or ~ 33.5 million km.



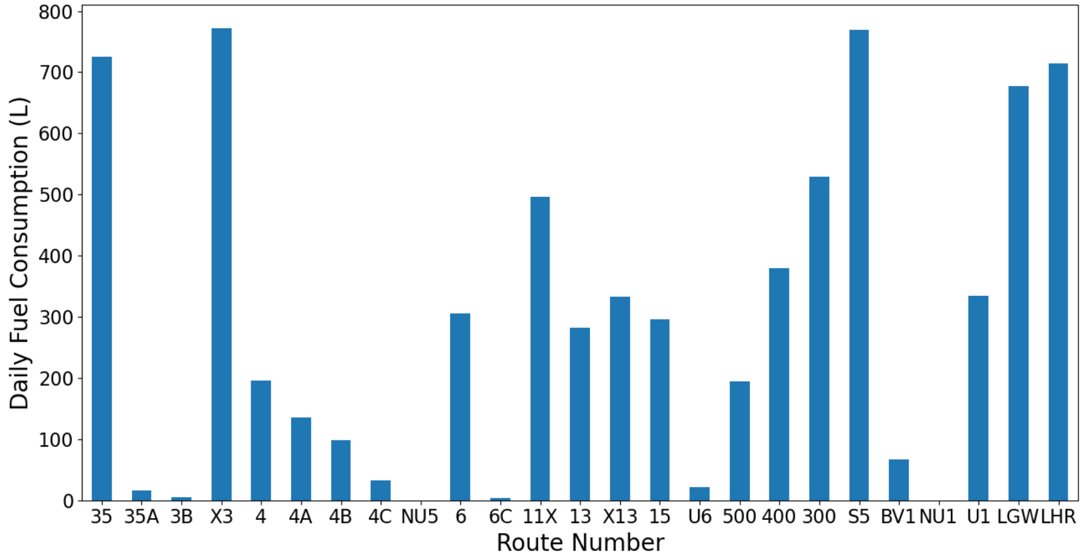
< Fig. 4.1: Estimate of the (a) weekday and (b) weekend mileage for OBC operated routes >

Both graphs have a similar shape with the weekend mileage being lower overall as expected. Routes 300, 400, 500 and S5 are park and ride routes and hence travel significantly more miles during the day. The inner city routes such as 4, 4A and 4B have a much lower mileage as their routes are much shorter. It is also important to note the peak of the LGW service to London Gatwick which sees a sharp increase on the weekends. This is further justification for a hydrogen based system over a battery electric one as the better range of FC buses is what will enable this route to continue running, an electric bus would simply not have the battery capacity to complete such a long route.

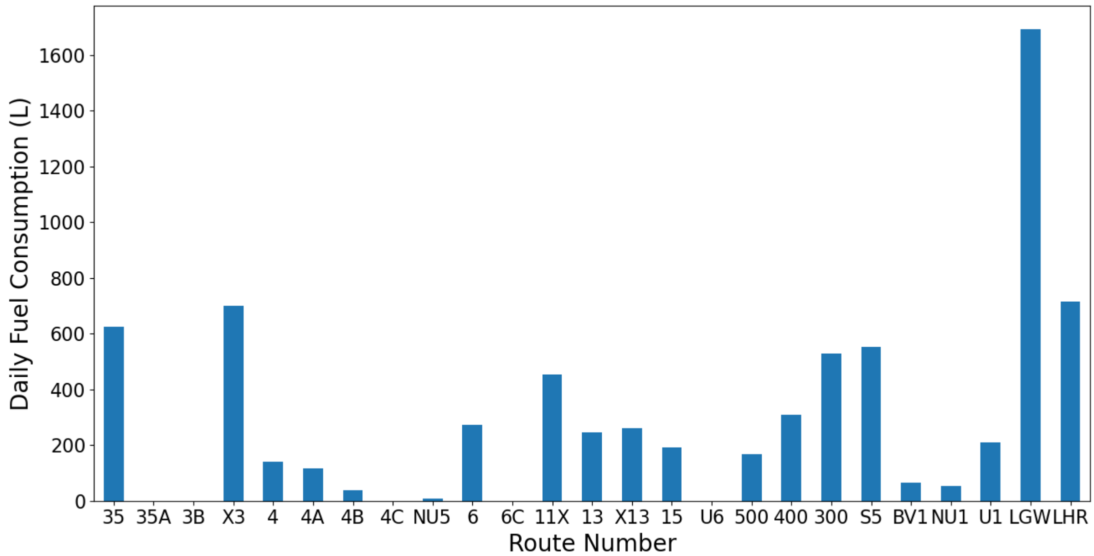
To calculate the fuel consumption from the estimates of distance, information about the mpg ratings of the buses running on each route was required. This task proved difficult as not only were there multiple, different, buses assigned to a single route such that there was not one single mpg rating associated with a particular route, there was also a significant lack of mpg data available online. This problem was partially resolved thanks to Luke Marion, who is the Finance and Commercial Director at OBC, who was able to provide us with specific mpg ratings for the different bus models, however, there was still the issue of multiple different mpg ratings associated with any particular route. The solution to this problem was that, in order to avoid underestimating the annual fuel consumption, the upper bound 'worst case scenario' solution would be used. This meant that for each route, the lowest mpg rating associated with it was always used in the calculation of fuel consumption, hence calculating the upper bound of annual fuel demand. The actual calculation used was simply to divide the distance travelled in miles by the mpg rating as shown in equation 4.1.

$$\text{fuel usage in gallons} = \text{distance travelled in miles} \div \text{mpg} \tag{4.1}$$

Again, using OBC as the example, Fig 4.2 shows the fuel consumption of each route on both a weekday and a weekend. Similar graphs were generated for Stagecoach and Thames Travel and the result was a diesel consumption of 13,383,242.6 L or ~ 13.4 million litres annually. This is hugely costly, both environmentally and financially, resulting in a carbon footprint of 35,867 tonnes and an annual fuel expenditure of £12,281,802, where the price of diesel has been taken to be £0.9177 per litre, including fuel duty [4.1]. Transitioning to a green hydrogen based system will not only significantly reduce carbon emissions but it will also reduce the annual fuel expenditure of the network operators. A detailed financial analysis will be presented in Section 8.



(a)



(b)

< Fig. 4.2: Estimate of the (a) weekday and (b) weekend fuel consumption for OBC operated routes >

Appendix A provides an example of the bus route data that was collected for different routes around Oxfordshire.

4.2 Energy equivalence method

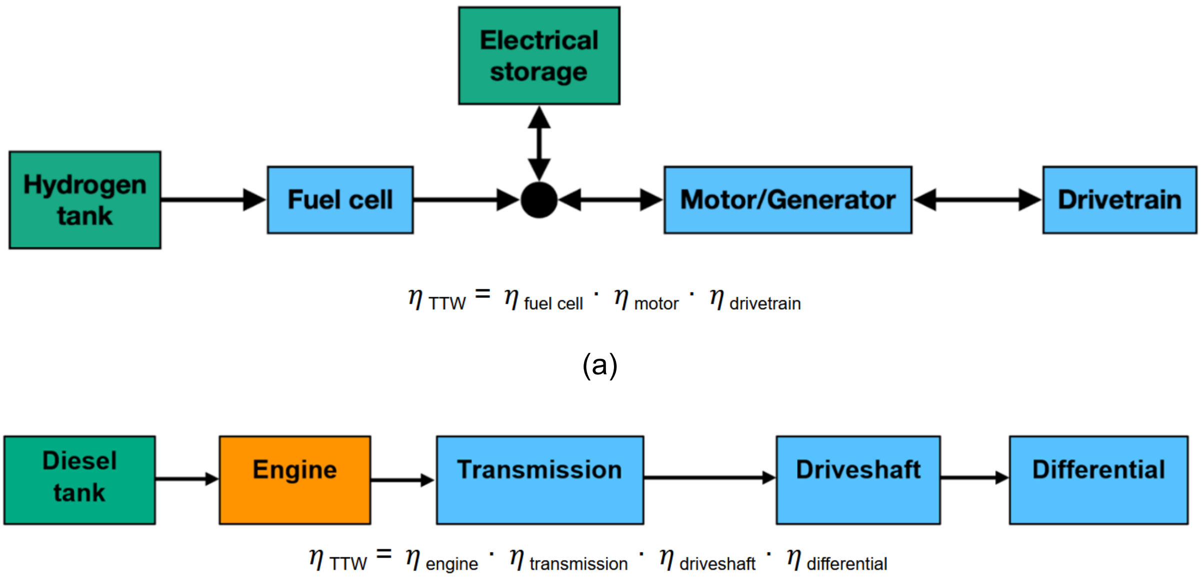
In order to estimate the hydrogen demand, an energy equivalence method was used. The assumption was made that the same amount of energy needed to be delivered to the wheels. This assumption is made on the basis that the buses will be driving along the same routes and at the same speeds (there are no changes being made to the speed limits on the roads of Oxfordshire). Kinetic energy is proportional to velocity squared and the assumption is that this will stay constant meaning the kinetic energy will stay constant. No doubt there will be differences in the mass of a hydrogen bus when compared to a diesel bus, however, as stated kinetic energy is dominated by the velocity term. On top of this the overall mass depends on the passenger load and this is also not changing meaning that the change in the mass of the bus will be negligible. To calculate the hydrogen demand, the amount of energy provided by diesel to the wheels would be required first. This led to the formation of equation 4.2,

$$E = V\rho\eta \tag{4.2}$$

where E is the amount of energy delivered to the wheels, V is the volume of fuel in litres, ρ is the volumetric energy density of the fuel and η is the tank-to-wheel efficiency of the vehicle. The $V\rho$ term represents the total stored chemical energy of the fuel and so multiplying this by the efficiency η gives us the total useful energy i.e. the energy delivered to the wheels.

4.2.1 Accounting for efficiency

The tank-to-wheel efficiency η incorporates all the possible sources of energy loss from the fuel tank through to the wheels, the main losses being in the engine/fuel cell and the drivetrain. Fig. 4.3 below shows the components within the drivetrains of both a fuel cell and diesel bus respectively, and how the tank-to-wheel efficiency is calculated.



(b)

< Fig. 4.3: Tank-to-wheel efficiency of (a) fuel cell and (b) diesel bus >

The literature values for the tank-to-wheel efficiency are extremely varied for both diesel and fuel cell vehicles giving a large range of possible efficiencies. For fuel cell vehicles, there was a range of 30 - 53.8% [4.2, 4.3, 4.4, 4.5] and for diesel a range of 20 - 24% [4.2]. These ranges, especially for the fuel cell vehicle, are extremely large and doing a calculation based on these numbers would be subject to a large error and so, in order to avoid significantly underestimating the required hydrogen demand, the decision was made to neglect the drivetrain efficiency and focus solely on the engine/fuel cell efficiency for which there were more more universally accepted figures. This simplification can be done as an electric drivetrain is significantly more efficient than a traditional mechanical drivetrain [4.5, 4.6]. This means that including these figures will decrease the amount of hydrogen required and so by excluding them a larger demand than actually necessary was calculated, thus ensuring the system has enough hydrogen.

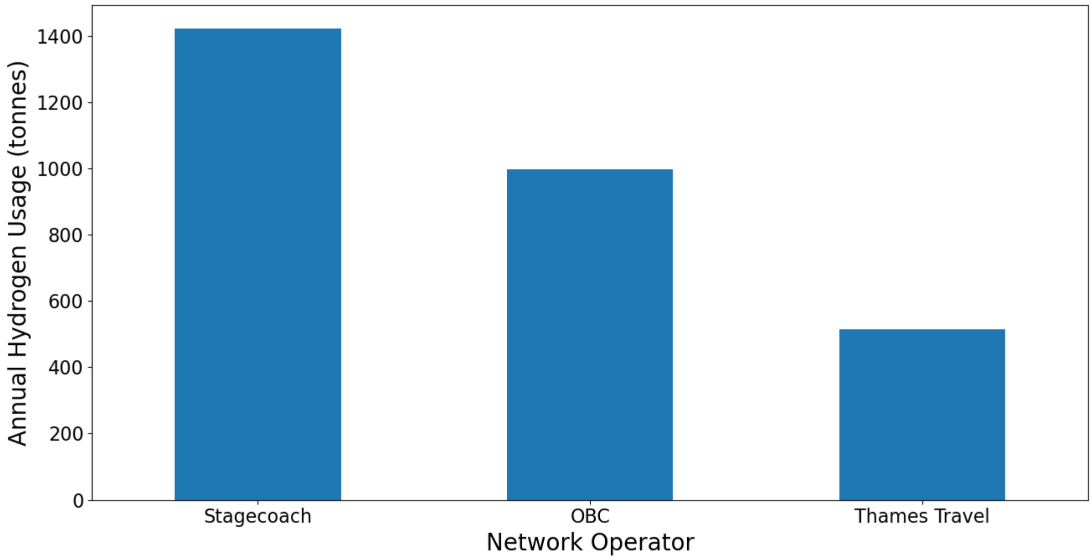
The efficiency of a modern PEM fuel cell sits at around 60% [2.6], 23% less than the theoretical maximum which is due to heating effects, electrical and ionic resistance and the kinetics of the chemical reaction [2.2]. This has been discussed in detail in Section 2.1.2. The efficiency of a modern diesel bus operating in urban, city-driving conditions is around 41% [4.7]. The volumetric energy density of both fuels has already been discussed. In this calculation the values are taken to be 2.80 MJ L^{-1} for hydrogen (at 27°C, 350 bar) [1.23] and 38.6 MJ L^{-1} for diesel [1.27]. The values used in the calculation of hydrogen demand are summarised in Table 4.1 below where η denotes efficiency and ρ denotes volumetric energy density.

Fuel Cell Bus		**Diesel Bus**	
η_{FC}	60%	η_{ICE}	41%
ρ_{FC}	2.80 $\mathrm{MJ\ L^{-1}}$	ρ_{ICE}	38.6 $\mathrm{MJ\ L^{-1}}$

< Table 4.1: Summary of the values used in the calculation of hydrogen demand >

4.3 Results

Using the estimate for the volume of diesel fuel used annually and by applying the energy conversion equation, $E = V\rho\eta$, fuel consumption was converted into energy consumption and then worked backwards to estimate the hydrogen demand. The total annual hydrogen required by the system is 2,933,738 kg (using a mass density of 23 kg m^{-3} at 350 bar [2.6] to convert from volume to mass). Thanks to the resolution of the route modelling, this figure could be broken down into the requirements on a weekday and weekend which the model calculated to be 8548.2 kg and 6838.6 kg respectively. This data was needed to design the distribution system ensuring that hydrogen is delivered from the production site to the various bus depots in the correct quantities each day. This will be discussed further in Section 6. The breakdown of the total annual hydrogen demand by bus operator is shown in Fig. 4.4.



< Fig. 4.4: Annual hydrogen demand of each network operator in tonnes >

This gave a hydrogen fuel usage of 8.7 kg per 100 km, agreeing with the literature values which are in the range 8 - 9 kg per 100 km [4.8].

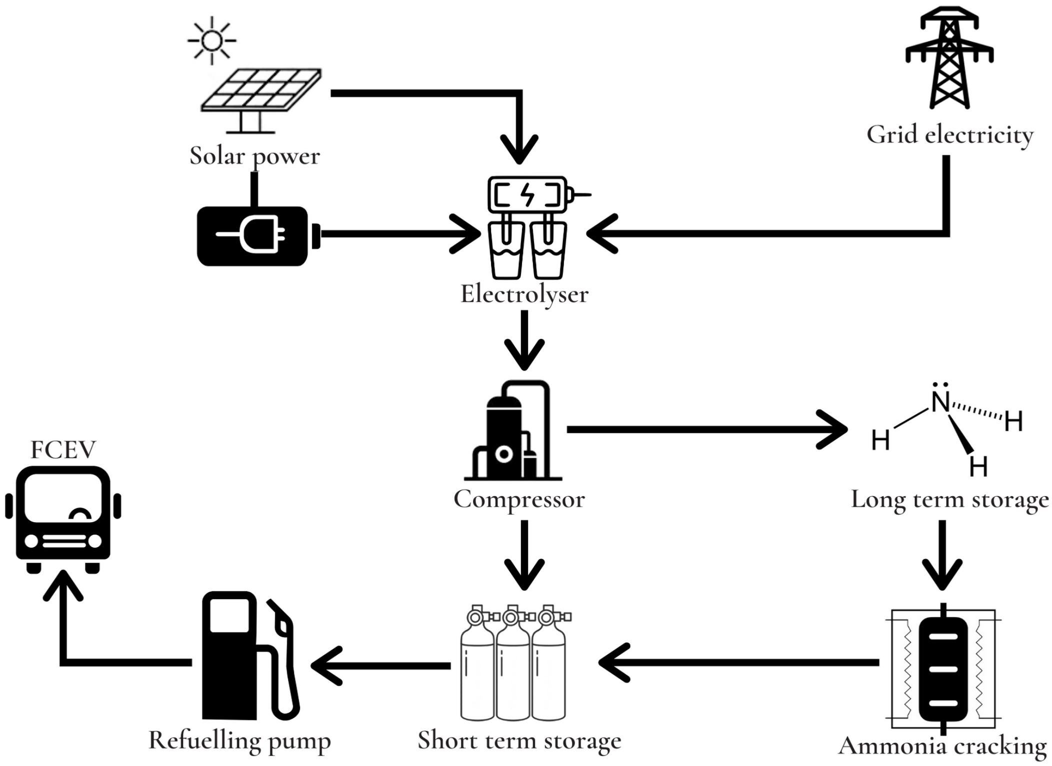
4.3.1 Distribution demand

In order to keep the system net zero, it is necessary to consider the fuel required to power the distribution of hydrogen from the production plant to the individual bus depots where refuelling will take place. This distribution cannot be done by diesel vehicles as the emissions caused by this would be counted in the total system carbon footprint, hence the extra demand caused by this needs to be considered. The value for the distribution demand is 26,800 kg. This value will be derived and discussed alongside the distribution strategy as a whole in Section 7.2.

4.3.2 Emergency demand

It is important to think about contingency plans in case of an emergency such as system failure preventing the production or distribution of hydrogen. This could be in the form of an electrolyser failing or trucks being unavailable to deliver the hydrogen from the production site to the bus depots. It was estimated that, in the case of an electrolyser failure, it would take a maximum of two weeks to solve the problem and so an emergency overheard that would last that amount of time would be required. This was simple to calculate as the weekly requirement of hydrogen (again broken down into weekdays and weekends) was known from the route modelling. This emergency overhead comes to 110,000 kg. However this is not included in the annual demand figure as this is not part of the normal operation of the system, it is a contingency store. This excess will be slowly built up during the course of operation.

4.4 System Overview



< Fig. 4.5: Green hydrogen production and storage system overview >

Fig. 4.5 above shows each component of the system which consists of a green energy production system to supply the hydrogen production plant with green energy where possible, supplementing with grid electricity when green production is insufficient. The hydrogen production plant itself contains the smart electrolyser-battery system and produces the hydrogen ready for storage. There are two forms of hydrogen storage, long term and short term. The distribution system delivers hydrogen to the various bus depots around Oxford ready for use by the bus operators. These systems will be expanded upon in great detail in the following sections which will explain the

choices that were made and provide detail on how these systems will operate and connect with each other to power the proposed net zero transport network.

5 Social and legal study

Before the technical details of the proposed system are discussed, it is important to consider the social and legal implications of the project. The purpose of this section is to explain regulations around the various areas of this project, as well as to show the public response to a hydrogen public transport network.

5.1 Social Study

FCEVs are yet to be brought into broad usage, especially in the UK. As a result of this, it is important for this project to consider the opinions of the public on a large-scale hydrogen based bus network.

Cummins, a global power company, recently published an article which showed the support that the UK public have for a public transport system involving hydrogen [5.1]. Collating the opinions of 6000 respondents across the UK, Belgium and Germany, the survey found that 48% of British citizens expressed that low-carbon technology would be vital for the UK's economic recovery from COVID-19 [5.1]. Furthermore, 40% of survey respondents were willing to pay up to £1 more for their daily commute in order to reduce their carbon footprint [5.1]. This shows the extent to which the public are willing to make sacrifices to encourage the switch to green transport, beyond simply being in support of the idea of a low-carbon solution. Significantly, according to the Oxford Bus Company website, passenger fares make up 80% of the financing for the bus services [5.2]. Given that a bus commute currently costs £2.30 on their city services [5.3], the potential passenger-supported increase in bus fare could make a huge difference to the financial prospects of the proposed system. When discussed with Mr. Marion [3.26], the communications and financial director of the Oxford Bus Company, he observed that these changes would certainly not be able to be made in the immediate aftermath of COVID-19. Competition law in the UK prohibits "anti-competitive behaviour", such as coordination of prices [5.4]. Due to the fact that Stagecoach Oxfordshire is an entirely independent company from the Oxford Bus Company, an increase in ticket price by one company could lead to the public largely favouring the other with the still lower price. Therefore, an increase in fare would be something to develop slowly, or under an exemption from the Competition Act of 1998 [5.5]. There are specific allowances for individual exemptions in circumstances where an agreement which infringes upon the regulations set out in Chapter 1 of the Competition Act is required to improve sustainability [5.6]. Due to the obvious environmental benefits of this project, it is likely to meet the criteria for an individual exemption, so long as the agreement does not permanently eliminate competition.

A more thorough study was conducted in Japan on public perception of hydrogen as an energy source, with responses taken in 2008, 2009 and 2015 [5.7]. The following results are from the 2015 survey. Although awareness had increased from 2008 to 2015, 19.8% of the 3133 respondents indicated that they had never heard of the use of hydrogen as an energy source [5.7]. 49.4% of respondents believed that utilising more hydrogen energy would solve global warming and air pollution, while 40.3% answered that they did not know [5.7]. When asked about the prospect of fuel cell buses being introduced into their communities, 58.7% of respondents answered that they thought it would be good, and 36.6% did not feel strongly one way or the other, leaving a very small percentage against the idea of a hydrogen-based public transport system. Furthermore, only 8.4% of respondents indicated any form of negative reaction to the idea of a gas station near their house also selling hydrogen [5.7]. These results show that the public are largely in favour of an increase of hydrogen usage in energy systems and, more importantly for this project, a hydrogen-based bus network.

5.2 Legal study

Hydrogen has a very wide range of flammability, from 4.0% to 75.0% by volume in air [5.8]. For reference, methane is flammable from 5.3% to 15.0% by volume in air, and other fuels have yet smaller ranges [5.8]. Hydrogen also requires a very low ignition energy. At stoichiometric ratios, only 0.02 mJ is required [5.8]. Methane requires 0.29 mJ in these conditions, and propane 0.26 mJ [5.8]. This means that almost any spark could cause ignition, and even mobile phones are a risk. Hydrogen is also known to cause embrittlement of metals, and therefore storage tanks must be regularly checked. These properties are reasons that hydrogen is classified as a hazardous substance. It is noteworthy, however, that there are properties in which hydrogen has a safety advantage over other substances. For instance, the low density (0.09 kg m^{-3} [5.8]) and very high diffusivity (0.61 $cm^2\ s^{-1}$ [5.8]) of hydrogen mean that, so long as hydrogen is kept in a well-ventilated area, the initially high risk caused by a leak reduces very quickly compared with other gases.

5.2.1 Hydrogen management regulations

There is little regulation that specifically focuses on hydrogen, however there are acts and regulations under which hydrogen must be managed. The most broad of these regulations is the Gas Act 1986 [5.9], which applies to all gases. Any party who supplies, ships or transports a gas must have a license to do so. Under this Act, there are several industry codes and standards which must be complied with. Under the Gas Safety (Management) Regulations 1996 [5.10], any transporters of gas must prepare and submit a safety case to the Health and Safety Executive (HSE). The Pipeline Safety Regulations 1996 set out requirements for the integrity of a pipeline, from the design through to operations, maintenance and decommissioning [5.11]. Given that the transportation of hydrogen between production, storage and refuelling locations will be a significant component of the proposed system, it is important that these regulations are kept in mind for system design.

The storage of hydrogen is governed by the Planning (Hazardous Substances) Regulations 2015, and the Control of Major Accidents Hazards Regulations 2015 (COMAH). Quantities of hydrogen in excess of 2 tonnes must comply with the Planning (Hazardous Substances) Regulations, while quantities in excess of 5 tonnes follow the COMAH regulations [5.12].

The Planning (Hazardous Substances) Regulations 2015 state that Hazardous Substance Consent (HSC) is required from the Hazardous Substance Authority (HSA) for planning to be approved [5.13]. The HSA is usually the local council, who must consult with HSE and the Environment Agency (EA) before granting HSC. A key element of a system adhering to these regulations is ensuring that the location of the planned site is an appropriate distance from other local establishments, so as to minimise risk in the surrounding area.

COMAH Regulations are divided into regulations for a lower tier (5 - 50 tonnes of hydrogen) and a top tier (in excess of 50 tonnes of hydrogen) [5.12]. All operators of establishments subject to

COMAH regulations have certain duties, the main aim of which is taking all necessary measures to prevent major accidents and their possible consequences to people and the environment [5.14]. Proper notification of site details must be provided to HSE and the EA [5.14].

Lower tier operators must prepare a Major Accident Prevention Policy (MAPP) [5.14]. This should include a summary of the safety management system that will be put into place in order to enact this policy [5.14]. The MAPP must also contain information regarding personnel, identification and evaluation of major hazards, operational control, management of change and planning for emergencies [5.14].

Top tier operators must prepare a full safety report, of which a MAPP is a component [5.14]. The safety report must also include full site details, including a description of operating methods and all dangerous substances involved [5.14]. It must also include relevant information about potential hazards; this includes information on possible major accidents, potential causes (both internal and external), and plans to mitigate and reduce consequences of these accidents [5.14]. Information on nearby establishments which may increase or be subjected to risk must also be included, as well as information about the emergency plan for the site which will be used by the local authority to prepare an external emergency plan [5.14]. In addition to preparing this plan for the safety report, the plan must be tested [5.14]. Some information must also be provided to the public, through the HSE website [5.14].

Any facility or system containing hydrogen must also meet the standards of the Dangerous Substances and Explosive Atmosphere Regulations 2002 (DSEAR) [5.15]. These regulations apply to explosive substances in the workplace, including those which are not intended to be used as such, which is the case for hydrogen in the system. These regulations implement the ATEX 137 Directive [5.16], which requires that the employer take certain risk-preventative measures. This should include identification of risks, classification of areas with potentially explosive atmospheres, and appropriate equipment allocation to prevent possible causes of ignition in these areas [5.16].

From all these regulations, it is clear that the amount of hydrogen stored at a given time should be minimised, and stored in a well-ventilated area, in order to minimise risk.

5.2.2 Hydrogen fleet regulations

For a bus to operate on public roads in the UK, they must follow the Road Vehicle (Construction and Use) Regulations 1986 (RVR) [5.17]. Regulation 94(2) would seem to prevent the use of hydrogen vehicles, indicating that no gas may be used in a gas supply system for a propelled vehicle other than liquefied petroleum gas [5.17]. However, orders such as the Road Vehicles (Authorisation of Special Types) (General) Order 2003 [5.18] provide specific constraints under which vehicles not within the specification of the RVR may operate. Furthermore, Section 44 of the Road Traffic Act 1988 [5.19] allows Special Vehicle Orders to be granted by the Vehicle Certification Authority. In the context of hydrogen buses, this means that a fleet would be a trial, test, or demonstration, however this would not inhibit their ability to operate. Examples of this can be seen in Birmingham [2.31] and Aberdeen [5.20], where hydrogen bus fleets have been operating.

5.2.3 Infrastructure and planning regulations

The proposed system for this project includes green energy generation, independent hydrogen production, and hydrogen storage. There are therefore a number of sites which will require extensive planning. For the required infrastructure and general site planning, smaller projects must follow legislation in the Town and Country Planning Act 1990 [5.21], and larger projects must follow the Planning Act 2008 [5.22].

The Town and Country Planning Act 1990 requires a two-part plan; a structure plan drawn up by the county council, stating policies and general proposals, taking into account relevant national and regional policies, and a local plan put together by the district council, relating the general structure plan to the specific proposal and location, relating all planning issues to the public [5.23]. Hydrogen pipelines are regulated by this Act.

The Planning Act 2008 (amended by the Localism Act 2011 [5.24]) specifically relates to “Nationally Significant Developments” [5.25]. This project comes under the label of a Nationally Significant Infrastructure Project (NSIP), as any projects related to energy and transport do. Under the Act, a Development Consent Order (DCO) can be issued, which removes the need for several other consents, including planning permission. The process takes 12 - 15 months from the time an application is formally submitted, alongside the appropriate pre-application consultations [5.26]. This will apply to planning for the energy source for hydrogen generation for this project, as well as for the generation and storage facilities.

6 Hydrogen production

In this section, the details of the hydrogen production components will be discussed. This will include a summary of the decisions made, and an in-depth explanation of how the components work.

6.1 Energy production

6.1.1 Selecting the energy source

In order to meet the system objectives of being local as well as net zero, the green energy generation method must be located within Oxfordshire. Due to the cost and location requirements of a hydro-electric solution, this was quickly ruled out, and the final decision came down to wind against solar. The main criteria for this decision included factors such as running cost, reliability, lifetime, and environmental factors.

Photovoltaic solar energy was decided upon for the energy generation component of this system for the reasons outlined below.

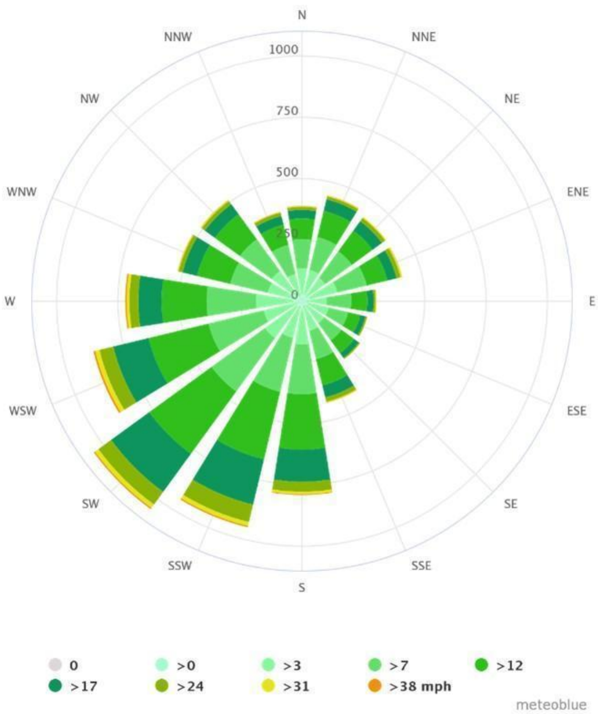
Generally, wind energy does have some advantages over solar; it currently has a lower carbon footprint [6.1], it can be produced day and night, and more consistently across the year (although there is a trend to decrease in summer, the curve is much less harsh than that of solar). However, there are many factors in which solar proves better.

At a large scale, solar panels require less land than wind turbines. However, of the land needed for wind turbines, only a very small proportion is used due to the narrow nature of the tower. This means that although the wind farm will require a larger area to be spread across, most of that area can still be used for agriculture. The main problem with the large area required for the wind farm comes due to the impact on the landscape. Wind farms are notorious eye sores. Taking the 500 kW EWT DW52/54 as an example, the tower stands up to 75 m from the ground, with the rotor radial length adding a further 27 m [6.2]. Larger turbines, likely to be used in projects of this scale, stand much taller. This makes the turbines visible from substantial distances, whereas solar panels on a ground mount tend to have a less offensive impact on the landscape. In a place like

Oxfordshire, this is likely to have an impact on obtaining planning permission, as locals are likely to oppose this [6.3].

Solar panels require much lower operational expenses than wind. The predicted prices for 2025 according to a government report on the cost of energy generation [6.4] given in pounds per megawatt per annum (£/MW/year) show how stark the difference is. The cost of operations and maintenance (O&M) was given as £6,700/MW/year for solar, and £23,500/MW/year for wind [6.4]. Furthermore, the already low fixed O&M cost for solar is predicted to drop fairly steadily to £5,700/MW/year by 2040, whereas the cost of wind isn't expected to decrease. In addition to this, the variable maintenance for solar is zero, whilst wind is expected to cost £6/MWh [6.4]. On top of this, a solar farm has a higher expected operational lifetime than that of wind, solar being 35 years, and wind being 25 years. Due to all these considerations, the levelized cost of electricity, or LCOE, is much lower for solar.

However, the main problem with a wind farm in Oxfordshire is the reliability. The wind in Oxford can be described as "light and sporadic" [6.3], and as shown in Fig. 5.1, this is true of both the direction and the speed. Note that the time scale is length of segment as opposed to area. The annual average wind speed in Oxford is 16.9 kmph [6.6], translating to just under 5 m s^{-1}. According to the Renewables First website, it is almost certainly not economically viable to operate a wind farm in an area with an average wind speed below 5 m s^{-1} [6.7]. Given that Oxfordshire does not meet the criteria even without taking into account the variation in the wind direction, which also decreases efficiency, it is clear that wind will not be an option for this project.



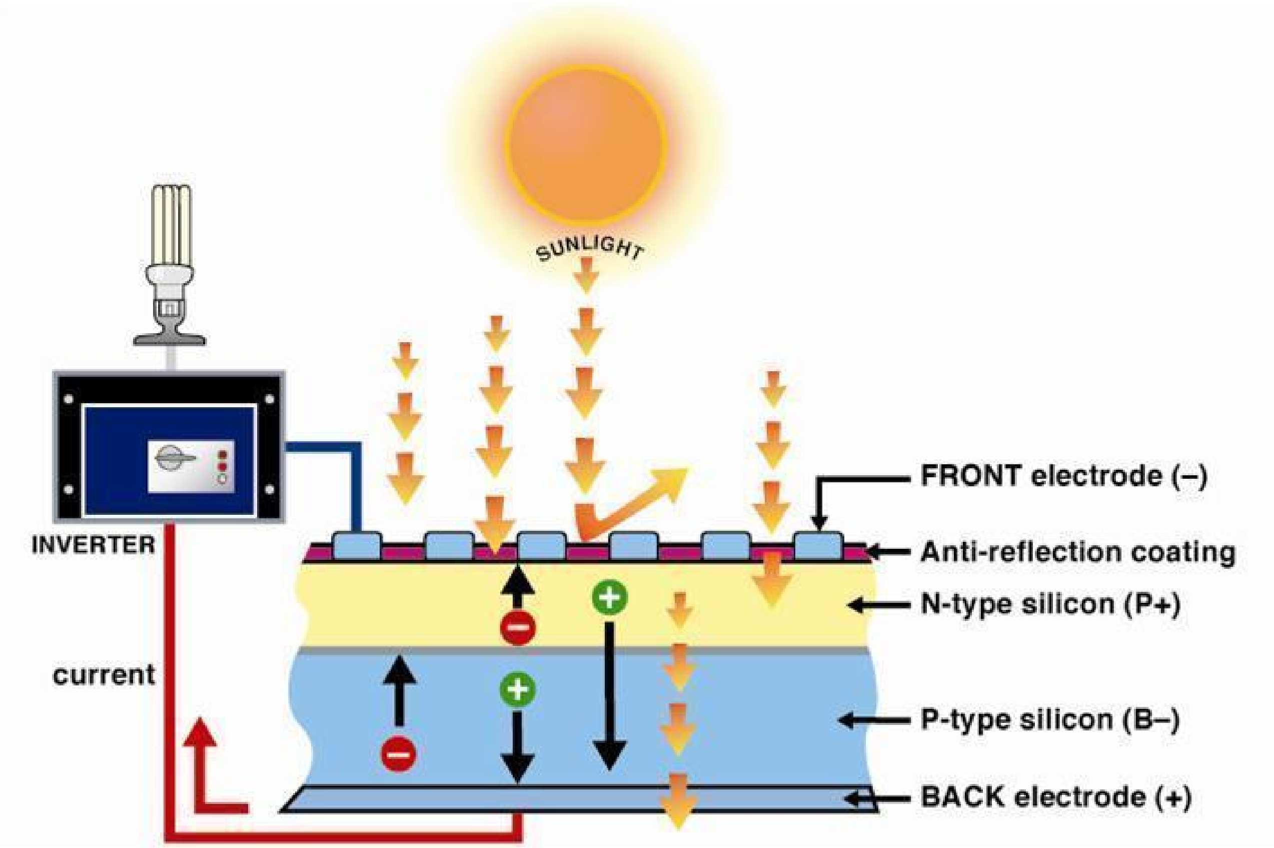
< Fig 6.1 : A wind rose for Oxford [6.5] >

6.1.2 Solar Energy

Once solar energy had been chosen as the power source for the proposed system, an accurate model of the hourly energy output for the year was needed.

How a solar panel works

The following is a brief summary of how solar panels work. A solar panel is made up of a series of photovoltaic cells. The photovoltaic cells themselves, as shown in Fig. 6.2, are made up of a negative electrode, an anti-reflection coating, a p-n semiconductor junction, and a positive

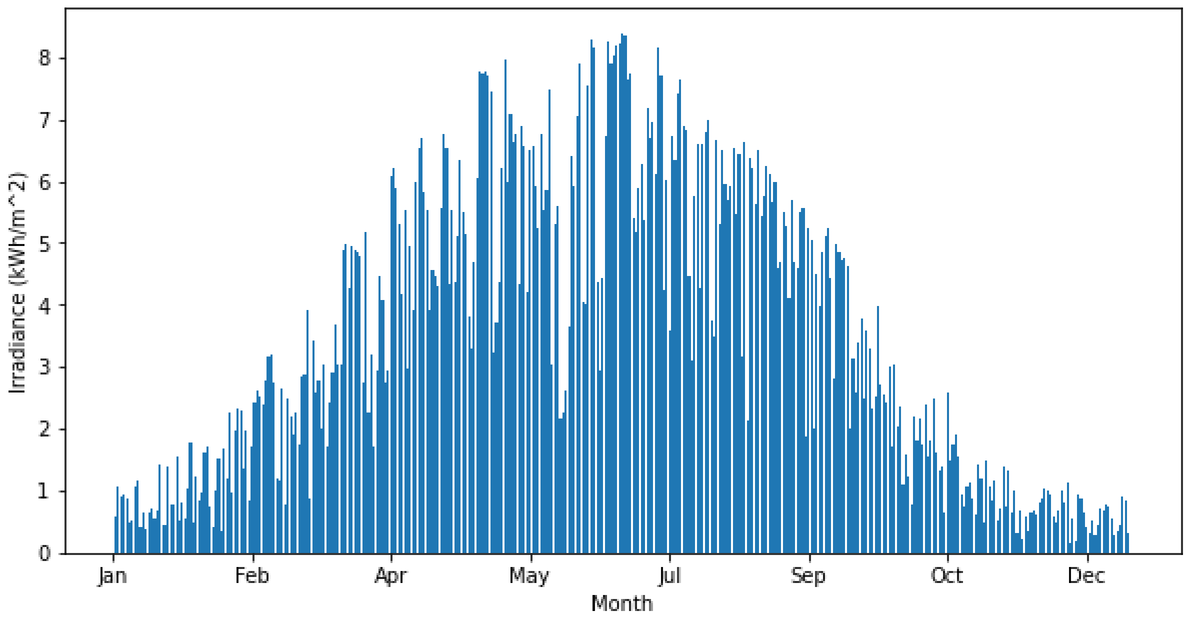


< Fig 6.2 : The components of a solar PV cell [6.8] >

electrode. The cell produces a current due to the photoelectric effect, by which the atoms of the semiconductor absorb photons of light and emit electrons. With the negative and positive electrodes on the front and back of the junction, the electrons can travel through the circuit formed and thereby create a current. The output current of the cell is direct current. Many modules join up along a DC string to form arrays, before the current enters an inverter, which converts the direct current to an alternating current.

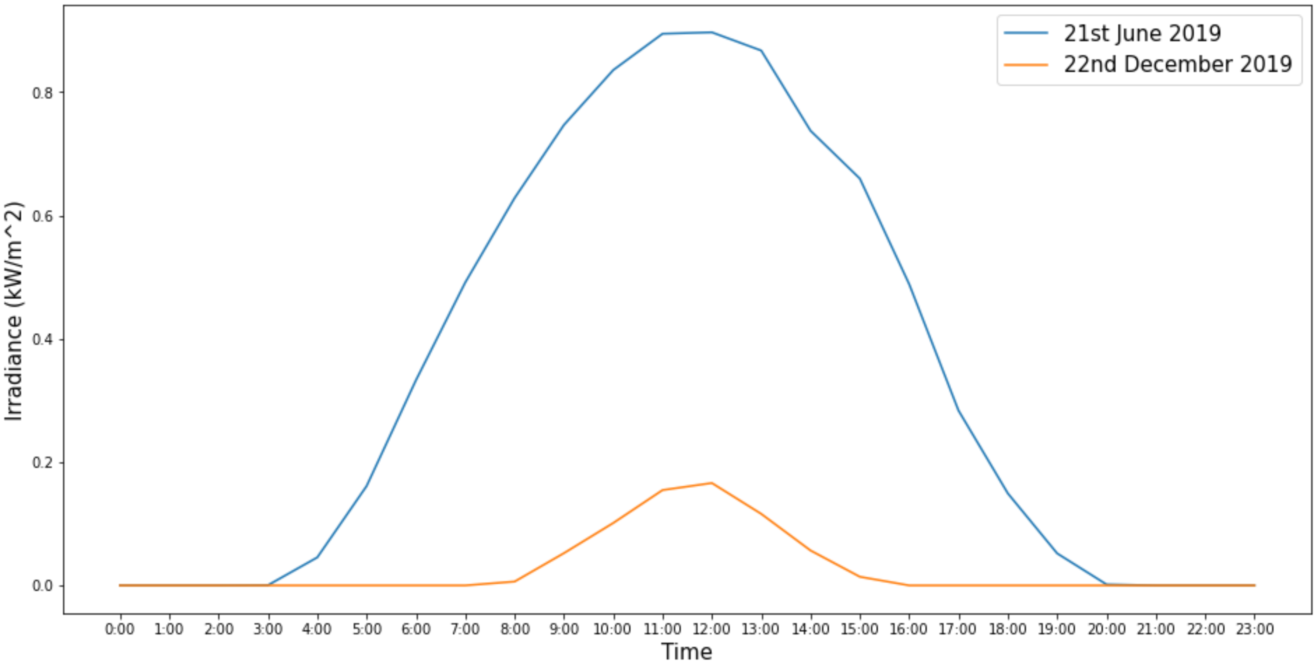
Modelling the solar farm

For this project, the solar panels used in the modelling were SHARP's NU_AC 300b, which is a 300 W panel, with 18.3% efficiency, and an area of 1.6368 m^2 [6.9]. The performance ratio, which accounts for losses in the system, including inverter losses, temperature losses, cable losses, shading losses, and others, was taken as 0.7, being in the middle of the standard range (0.5 - 0.9) [6.10]. The irradiance data used was from 2019, and provided an hourly average irradiance for Oxford [6.11]. The daily irradiance across the year is plotted in Fig. 6.3.



< Fig 6.3 : Daily irradiation in Oxford 2019 >

The graphs plotted in Fig. 6.4 show the solar irradiation for June 21st and December 22nd 2019, the longest and shortest days of that year respectively. These plots show how dramatically solar irradiance, and therefore the power output of a solar farm, varies throughout the day, as well as showing the stark contrast between irradiance at the height of summer and in deepest winter. Given these seasonal, daily and hourly differences in power output, it was clear that the system would require smart control in order to optimise the use of the locally generated power for hydrogen production. The details of this smart system, including the optimisation process by which it was determined, will be presented in Section 6.3.



< Fig 6.4 : Average hourly irradiance in Oxford on June 21st and December 22nd 2019 >

Estimating cost of installation

The cost of installation of a solar farm is made up of a variety of factors. The solar panels themselves only take up a small percentage of the price. The rest is made up of various associated costs including construction, land, planning, grid integration, technical analyses, as well as financial and legal services. There is however an economy of scale when considering a solar project of a larger size, and factors such as planning and financial/legal services are likely to have a less significant increase than the cost of panels, which would increase approximately linearly with the size of the project.

For a large-scale solar project, the government estimates that by 2025, the pre-construction costs will be £50/kW, and the construction costs will be £400/kW, meaning £450,000/MW for installation [6.4]. This is a result of a significant decrease in cost in recent years, with the cost decreasing faster than predicted [6.12].

6.2 Hydrogen Production Components

Now that the source of power is finalised, Section 6.2 aims to examine the electrolyser and battery to be used in the hydrogen production system. In this subsection, different electrolyser and battery technologies will be explored before justifying the specific choices and parameters for these components.

6.2.1 Electrolyser Type

In order to determine a suitable electrolyser model to produce green hydrogen, comparisons will be made between the two most commercially viable electrolyser types: alkaline and PEM, as mentioned in Section 2.1.3.

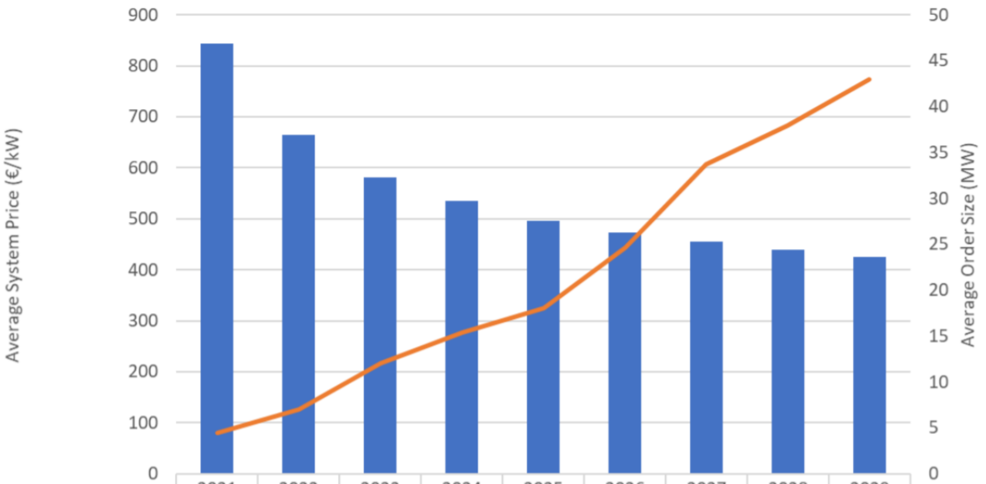
Characteristic/Electrolyser Type	Alkaline	PEM
System Energy Consumption	4.5 - 6.6 $\mathrm{kWh_{el}m_{H_2}^{-3}}$	4.2 - 6.6 $\mathrm{kWh_{el}m_{H_2}^{-3}}$
Start-up Time	30 - 60 min	5 - 15 min
System Response Time	Seconds	Milliseconds
Min. Power Load	20 - 40%	3 - 10%
Lifetime	Long	Short
Technology Maturity	Mature	Commercial
Capital Cost	Low	Medium (but decreasing fast)

< Table 6.1: Technical Comparison between Alkaline and PEM Electrolysers [2.13, 6.13, 6.14] >

There are many literature pieces which compare the general technical specifications and costs of alkaline and PEM electrolysers [2.13, 6.13, 6.14, 6.15, 6.16]. The relevant specifications are compiled in Table 6.1 above. For values with different ranges in different sources, the smallest number range is recorded in Table 6.1 to ensure that its values are included in each literature source's range. For example, for start-up time, alkaline electrolysers are estimated to take 20 - 60+ min [6.13], >30 min [2.13], or <60 min [6.14] depending on the literature source, thus 30 - 60 min is the range which is included by all these sources, and will be recorded in the table above.

For lifetime and capital cost, there is no common range between the values provided in each source. Depending on the literature source, alkaline electrolysers have a lifetime of 20 - 30 years [2.13, 6.13], 10 years [6.16] or 60,000 - 90,000 hours [6.14] and PEM electrolysers last for 10 - 20 years [2.13], 10 - 30 years [6.13], 3 - 4 years [6.16], or 20,000 - 60,000 hours [6.14]. Despite the widely varying ranges, it is generally agreed that alkaline electrolysers have longer operating lifetimes than their PEM counterparts, at about 1.5 - 2 times the duration. For capital costs, alkaline electrolysers cost £870/kW - £1044/kW [6.14] or £547 - £792 (units are not specified) [6.13] while PEM electrolysers cost £1618/kW - £2018/kW [6.14] or £864 - £1397 [6.13]. Once again, while the sources do not agree with the absolute values of cost, they both substantiate the fact that PEM electrolysers cost up to 2 times the price of alkaline electrolysers.

While PEM electrolysers currently still lag behind alkaline in terms of lifetime and costs, they are catching up quickly in both areas. According to the 2017 research paper by Schmidt [6.15], the median PEM electrolyser will have a lifetime of 41,000 - 60,000 hours by 2020, with alkaline electrolysers improving minimally. By 2030, PEM electrolysers will have similar lifetimes to their alkaline counterparts.



	2021	2022	2023	2024	2025	2026	2027	2028	2029
System Price	844	664	581	536	496	473	455	440	424
Average Order	5	7	12	15	18	25	34	38	43

< Fig. 6.5: Predicted Average system price and Average Order Size of ITM Power PEM Electrolysers from 2021 to 2029 [6.15] >

In terms of pricing, ITM Power, a British manufacturer of PEM electrolysers is well on track to producing electrolysers at a price comparable to alkaline electrolysers. This year, ITM Power predicts to produce PEM electrolysers at just €884/kW or £769/kW . This is expected to fall over the next decade, as the average order size of electrolysers increases from under 5 MW to nearly 45 MW by 2029.

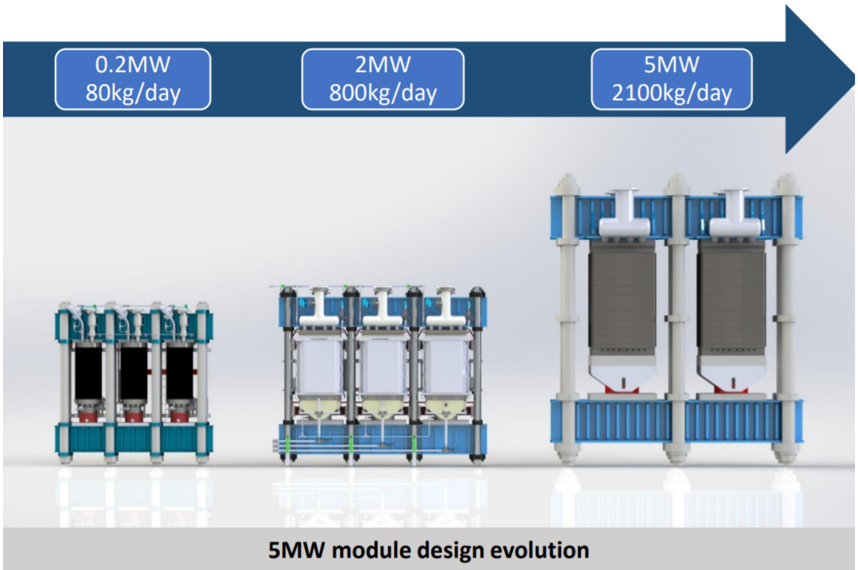
With similar energy consumption per amount of hydrogen produced, PEM electrolysers are superior to alkaline electrolysers in terms of load flexibility: it can start operation quickly, handle low power production and respond to power changes quickly. These features are especially useful for electrolysers powered by solar energy which can change quickly throughout the day and is intermittent. Not only are PEM electrolysers technically superior, it is also fortunate that their costs have recently been driven down to become competitive with alkaline electrolysers. This makes PEM electrolysers the clear choice for green hydrogen production at Oxfordshire.

6.2.2 Electrolyser Model

Now that PEM electrolysers have been selected to be the desired electrolyser type, the specific choice of electrolyser supplier and model will now be decided.

While there are many companies globally which manufacture PEM electrolysers, such as NEL Hydrogen, Siemens and Hydrogenics, only ITM Power has provided public data on their electrolyser capital costs (from Fig. 6.5 above), which will be essential for the financial analysis later. It is also reasonable to assume that ITM Power's prices are competitive, given that their prices are even cheaper than price estimates for alkaline electrolysers mentioned in Section 6.2.1. Additionally, with an upcoming electrolyser factory based in the UK at Bessemer Park, Sheffield [6.15], ITM Power will be able to supply PEM electrolysers to Oxford with minimal transportation costs and international trade taxation. As such, electrolysers from ITM Power will be used to produce fuel to power the Green Hydrogen Mobility Project.

Specifically, ITM Power's upcoming 5MW stack module will be used. These are currently being developed for the Gigastack project (large scale Humber-based hydrogen generation project using PEM electrolyser powered by wind energy) and are expected to be ready by mid-2021 [6.17]. Each 5 MW stack module can produce up to 2,100 kg of hydrogen per day [6.15] which is equivalent to a production rate of 0.00486 kg of hydrogen produced per second per MW of electricity. ITM Power has also advertised their electrolysers to require water of "drinking quality", thus there will be no additional cost of water purification. It will be assumed that the weight of water consumed is 9 times the weight of hydrogen produced [6.18]. To estimate the cost of the electrolyser, the predicted system price in 2025, which is ~£432/kW, translates to £2,160,000 for each 5MW stack. The electrolyser's dynamic power range will be set at 10 - 100% of maximum power, based on a conservative estimate of PEM electrolyser's minimum power load (Table 5.1).



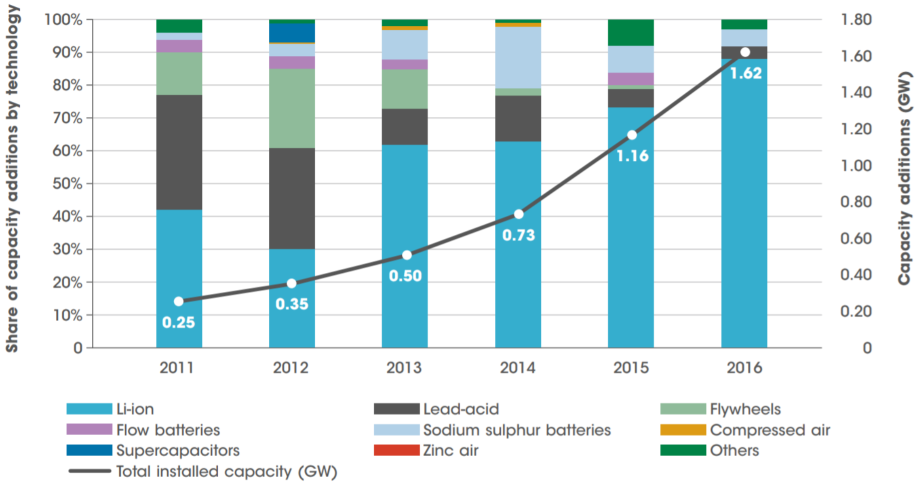
< Fig. 6.6: Evolution of ITM Power Electrolyser Stack Design [6.15] >

6.2.3 Battery Technology

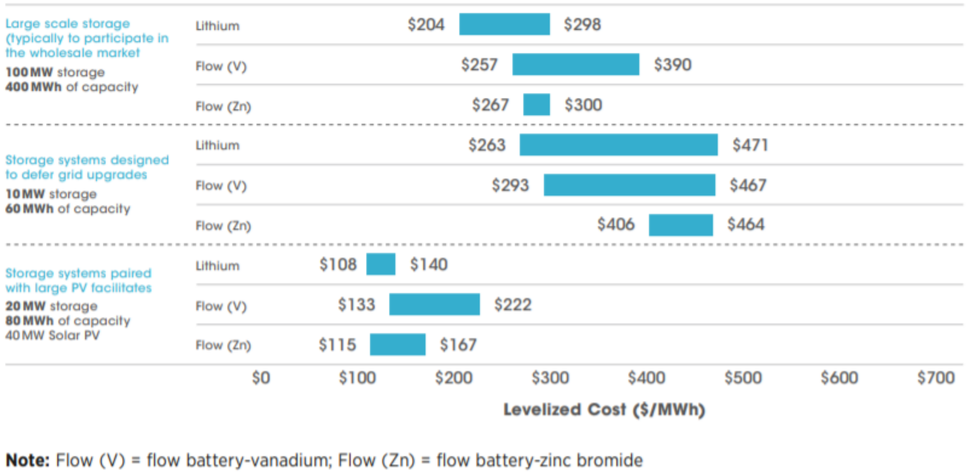
Prevalence and cost of Li-ion

Accounting for nearly 90% of global large-scale battery storage additions in 2017 [6.19] and 95% of deployed grid-scale battery systems in the US [6.20], lithium-ion (Li-ion) batteries are the dominant technology for grid-scale energy storage. This market dominance is driven by the declining costs of Li-ion technology which is, in turn, fuelled by the growing demand and production of Li-ion batteries for electric vehicles [6.19] and consumer electronics [6.22].

The versatility of Li-ion batteries ensure that the cost reductions are also felt in the energy storage market, where Li-ion technology offers the cheapest solutions for a wide range of grid-scale energy storage solutions compared to alternatives such as vanadium-based flow batteries and zinc-based flow batteries. Given Li-ion batteries' low cost and applicability as energy storage for solar energy, it is the ideal technology for the smart electrolyser-battery system.



< Fig. 6.7: Share of difference battery technologies in annual battery storage capacity additions globally [6.19] >



< Fig. 6.8: Comparison of levelised cost of storage of different battery technologies for 3 different applications (USD/MWh) [6.19] >

Battery Parameters

Batteries have two main design parameters: Power capacity and Energy Capacity. These parameters will differ based on application. Power capacity refers to the maximum rate of electricity charge or discharge of the battery and is usually expressed in kilowatts (kW) or megawatts (MW). Energy capacity refers to the maximum amount of energy which can be stored in a battery and is usually expressed in kilowatt-hours (kWh) or megawatt-hours (MWh).

According to the Innovation Landscape Brief on Utility Scale Batteries by IRENA, “storage systems paired with large PV systems" with 20 MW power capacity and 80 MWh energy capacity cost £77.76 - £100.80 per MWh of storage [6.19]. Thus, for the purposes of this project, battery’s power-energy capacity ratio will be fixed at 20:80 = 1:4 and battery costs will be the average of the cost range at £89.28/MWh. Thus, the sole design parameter for the battery will be its energy capacity in MWh. From here on, battery energy capacity will be referred to simply as battery capacity.

6.3 Smart Electrolyser-Battery System

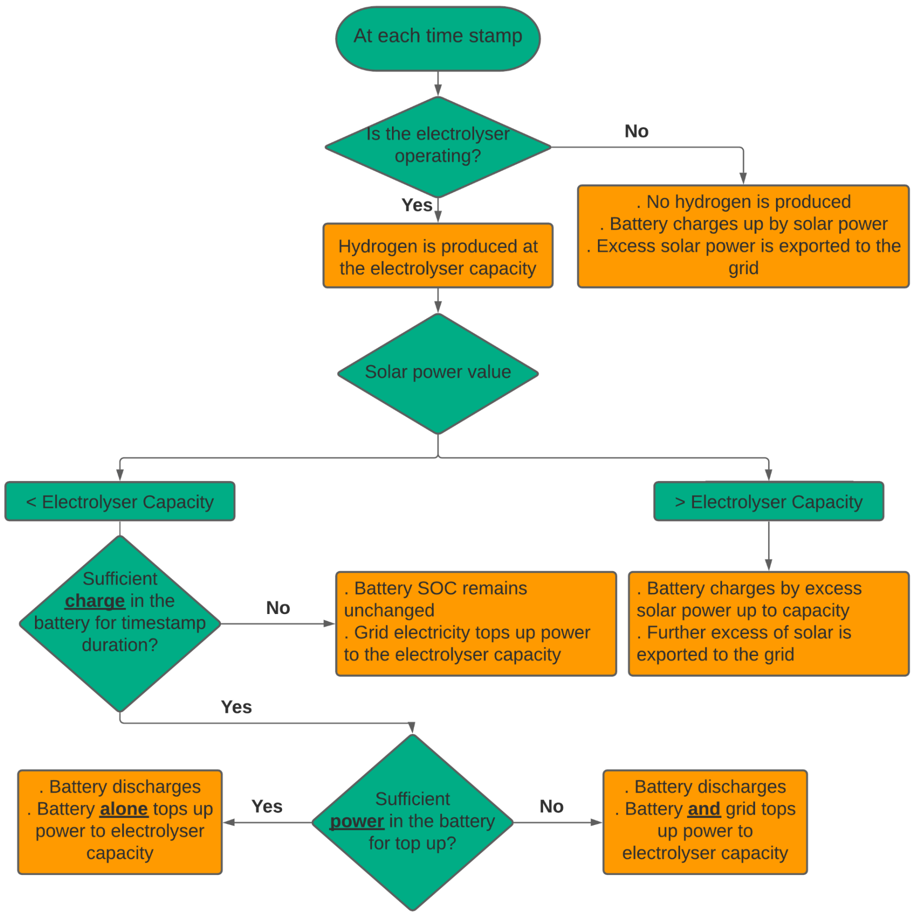
6.3.1 System Operations

In order to produce green hydrogen efficiently using locally generated solar power, the smart electrolyser-battery system is proposed. The system comprises three main components, which need to be designed: solar farm, electrolyser and battery. The electrolyser will run at its maximum power during its operating hours since varying the electrolyser's operating power will reduce its lifetime. The electrolyser's source of power will vary between combinations of solar power, battery and the grid based on three indicators: operating hours, solar power available and battery state of charge (SOC).

Operating hours will be fixed, for the purpose of this report, at 0700 - 1700 from 1 January to 15 April and 1 September to 31 December, and 0500 - 1900 from 16 April to 31 August; all times are in GMT. These times are chosen for convenient operation and to coincide with daylight hours as much as possible. They can be further tuned to changing needs in the future. The operation flowchart of the smart system can be seen below in Fig. 6.9. The smart system monitors the three indicators mentioned earlier in real-time using on-site sensors. which will be connected to each other via a cloud computing service such as Amazon Web Services. The combined indicators then determines one of the output decisions (shown in orange) based on the decision flowchart, shown in Fig. 6.9. Ideally, timestamps are as short as possible so decisions can be made based on the most up-to-date information.

6.3.2 System Parameter Design

In order to simulate hydrogen production from the smart electrolyser-battery system, a Python simulation model was created to calculate annual OPEX and CAPEX based on prices shown in Table 6.2 below. The pseudocode for the model is seen in Fig. 6.10. Note that solar power sale revenue is negative as it reduces OPEX.



< Fig. 6.9: Operation Flowchart of Smart Electrolyser-Battery System >

Operating Expenditure (OPEX)	Variable Cost	Annual Fixed Cost
Water	£1.457 m^{-3} [6.23]	£17.84 [6.23]
Grid Electricity	13.64p kWh^{-1} [6.24]	£100.01 [6.24]
Solar Farm Operation and Maintenance	-	£6,700 $\mathrm{MW}_{\mathrm{capacity}}^{-1}$ [6.4]
Revenue from sale of excess solar power	-5.57p kWh^{-1} [6.25]	-
Capital Expenditure (CAPEX)		
Solar Farm	£450,000 $\mathrm{MW}_{\mathrm{capacity}}^{-1}$ [6.4]	
Electrolyser	£432,000 $\mathrm{MW}_{\mathrm{max\ power}}^{-1}$ [6.15]	
Battery	£89.28 MWh^{-1} [6.19]	

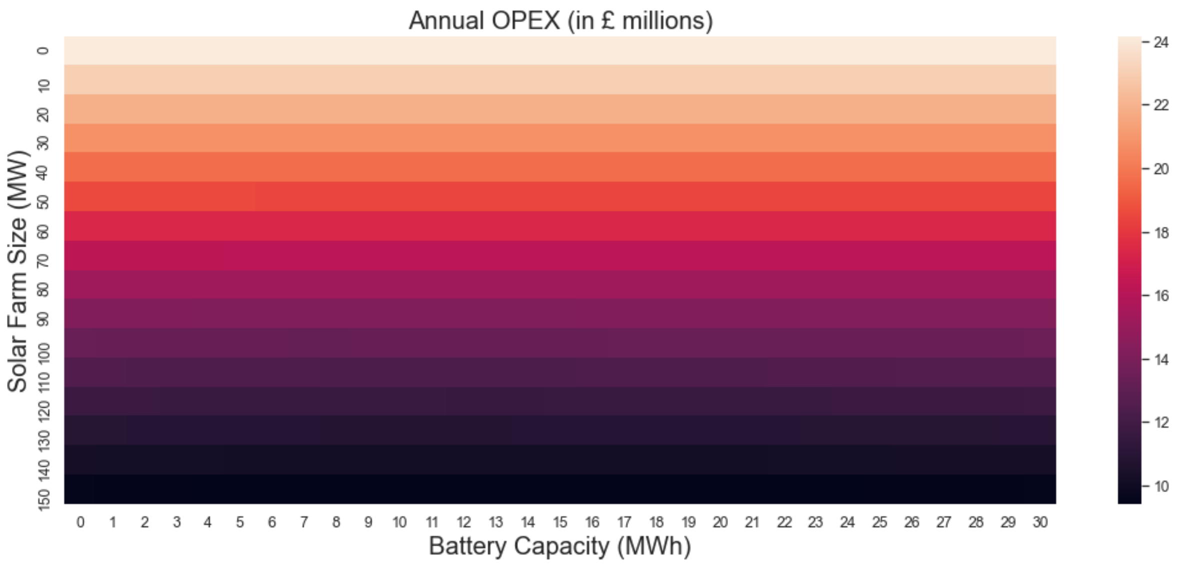
< Table 6.2: Variable Unit Cost and Annual Fixed Cost of components of smart electrolyser-battery system >

Given the operating hours and a minimum annual hydrogen demand of 2,933,738 kg (see Section 4.3), a 42 MW electrolyser (comprising eight 5 MW stacks and one 2 MW stack) will be used to produce ~ 3,093,643 kg of hydrogen annually. This is enough to cover both the minimum and emergency demand, which totals to 3,043,738 kg. There are two system component parameters which are to be designed: solar farm size and battery energy capacity. The specific combination of parameters which gives the lowest expenditures will be chosen for the system.

```
Initialise
   Input solar irradiation data
   Declare solar farm size, electrolyser power and battery energy capacity
   Declare operating hours
   Initialise zero arrays for hydrogen produced, battery SOC and solar power exported to grid
Main
   for each timestamp
      if timestamp is within operating hours
      hydrogen produced based on max power
         if solar power exceeds electrolyser power
             battery charges at power capacity or excess solar power, whichever is smaller
            if battery charges at power capacity
               solar power exported to grid = solar power - battery power - electrolyser power
               battery SOC increases based on power capacity, capped at energy capacity
             if battery was already full in previous time stamp
               solar power exported to grid = solar power - electrolyser power
               battery SOC remains unchanged
          else
             additional power required = electrolyser power - solar power
             if additional power required > battery power capacity
                if battery has sufficient charge for the timestamp duration
                   battery SOC decreases based on discharge at power capacity
                   grid electricity demand = additional power required - battery power capacity
                else
                    battery SOC is set at SOC of previous timestamp
             elseif additional power required < battery power capacity
                if battery has sufficient charge for the timestamp duration
                    battery SOC decreases based on discharge at power required
                else
                    battery SOC is set at SOC of previous timestamp
      if timestamp is outside operating hours
         no hydrogen produced
          if battery was already full in previous time stamp
             excess solar power exported to grid = solar power
             battery SOC remains unchanged
          else
             if solar power > battery power capacity
                excess solar power exported to grid = solar power - battery power capacity
                battery SOC increases based on charging at power capacity, capped at energy capacity
             else
                battery SOC increases based on charging at solar power, capped at energy capacity
Results
   Calculate total hydrogen produced by summing hydrogen produced at each timestamp
   Calculate OPEX and CAPEX
End
```

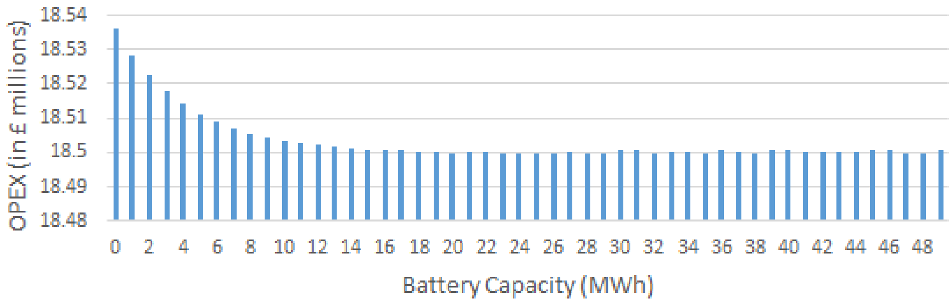
< Fig. 6.10: Pseudocode for Smart Electrolyser-Battery System simulation model >

To determine the desired parameters, the OPEX and CAPEX were recorded for every combination of system component parameters where solar farm size is from 0 to 50 MW, in intervals of 1 MW and battery capacity is from 0 to 49 MWh, in intervals of 1 MWh. Solar farm size was first tested up to 50 MW as the upcoming South Oxfordshire Solar Farm is taken to be a feasible standard size of solar farm in Oxfordshire. From the results of this first experiment, a 42 MW electrolyser powered by a 50 MW solar farm and 29 MWh battery would produce the lowest OPEX of £18,499,549. However, this is financially unattractive as this is much more expensive than the current annual diesel spending of £12,281,802 (this value will be explained in Section 8). Thus, in order to achieve lower OPEX, more solar farms of sizes up to 50 MW can be built to power affordable green gas production. As such, solar farm sizes of up to 100 MW and up to 150 MW, with battery sizes up to 30 MWh, were trialled to finally obtain an annual OPEX of £9,402,416. The change of OPEX in response to solar farm capacity and battery capacity can be seen in Fig. 6.11. It can be seen that annual OPEX decreases sharply with increasing solar farm capacity, with minimal impact from changing battery capacity. To see the impact from changing battery capacity, Fig. 6.12 plots OPEX against battery capacity for solar farms of three sizes, where it can be seen that OPEX barely decreases beyond ~20 MWh for a 50 MW solar farm and is minimised at 8 MWh and 13 MWh for 100 MW and 150 MW solar farms respectively. This also explains why battery sizes were only trialled up to 49 MWh and 29 MWh since battery sizes above these values did not lower OPEX further.

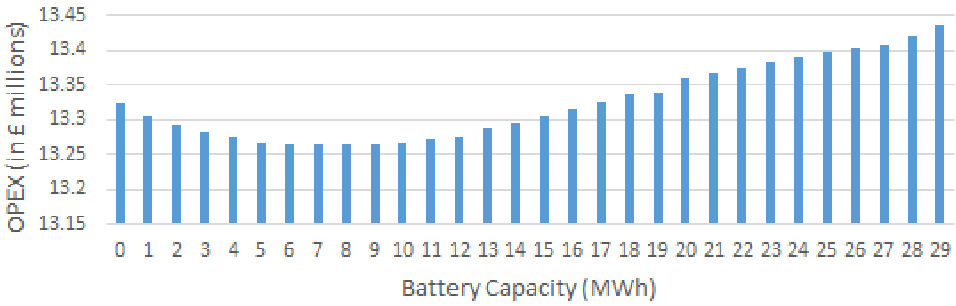


< Fig. 6.11: Change of Annual Operating Expenditure in response to changing solar farm size and battery capacity >

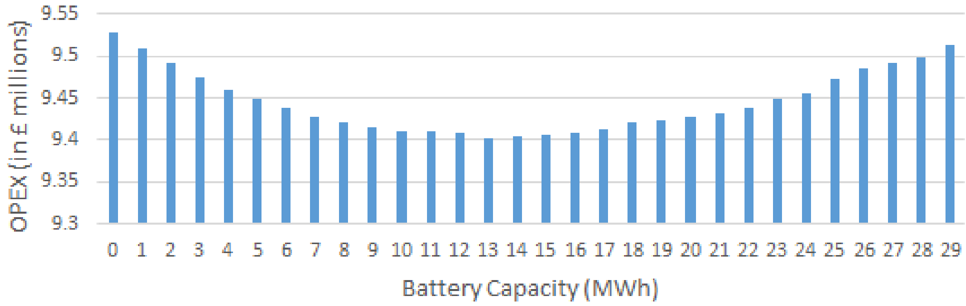
For comparison purposes, a standalone electrolyser is also trialled. From Table 6.3, it can be seen that the savings in OPEX can break-even the additional capital investments of solar farm, electrolyser and battery in less than 5 years, regardless of the solar farm size. This timeframe is well below a lifetime of 35 years for the solar farm [6.4] and 10 years for the electrolyser [2.13, 6.13]. This means that the savings from smart solar powered electrolyser-battery system will break-even its capital costs well before any major component needs replacement due to the end of their lifetime (cost of battery replacement will be assumed to be insignificant since even the largest 29 MWh battery tested costs only about £2,589). This not only financially justifies investing in the smart electrolyser-battery system, it also means that OPEX minimisation is equivalent to minimising the total cost (including CAPEX and OPEX) over the system's lifetime.



(a)



(b)



(c)

< Fig. 6.12: OPEX vs Battery capacity for (a) 50 MW solar farm (b) 100 MW solar farm (c) 150 MW solar farm >

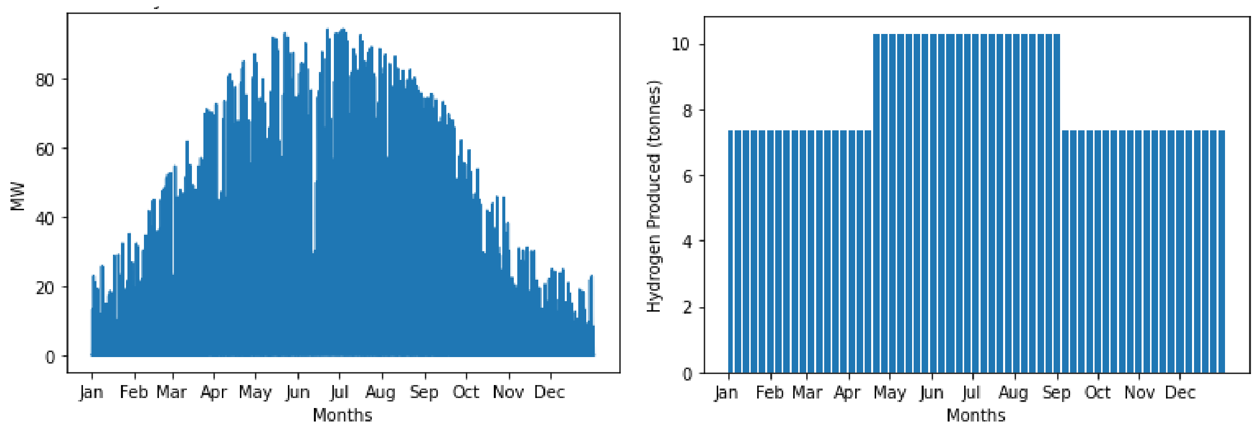
Solar Farm Size (MW)	0	50	100	150
Battery Energy Capacity (MWh)	0	29	8	13
CAPEX	£18,144,000	£40,646,589	£63,144,714	£85,645,161
Annual OPEX	£24,158,933	£18,499,549	£13,263,094	£9,402,416
Breakeven Period for additional CAPEX (years)	-	3.97	4.13	4.57

< Table 6.3 : Financial information and system component parameters of lowest OPEX options >

From Table 6.3, it can be generalised that there is a tradeoff between initial CAPEX and annual OPEX. Thus, a main factor to consider when deciding the ideal system parameters would be the capital available, including assets and loans. Assuming unlimited capital, one might invest in a solar project large enough for the electrolyser to be completely solar-powered, minimising spending on grid electricity within OPEX. However, it is worth noting that there are other important decision factors such as legal considerations of land usage in Oxfordshire for solar project development (as mentioned in Section 5) and diminishing rate of returns from additional solar power investments (notice the trend of increasing break-even periods for larger solar farms in Table 6.3). Given these limitations, further testing for larger solar farms will not be considered and a 150 MW solar farm, 42 MW electrolyser and 13 MWh battery system will be analysed for the rest of this report.

6.3.3 System Performance Results

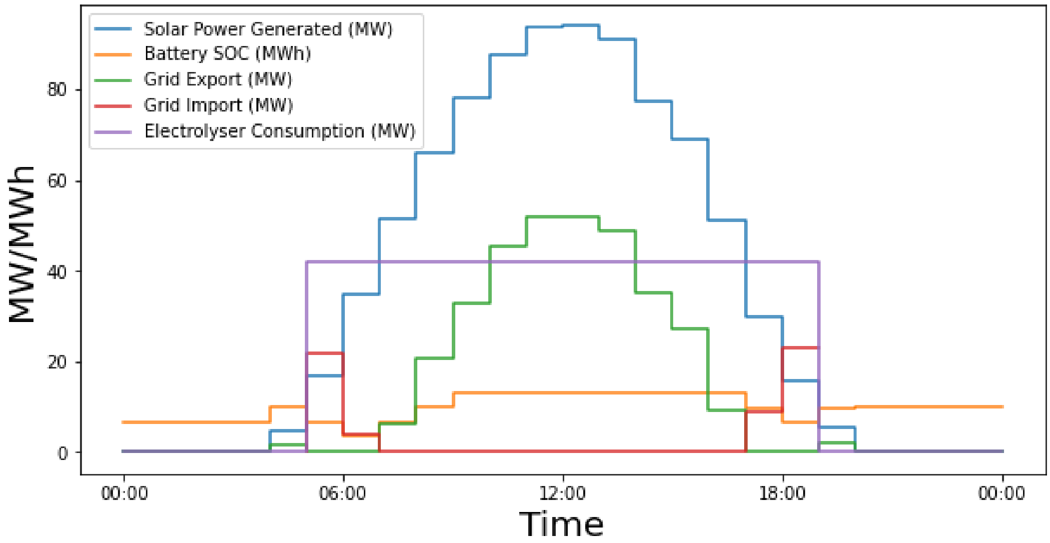
With system component parameters specified and using the irradiation data seen in Fig. 6.3, solar power generation and daily hydrogen produced are plotted in Fig. 6.13. It can be observed that solar power generation is expectedly linked closely to solar irradiation (see Fig. 6.3) and daily hydrogen production is constant at 10.290 tonnes in summer and 7.350 tonnes in winter. The constant production values are due to fixed operating hours.



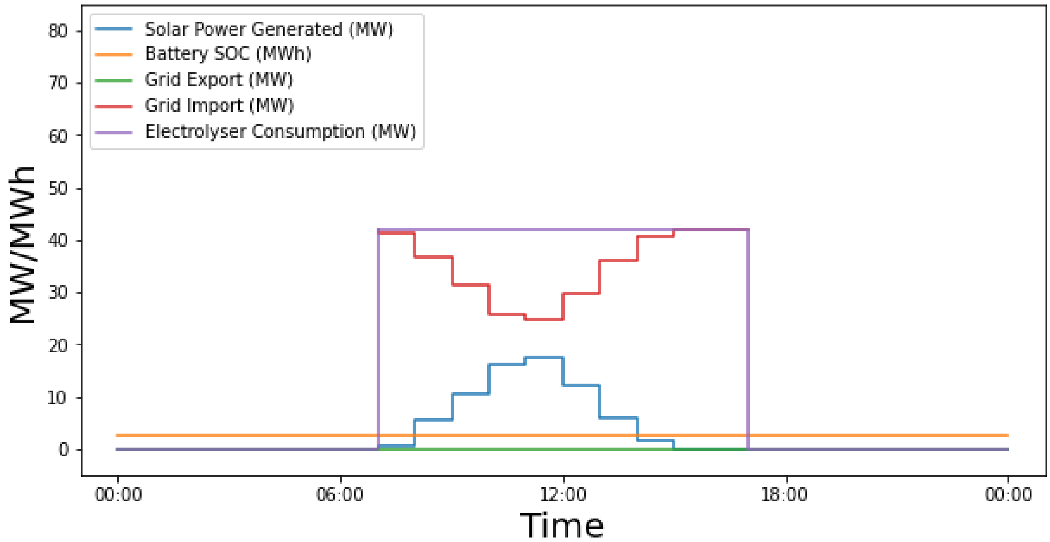
(a) (b)

< Fig. 6.13: (a) Hourly Power Generation from a 150 MW solar farm based in Oxford (b) Daily Hydrogen Produced >

To provide a sense of energy and power balance between the system components, the status of solar power generation, battery SOC, grid import/export and electrolyser power consumption on two days are plotted in Fig. 6.14. The two days are the 21-June and 22-Dec, of which the solar irradiation plots are seen in Fig. 6.4. Thus, Fig. 6.14 shows the two extremes of solar overgeneration and undergeneration. In summer, electricity is imported from the grid and obtained from the battery in early morning and evening to compensate for the reduced solar power. However, much solar power is exported to the grid throughout the day. In winter, the electrolyser is heavily reliant on the grid, with some support from solar power during the day. The battery remains a constant state of low charge as it does not have enough energy to discharge for an hour (see Fig. 6.9), which is the time resolution of the irradiation data. If a dataset of higher resolution was used, the battery would be discharged till empty. The low time resolution also explains the staircase plot rather than a smooth curve.



(a)



(b)

< Fig. 6.14: Status of solar power generation, battery SOC, solar power exports, grid power consumption and electrolyser power consumption based on solar irradiation on (a) 21-Jun- 2019 and (b) 22-Dec-2019 >

7 Hydrogen storage and distribution

The next part of the proposed system is storing the hydrogen produced by the electrolyser, and distributing it to refuelling sites. This section will explore the design principles of the proposed hydrogen storage and distribution solution, as well as presenting the details of these system components.

7.1 Hydrogen storage

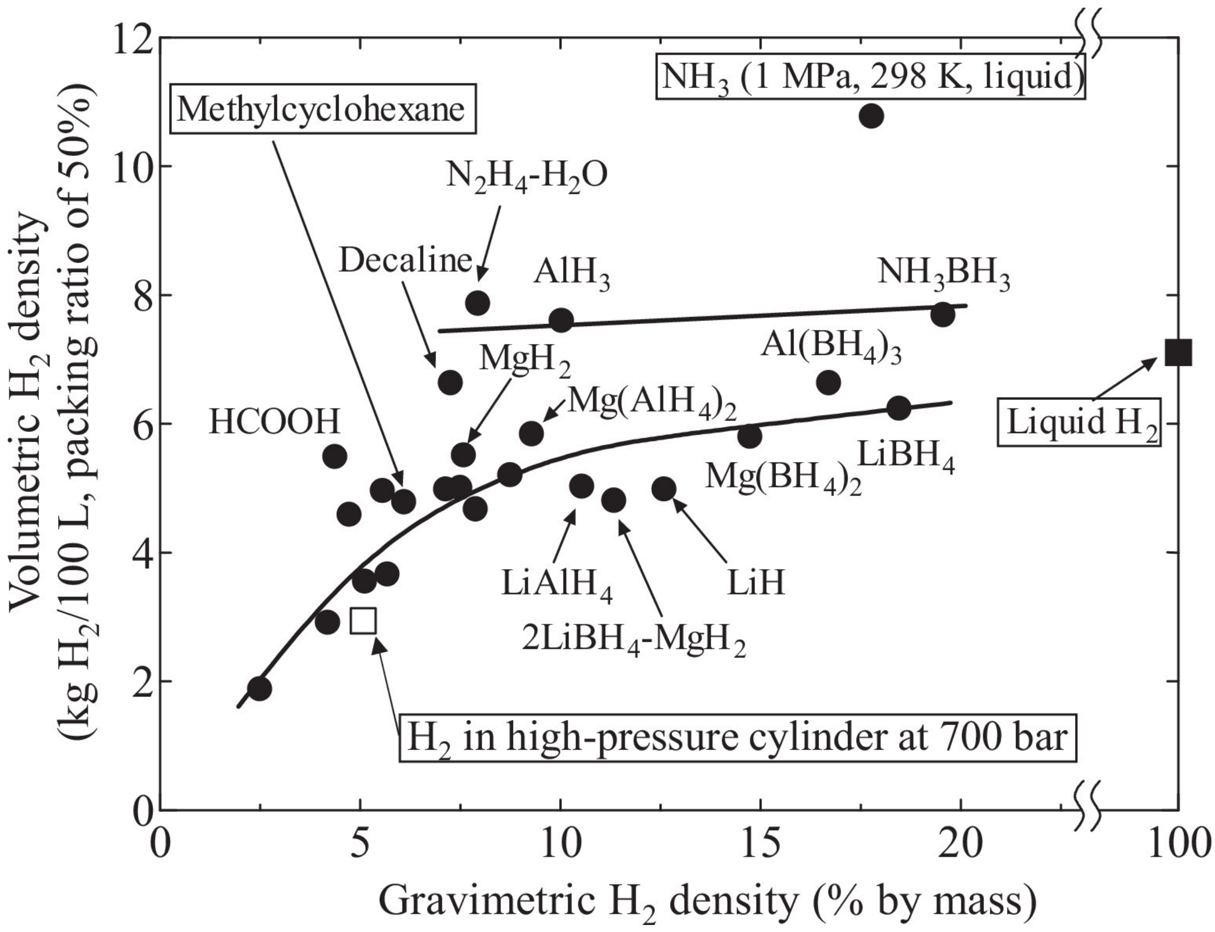
In the proposed system, the seasonal nature of the production of hydrogen means that for around half the year, more hydrogen will be produced than will be used, and for the other half more hydrogen will be required than will be produced. This means that the system requires a significant capacity of hydrogen storage, so that the surplus from the summer months can balance out the deficit in the winter months.

7.1.1 Evaluation of different storage methods

Hydrogen storage, as discussed in Section 2, can be divided into three main types: gaseous hydrogen storage, liquid hydrogen storage, and hydrogen carrier storage. Fig 7.1 shows how the density of hydrogen varies with different methods of storage.

There are two main methods of storing hydrogen as a gas: in pressurised cylinders and in underground reservoirs, such as salt caverns or depleted oil wells. Due to the lack of salt caverns and oil wells in Oxfordshire, this was ruled out as an option. Hydrogen has the lowest atomic weight of any element, and therefore has very low density. The density of hydrogen gas can be taken as 0.090 kg m^{-3} [2.1]. As a result of this, to store any significant amount of hydrogen in gaseous form in a reasonable amount of space requires pressurised storage. Compressed hydrogen gas can be stored in cylinders. Compressed gas can be stored at various pressures, usually 180 bar or above.

Hydrogen can also be stored in liquefied form. During liquefaction, the hydrogen must be cooled to −253°C, as the boiling point of hydrogen at atmospheric pressure is −252.8°C [2.20]. To remain at these temperatures, the hydrogen has to be stored in cryogenically insulated tanks. The equivalent



< Fig 7.1 : Gravimetric and volumetric H_2 density of hydrogen carriers [2.19] >

of around 30% of the energy content of the hydrogen is required to cool the hydrogen to temperatures as low as this [7.1]. In addition, boil-off becomes a problem when storing hydrogen as a liquid. The temperature of the stored liquid inevitably rises, although slowed by the cryogenic insulation. This leads to some of the hydrogen becoming a gas, which raises the pressure in the tank. Therefore, the tank needs to release this gas, to keep the pressure low. This leads to an inevitable loss of hydrogen. The main advantage of storing hydrogen as a liquid is that it is very compact. The density of hydrogen in liquid state can be taken as 70.8 kg m^{-3} [7.2]. This is about 787 times denser than hydrogen gas, reducing the required storage space by a huge amount. Hydrogen can also be delivered in liquid tanks. This is particularly advantageous over long distances, at which point the benefits of the much higher density outweigh the disadvantages of the hydrogen losses and extra energy requirements for liquefaction.

Metal hydrides are a solid form of hydrogen carrier, of which magnesium and aluminium hydrides are examples. Metal hydrides are one of the safest ways to store hydrogen, as they take the form of stable solids. However, breaking the bonds to release the hydrogen is a slow and energy-intensive process [2.16], which can hinder a system in which hydrogen is required consistently in large quantities.

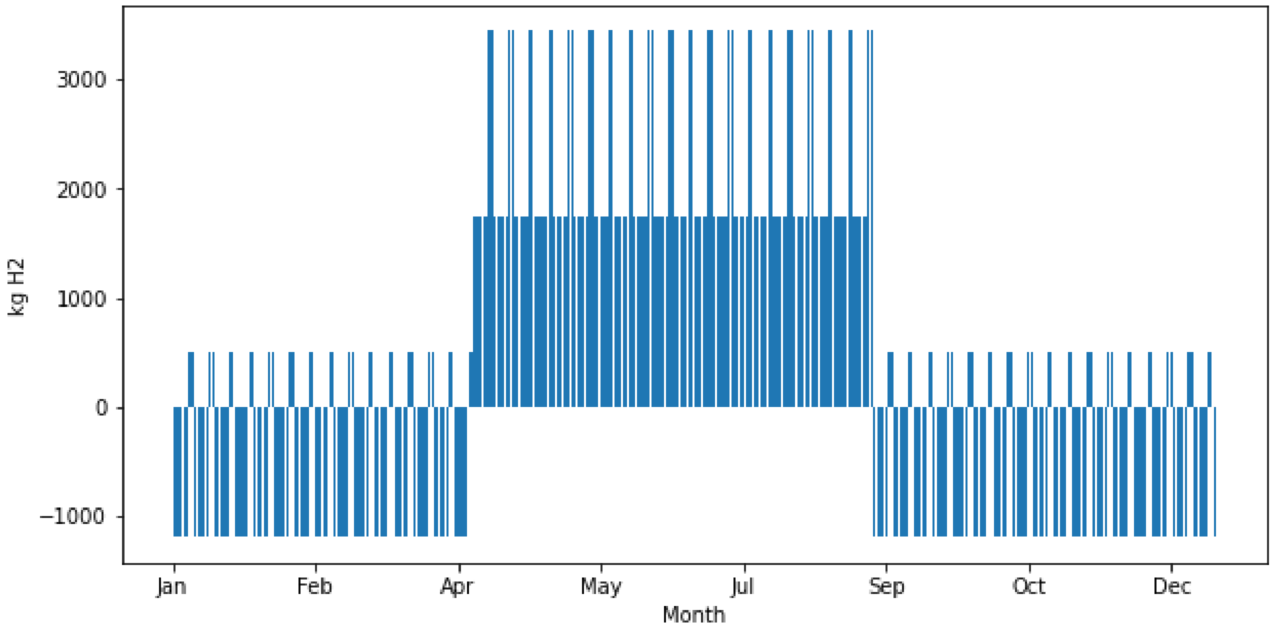
Liquid organic hydrogen carriers (or LOHCs) are examples of the second type of hydrogen carrier. The most viable example is dibenzyltoluene ($C_{21}H_2O$) [7.3], which is currently used as a heat transfer oil. Since the carbon involved can be recycled, this would still meet the net zero condition. LOHCs are most useful for hydrogen which will be travelling long distances, however they are not particularly cost effective for shorter range supply, as the system would require [7.3].

The final storage option considered was ammonia. Ammonia already plays a large part in the UK, especially in the agricultural industry, so there is broad infrastructure to connect to. In addition to this, ammonia has a 45% higher hydrogen density than liquid hydrogen [7.1]. Ammonia can be stored in very mild conditions as shown in Fig. 7.1. The high hydrogen density and existing infrastructure mean that ammonia is one of the cheapest ways to store hydrogen.

7.1.2 Storage requirements

From the route modelling in Section 4, the daily requirement of hydrogen is 8,548.2 kg on a weekday, and 6,838.6 kg on a weekend. As discussed in Section 6, the production of hydrogen is produced at two rates depending on the time of year. From 1st September to 15th April, when there are fewer sunlight hours, the operating hours of the electrolyser (which track solar energy production) are shorter, and therefore less hydrogen is produced per day. During this period of the year, the weekly production is lower than the demand. For the remainder of the year (16th April to 31st August), the operating hours are longer, and the production exceeds the demand. Fig. 7.2 shows the difference between production and demand throughout the year.

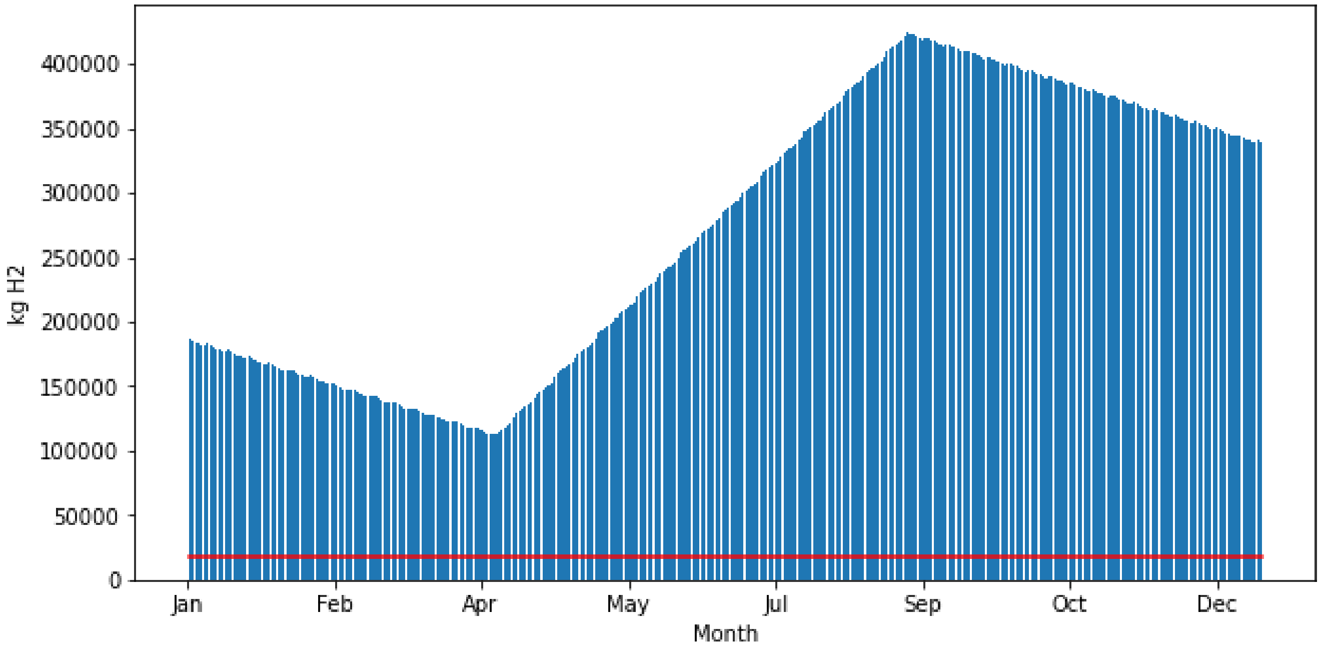
Note that the demand during the weekend is lower than the weekdays, hence the spikes. During the over-production period, the system must be able to store the excess, so that it can balance out the insufficiency of production for the rest of the year.



< Fig 7.2 : Difference between hydrogen production and demand throughout the year >

Fig. 7.3 shows the total mass of hydrogen stored on each day of the year. As large quantities of hydrogen (up to 425,116 kg at the end of the over-production phase) will have to be stored to last through the lower production phase of the year, a much more compact form of storage than compressed hydrogen gas is needed. From previous evaluations, it was clear that the simplest, and most compact, alternative method of storage is in the form of ammonia. During the over-production phase, the excess hydrogen each day will be converted to ammonia in a synthesis reactor. During the period of the year for which production is lacking, the required amount of hydrogen will be provided by cracking ammonia on site.

The depots themselves will require the hydrogen in gaseous form, ready for refuelling of the FCEVs. This means that the main method of distribution will be in gaseous form, which requires that there be at least a day's supply of hydrogen stored as compressed gas. In order to account for possible complications, the hydrogen demand for two weekdays will be stored as compressed gas, ready for distribution. This amounts to just under 17,100 kg of hydrogen, which is indicated by the red line on Fig 7.3. This will be stored in pressurised cylinders, in an open, well-ventilated space.



< Fig 7.3 : Amount of hydrogen in storage on each day of the year. Hydrogen stored as compressed gas up to red line, stored as ammonia from red line upward >

As discussed in Section 5, special measures must be taken for the storage of a hazardous gas such as hydrogen in quantities of more than 5 tonnes [5.12]. Planning for an event in which the hydrogen supply is halted, the system will contain a minimum of two weeks' demand of hydrogen to allow for time to fix a potential problem in the supply chain. This means that on top of the 17,100 kg as compressed gas, a further 95,380 kg of hydrogen will be stored as ammonia, so that at the lowest point in the year, there is enough hydrogen in storage to last for two weeks of normal operation. For the cracking of 95,380 kg hydrogen from ammonia in under 14 days, the required cracking capacity is 6,800 kg of hydrogen per day.

During the over-production period, approximately 15,680 kg of excess hydrogen will be produced each week. This is the amount that will be converted to ammonia weekly, which will be done at an external ammonia synthesis plant. For this purpose, the project could connect to the plant at Ince, which can produce just under 1,000 tonnes of ammonia per day [7.4], or the plant at Billingham, which can synthesise up to 1,500 tonnes of ammonia per day [7.4]. Another option would be to connect to a number of separate synthesis plants which operate more locally, in order to reduce the distance that the hydrogen would have to travel.

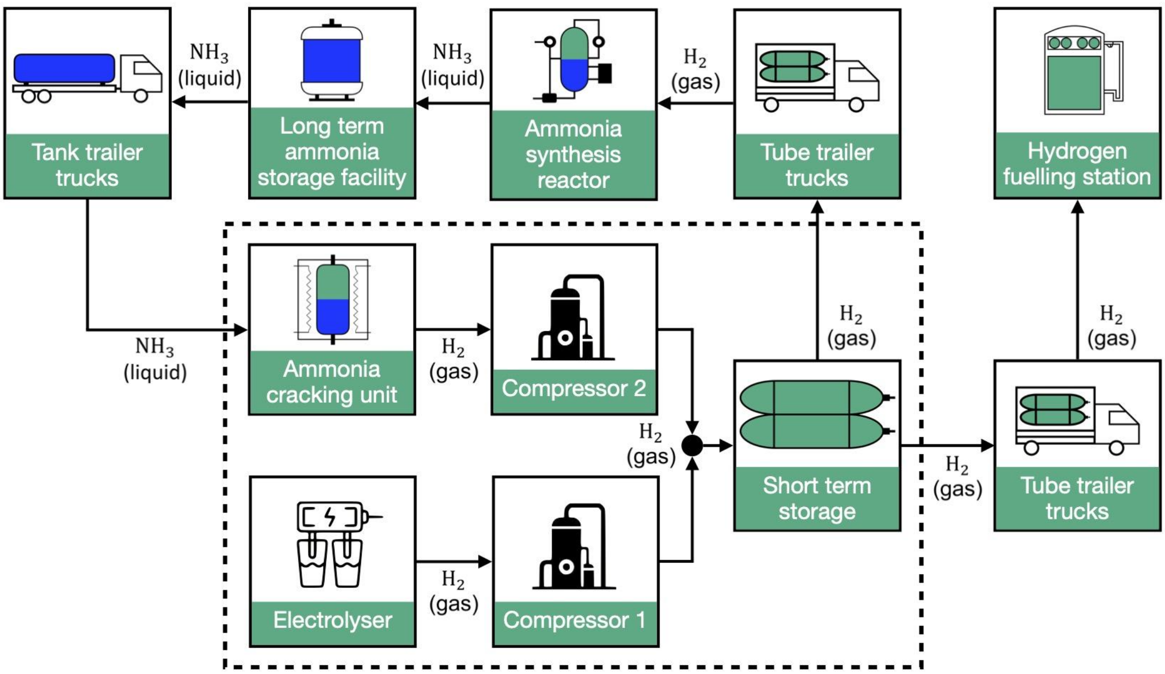
During the under-production phase, up to 1,400 kg hydrogen will be required in excess of what is being produced by the electrolyser per day. This will be provided by cracking the required amount of ammonia from the long-term storage. As the ammonia will need to be cracked to fit the daily demand, it will be necessary to crack on site, rather than to link to an external ammonia cracker. The capital cost of an ammonia cracking facility can be taken as $405,000 (£291,600) per tonne of hydrogen production capacity per day [7.5]. As mentioned earlier, the cracking facility will need to be able to crack up to 6,800 kg of hydrogen per day. This would cost approximately £1,955,340 to set up. The energy required to crack ammonia can be taken as 96.6 kJ mol^{-1} of hydrogen [2.28], which equates to 13.42 kWh kg^{-1} of hydrogen. This gives the yearly required running cost as £293,519 [7.6], assuming normal running.

As discussed in Section 6, the system produces a yearly excess of 152,413.6 kg of hydrogen. Fig 7.3 shows the excess as the difference between the total hydrogen in storage at the end of the year and total hydrogen in storage at the beginning of the year. This could be sold as ammonia or hydrogen to boost profits from the system. The market price for hydrogen is currently £10 - £15 per kg [7.7], meaning that the yearly excess could boost profits by upwards of £1.5 million.

7.2 Hydrogen distribution

Now that short term and long term storage options have been explored, a hydrogen distribution system will be designed. A general delivery strategy from the hydrogen production plant to the refuelling stations will first be explored. Secondly, the optimal location for the hydrogen production plant will be considered. Finally, a detailed tube trailer and truck solution will be discussed.

Hydrogen will be distributed in gaseous form at 180 bar in cylinders [7.8]. These cylinders are carried in tube trailers [7.8] which are transported by trucks. Fig. 7.4 below illustrates the strategy proposed for distributing hydrogen from the hydrogen production plant to the hydrogen fuelling stations and long term ammonia storage facilities. The dotted rectangle represents the hydrogen production plant perimeter consisting of an electrolyser, an ammonia cracking unit, a short term hydrogen storage facility and compressors.



< Fig. 7.4: Distribution schematic adapted from [7.9, 7.10] and Fig. 2.6 >

As described in Section 7.1.2, a maximum of around 8,550 kg of hydrogen will be required by all Oxford bus fleets in a single day. The tube trailers will have a capacity of 280 kg of hydrogen each [7.8]. This results in around 32 tube trailer deliveries per day to fuel all 399 buses in Oxford. To reduce costs, 16 tube trailers can be purchased and used in two batches per day. As buses operate during the day [3.18], refuelling will take place during the evening or early morning before the routes begin.

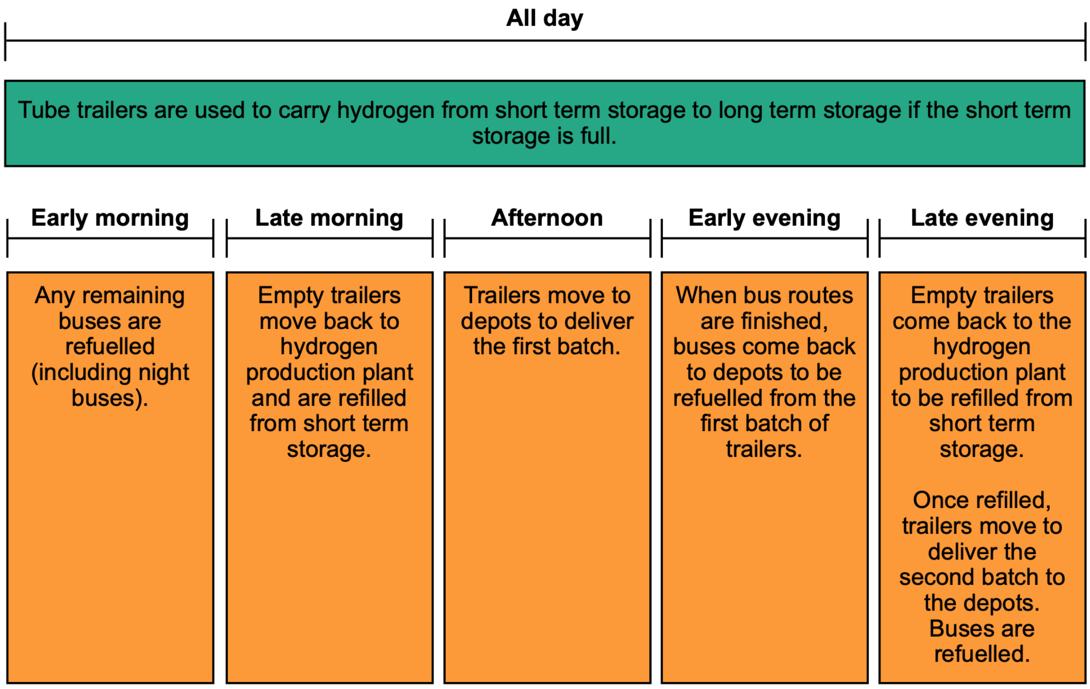
While the hydrogen buses are operating passenger routes during the day, the tube trailers and trucks will be used for distributing hydrogen from the production plant to the long term storage facilities. As mentioned in Section 6.3.3, a maximum of 10,290 kg of hydrogen will be produced by the electrolyser in a single day, which represents 37 deliveries, or 5 trailers in addition to the daily fleet needs. It will then be possible to supply an average of 5 trailers per day from the hydrogen production plant to long term storage facilities.

7.2.1 Oxford depots and general delivery strategy

There are 4 major depots owned by the Oxford Bus Company (OBC), Thames Travel and Stagecoach in Oxford [1.40]. These depots are spread around Cowley, Didcot and Witney [1.40]. Diesel fuel is currently stored at the depot locations [3.26]. This allows buses to be refuelled at specified locations, minimising the refuelling time.

To minimise disruptions to the refuelling schedules of the bus routes, these depots can be used as refuelling stations for the hydrogen bus fleet as well. Seacourt Park and Ride is also planning a new bus terminal [7.11]. It can be suggested to locate a refuelling station at Seacourt Park and Ride.

A delivery strategy from the hydrogen production plant to the depots will now be discussed. Throughout the day, the tube trailers will visit the hydrogen production plant to be filled to maximum capacity. In the afternoon, the tube trailers will move to the depots. In the late evening, after the first batch of busses are refuelled, the empty trailers will come back to the hydrogen production plant to be refilled from short term storage. When full, the tube trailers will move to deliver the second batch to the depots. In the early morning, before the bus routes begin operating, the remaining buses will be refuelled at the depots. In the late morning, the empty trailers will move back to the hydrogen production plant and the cycle repeats. This cycle is illustrated in Fig. 7.5 below.



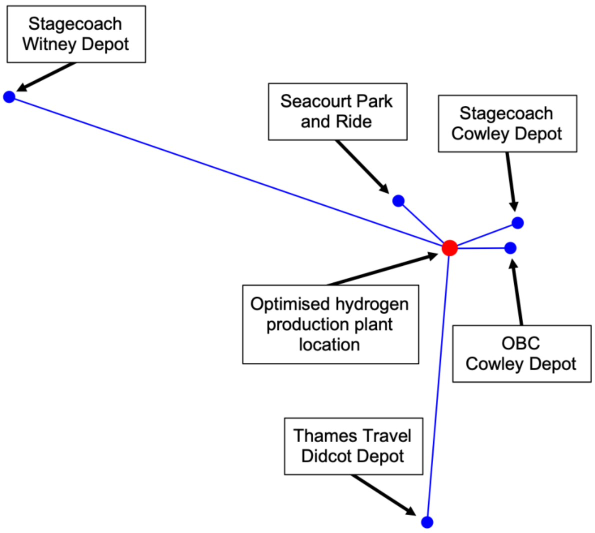
< Fig 7.5: General delivery strategy >

7.2.2 Hydrogen production plant location

As shown in Fig. 7.4, the hydrogen production plant will consist of both the electrolyser and short term storage facility. For determining a best possible location, the following factors will be discussed: distance to depots, distance to residential areas and available land area for the construction of the electrolyser and short term storage facility.

Each tube trailer will return to the hydrogen production plant typically twice a day. Using trailer deliveries twice a day is also a strategy proposed by the Oxford Bus Company [3.26]. It is therefore important to minimise the distances between the hydrogen production plant and the depots hosting the fuelling stations. A model was created to optimise the hydrogen production plant location, minimising the total distance between the plant and all depots. Coordinates were taken from [1.40]. As a first approximation, the model assumed straight line distances between the different refuelling locations.

The results are shown in Fig. 7.6 below. The optimised hydrogen plant location coordinates are (51.7270,-1.2325). To visualise how this solution could be implemented into Oxford's road structure, roads were traced between the optimised hydrogen production plant location and the refuelling stations. This is shown in Fig. 7.7 below.



< Fig. 7.6: Locations of refuelling stations and optimised hydrogen production plant >

< Fig. 7.7: Roads joining hydrogen production plant to refuelling stations [7.12] >

As shown in Fig. 7.6, the optimised location is situated closely to two main bus depots for Stagecoach and the Oxford Bus Company. The distances between the hydrogen production plant and the depots are outlined in Appendix B.

The optimised location can be further analysed with respect to the necessary conditions required for storing hydrogen and installing an electrolyser. Fig. 7.8 below shows a map of the proposed area, with some key features annotated.

< Fig. 7.8: Enlarged view of the hydrogen production plant location taken from [7.12, 7.13] >

As shown in Fig. 7.8, the optimised location is situated close to school grounds, a residential area and a nature reserve. As discussed in Section 5.2.1, safety distances must be respected when considering storage locations for hazardous gases. To keep some distance from these sensitive areas, it is proposed to build the hydrogen production plant at the location marked in blue. This location is also situated near Redbridge Park and Ride, far from residence and near main roads to facilitate truck access.

7.2.3 Transporting hydrogen to fuelling stations

The amount of buses which can be stored inside each depot can be analysed to indicate the daily refuelling needs of each fuelling station. The depot's sizes will be used as an indicator of their relative importance. Using satellite images from Google Maps [1.40], the capacity of each Oxford depot was estimated. This was done by superimposing rectangles representing bus dimensions onto the satellite images. The estimated size of the proposed Seacourt Park and Ride expansion terminal was estimated by using rendered images from [7.14]. Considering that the refuelling needs are proportional to the size of each depot, it can be estimated how many tube trailer deliveries would be required daily to each depot. One can then suggest how many tube trailers are delivered to each individual depot during the first and second batches of the day. This is illustrated below in Table 7.1.

Proposed hydrogen fuelling station	**Estimated number of buses which can be stored inside stations [1.40, 7.14]**	**Amount of tube trailer deliveries required per day**	**Suggested amount of tube trailers delivered in first batch of the day**	**Suggested amount of tube trailers delivered in second batch of the day**
Cowley OBC	40	$\frac{40}{139} \times 32 \approx 9$	5	4
Cowley Stagecoach	40	$\frac{40}{139} \times 32 \approx 9$	4	5
Didcot Thames Travel	38	$\frac{38}{139} \times 32 \approx 9$	4	5
Witney Stagecoach	15	$\frac{15}{139} \times 32 \approx 4$	2	2
Seacourt Park and Ride	6	$\frac{6}{139} \times 32 \approx 1$	1	0
All stations	139	32	16	16

< Table 7.1: Estimating the number of trailers required for each depot >

The amount of trucks required for delivering these tube trailers will now be estimated. As shown in Appendix B, the tube trailers mentioned in Table 7.1 will have to travel a combined distance of around 844 km per day. This is not suitable for a single truck in an urban road network. It can be suggested to have one truck used for each major station (Cowley OBC, Cowley Stagecoach and Didcot Thames Travel) and one additional truck for the smaller stations (Witney Stagecoach and Seacourt Park and Ride). This represents 4 trucks. According to the trailer delivery strategy, taking the example of Cowley OBC, the truck would bring 4 empty trailers back to the production plant in the afternoon, and then make 5 trips to the depot in the evening. This represents around 9 trips during a typical truck driver's shift. Depending on the location of long term storage, an additional truck may also be needed for daytime deliveries of excess hydrogen production. 5 trucks will therefore be planned for the distribution strategy.

One can also calculate how much fuel the truck fleet would consume per year. Appendix B applies a similar model to the one used in Section 4 for determining how much diesel these trucks would consume per year, or hydrogen if fuel cell trucks are used. In summary, around 32,000 gallons of diesel will be required per year for a diesel truck fleet. Around 26,800 kg of hydrogen will be required per year for a hydrogen truck fleet. Hydrogen trucks such as the Hyundai Xcient are anticipated in the future [7.15]. These trucks will also run on hydrogen compressed to 350 bar [7.15]. This implies that the same compressors and storage infrastructure used for buses can be used for the trucks.

High capacity hydrogen storage is a major stepping stone for hydrogen fleets in the future. Companies such as Everfuel develop high capacity hydrogen distribution solutions [3.17]. By transporting larger quantities of hydrogen in one single delivery, this solution would require less than 32 deliveries to fuelling stations per day, and therefore reduce the number of trucks needed to operate the network.

8 Financial analysis

The aim of this section is to provide an overview of all relevant spending and costs of the Green Hydrogen Public Mobility Project. A financial comparison will also be made between embarking on this net zero transition and Business-As-Usual (BAU) - a scenario where the Oxford public transport network continues to be powered by diesel.

8.1 Transition to net zero

Given the Oxford City Council's goal of having all public buses to be zero emissions by 2035, the transition period for this project will be from 2025 to 2035. The delay in starting time will be reserved for planning, approval and other administrative matters. During this transition period, two major changes will occur. Firstly, the transition of fuel usage from diesel to locally produced green hydrogen and secondly, the transition of bus fleet technology from being powered by diesel engines to hydrogen fuel cells. The first transition will involve investing in a solar farm, smart electrolyser-battery system, ammonia cracker and gradually transferring expenditure on diesel to expenditure on hydrogen production, specifically water, electricity and solar farm maintenance, and hydrogen storage. The second transition will involve the gradual replacement of Oxford's bus fleet of 399 buses, by selling 40 diesel buses and purchasing 40 Wrightbus hydrogen buses every year for 9 years, before replacing the final 39 diesel buses in the 10th year.

8.2 Expenditure Outline

In this subsection, the annual expenditures of both BAU and transitioning to the Green Hydrogen Public Mobility Project will be examined in detail. The OPEX and CAPEX of each component and how they contribute to cash flow will now be explained. Generally, the CAPEX of each component is reflected by annual depreciation using the Diminishing Value Method [3.49], which is shown in equation 3.5. For BAU, the relevant annual expenditure is assumed to be constant and includes purchase of diesel, fleet renewal costs and vehicle maintenance. Diesel expenditure is based on an annual demand of 13.38 million litres, as discussed in Section 4 4, and a price of £0.9177/litre [4.1], which includes fuel duty. Annual fleet renewal expenditure is the expenditure on new buses to keep the fleet operationally healthy. It is assumed to be constant and is based on the amount spent by OBC (£6.9 million [1.41]) and Stagecoach (£5 million [1.42]) in 2019, adding up to a total of £11.9 million. Maintenance cost for diesel vehicles is derived from an annual mileage of 33,542,939 km and £0.10/km (from Section 3.4.2). Putting everything together, the breakdown of BAU's annual expenditure is seen below in Table 8.1.

Component	Annual OPEX
Diesel	£12,281,802
Fleet renewal	£11,900,000
Diesel Bus Maintenance	£3,354,294

< Table 8.1: Expenditure related to Business-As-Usual >

For the net zero system, the CAPEX of each component under Hydrogen Production (see Table 8.2) and the solar farm's annual OPEX is based on a 150 MW solar farm, a 42 MW electrolyser and a 13 MWh battery and derived from the values in Table 5.2. The electrolyser's annual OPEX is output from the Python simulation model seen in Fig. 5.11. The lifetime of the electrolyser in years is calculated based on the fixed operating hours. Based on a predicted average operating lifetime of 50,500 hours [6.14] and an annual operation time of 4,205 hours, the electrolyser is expected to last for 12 years. The expenditures for hydrogen storage were discussed in Section 7.1.2. The total CAPEX of a fleet of 399 hydrogen buses has been discussed in Section 3.5.4 and the maintenance cost of hydrogen buses was discussed in Section 3.4.2. The revenue from the sale of the diesel bus fleet is obtained by multiplying the value of (diesel or hybrid) buses in Table 3.8 and the number of (diesel or hybrid) buses in Table 3.5. Hydrogen bus fleet renewal expenditure is estimated using the cost of purchasing 40 new hydrogen buses and subtracting it with the depreciated value of 40 hydrogen buses after 12 years of service. Using the Diminishing Value method again, with an initial value of £304,500 (see Table 3.2), a hydrogen bus depreciates to a value of ~£34,152 after 12 full years of service. Thus, annual hydrogen fleet renewal will cost £10,813,920. This expenditure drops to £10,543,572 every 10 years when only 39 buses need to be renewed. It is important to note that the hydrogen fleet renewable expenditure will only begin in the 13th year, or year 2038, after the first batch of hydrogen bus reaches its lifetime of 12 years. This is why the 2030 predicted price, and not the current price, of hydrogen bus is used. A summary of expenditures related to the Green Hydrogen Public Mobility Project is seen below in Table 8.2.

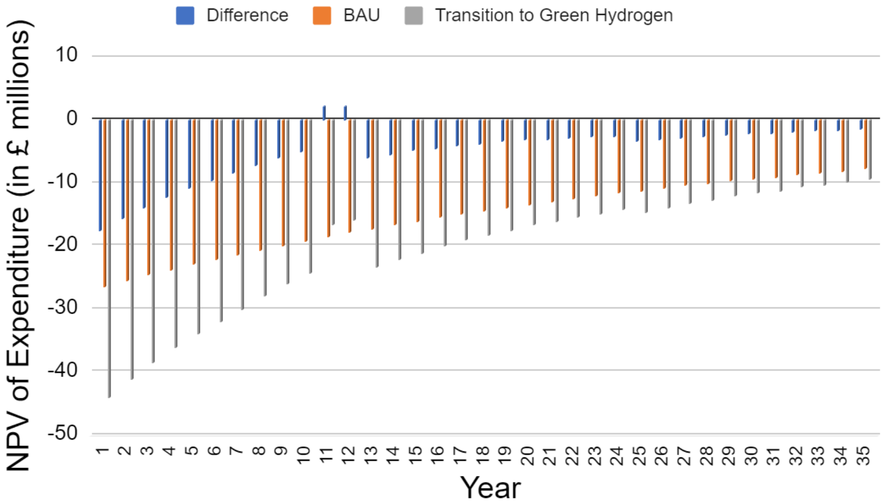
Hydrogen Production			
	Annual OPEX	**CAPEX**	**Lifetime**
Solar Farm	£1,005,000	£67,500,000	35 years [6.4]
Electrolyser	£8,397,416 (includes electricity/water costs and excess solar electricity revenue)	£18,144,000	12 years
Battery	-	£1,161	10 years [8.1]
Hydrogen Storage			
Compressor	£3,136,348	-	-
Ammonia Cracker	£293,519	£1,955,340	10 years
Hydrogen Bus			
Purchase of hydrogen fleet	-	£137,755,800	Over 10 years
Sale of diesel fleet	-	£26,448,300	Over 10 years
Hydrogen Fleet renewal	£10,813,920 (£10,543,572 every 10 years)	-	-
Hydrogen Bus Maintenance	£8,754,707	-	-

< Table 8.2: Expenditure related to Green Hydrogen Public Mobility Project >

While the depreciations of the solar farm, electrolyser, battery and cracker are based on the diminishing value method, the purchase and sale of buses is constant for the first ten years. As mentioned earlier, 40 diesel or hybrid buses will be replaced by 40 hydrogen buses every year (39 in the final year) during the 10-year transition period from BAU to net zero. Thus, one-tenth of hydrogen fleet purchase costs will be accounted for annually in the first ten years to reflect annual purchases of hydrogen buses. Diesel buses will be replaced first before hybrid buses begin to be replaced. During this period, as the number of diesel bus decreases by $\frac{40}{399}$ or ~ 10%, so does the annual OPEX of BAU. Simultaneously, hydrogen bus maintenance costs will increase by 10% every year, starting from $£8,754,707 \times \frac{40}{399} = £877,664.86$ in the first year, up to a constant annual maintenance expenditure of £8,754,707 from the 10th year onwards once the full hydrogen fleet is purchased.

8.3 Comparison with Business As Usual

Combining the expenditures discussed and applying a real discount rate of 3.5% [8.2], the net present values (NPV) of the annual expenditure for both Green Hydrogen and BAU up to 35 years after the transition begins are tabulated in Fig. 8.1 below. The difference between the two is also plotted to show how much more spending is expected due to the transition. The compiled numerical data for the first ten years can be found in Appendix C.



< Fig. 8.1: Net Present Value of annual expenditure over the first 35 years of transition >

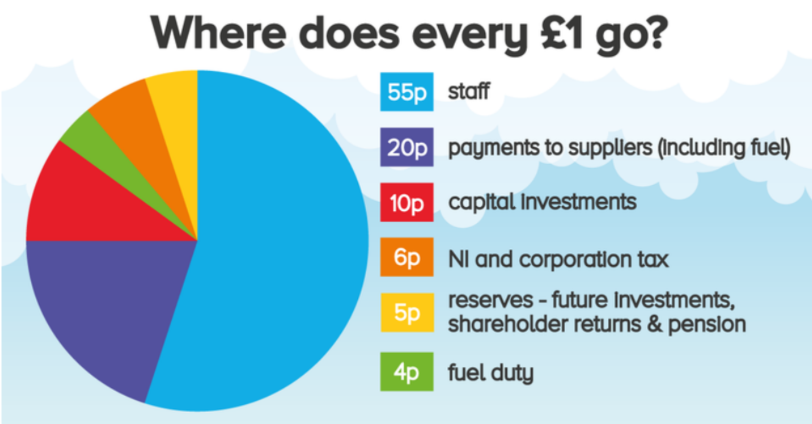
Generally, the value of expenditure NPV decreases over the years due to discounting. Note that the cost of maintaining BAU is constant every year but decreases in NPV due to discounting. Also, there will always be the cost of asset depreciation, namely due to the solar farm, electrolyser, battery and ammonia cracker, for as long as the project stays online. This cost is based on the assumption that each component is replaced immediately after their lifetime. From Fig. 8.1, it can be observed that the purchase of the hydrogen fleet will incur a large additional annual expenditure for the first ten years, resulting in the sudden decrease in expenditure in year 11. From year 13 onwards, the net zero transition then begins to cost more as hydrogen fleet renewal cost sets in. Once the transition process is fully complete by year 23, maintaining the green hydrogen public mobility system will cost ~ £6.39 million more than BAU annually, which translates to ~ £2.82 million with discounting. Given that producing hydrogen is already cheaper than buying diesel, this additional cost will come from purchasing the solar farm, smart electrolyser-battery system, hydrogen storage and maintenance of the hydrogen bus fleet (which is more expensive than that of diesel fleet).

While this long-term additional cost may seem financially unattractive, there are two important financial arguments which further justifies the Green Hydrogen Public Mobility Project. First of all, a net zero transition based on green hydrogen is likely to be cheaper than that based on electric vehicles due to the higher costs of electric buses and charging infrastructure, making this the better alternative for an essential transition to net zero. Secondly, the cost analysis of BAU assumes that diesel costs and diesel bus maintenance costs remain constant up till 2060, which is unlikely to be true. According to the future price assumptions by the Department of Business, Energy and Industrial Strategy (BEIS), the "Central Price" of oil is expected to increase from $63/bbl (barrel) in 2019 to $90/bbl in 2035 [8.3]. Diesel bus maintenance costs are also likely to increase due to more intensive fleet retrofitting to meet low emissions standards imposed by the ZEZ.

8.4 Financing the transition

Now that the additional expenditure required for this green transition is ascertained, this subsection aims to take revenue into account to complete a cash flow analysis.

Due to the sensitive nature of financial information, exact revenue and profits are difficult to obtain. Nonetheless, profits of the main bus companies will be estimated based on the approximate percentage of reserves within OBC's revenue (see Fig. 8.2).



< Fig. 8.2: Breakdown of revenue spending by Oxford Bus Company [5.2] >

As such, it will be assumed that 5% of revenue is profit. From Fig 8.2, 4% of revenue is spent on fuel duty, which costs £0.5795/litre of diesel [8.4]. The annual diesel consumption of 13,383,242.6 litres (mentioned in Section 4.3) translates to an annual spending of £7,755,589.09 on fuel duty. Thus, this amounts to an annual revenue of ~ £193,842,750 and annual profits of £7,753,710 across all three major bus companies in Oxford.

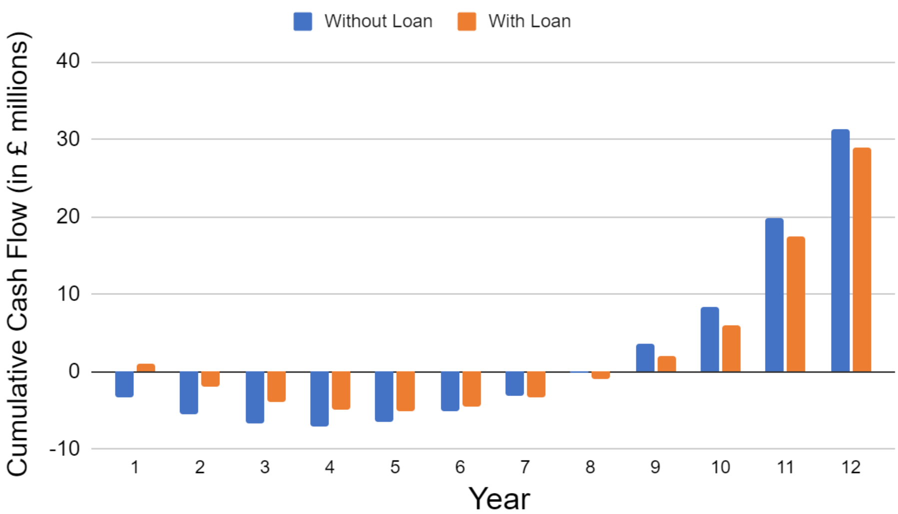
Since the UK Government plans to have 5000 MW of "low carbon" hydrogen production capacity by 2030 [8.5], it will be assumed that the solar farm, electrolyser and battery would be publicly financed. Thus, the following cash flow analysis will not take into account the costs of those components. The annual cash flow is calculated by subtracting profits by the difference between BAU and Green Hydrogen transition, the latter shown in Fig. 8.1. The yearly cumulative cash flow is tabulated in Fig. 8.3 below and specific values for up to year 10 can be found in Appendix D. Without any additional sources of funding, the bus companies will face a maximum negative balance of ~ − £6,976,441 in Year 4 and break-even occurs in Year 9.

8.4.1 Loan

To relieve this financial debt, a £5 million business loan is proposed. Assuming an annual interest rate of 7.5%, a repayment period of 10 years and using the amortisation formula:

$$r = \frac{Pi}{\left(1 - (1+i)^{-N}\right)} \tag{8.1}$$

where r is the yearly repayment, P is the initial loan amount, i is the interest rate and N is the repayment duration in years, the yearly repayment amount is ~ £728,430. Taking the initial loan and yearly repayments into account, the maximum negative cash balance is delayed to year 5 and reduced to ~ − £5,104,011, as can be seen in Fig. 8.3. This debt amount is reduced even further if the future is discounted. Taking the loan into account, the updated yearly cumulative cash flow up to Year 10 is in Appendix D.



< Fig. 8.3: Cash Flow of Green Hydrogen transition with and without an initial loan >

8.4.2 Increase of Passenger Fare

Despite the substantial loan amount, the negative cumulative cash balance is still financially unattractive. Increasing passenger ticket prices would be a viable method to increase revenue; after all, 40% of respondents are willing to pay up to £1 (see Section 5), which is ~ 43.5% of the current average Oxford bus ticket price of £2.30. Currently, revenue from passenger fares is at £193,842,750 × 80% = £155,074,200. If passenger fares increase by just 5% (11.5p for average

Oxford bus ticket), this would amount to an additional yearly revenue of ~ £7,753,710 and thus annual profits of £15,507,420. This increase in revenue will negate the need for a loan since the profits are enough to cover the additional cost of transition to green hydrogen from the start of the transition period. Yearly cumulative cash flow, with just the expenditure, increased revenue and without the loan can be found in Appendix D. Having said this, it is important to note that increasing fares might face social and political barriers due to its unpopular nature, and also legal barriers, as explained in Section 5. While possessing its challenges, this solution is incredibly lucrative, making it a necessary financial solution for this sustainable transition.

8.4.3 Grants

Given the UK government's general support for sustainability and more specifically, its plan to potentially ban sales of new diesel buses [8.6], additional financial support can be expected from the Government to assist transition towards a hydrogen bus fleet in Oxford. This is on top of the Climate Emergency Budget mentioned in Section 1.2.

The Department for Transport (DfT) has recently announced the Zero Emission Buses Regional Area (ZEBRA) scheme, which makes up to £120 million available for local transport authorities to bid for the purchase of zero-emission buses [8.7]. Applications are now open for this funding and end on 21 May 2021. This initiative is part of the Bus Back Better campaign, backed by £3 billion, to accelerate the transition to greener and more sustainable transport in the UK. This campaign aims to deliver 4,000 electric or hydrogen buses and to ban sales of new diesel buses [8.8]. As such, the goals of this campaign ties in closely with this project.

The new ZEBRA scheme is just one of many funding campaigns to support clean and green local public transport systems from the DfT, with past campaigns such as the Ultra Low Emissions Bus scheme which awarded ~ £48 million to local authorities in 2018 [8.9] and the Low Emissions Bus scheme which awarded more than £30 million in 2015 [8.10]. Oxford City Council had also been awarded £2.3 million [8.11] from the Clean Bus Technology Fund in 2018 to 2019 to reduce air pollution from public buses. Thus, extrapolating from history, financial support from the Government to transform public transport to become powered by green gas is likely.

9 Conclusion

To summarise, this report proposes an Oxford public transport system comprising a bus fleet of 399 hydrogen buses, with fuel production powered by a local 150 MW solar farm, 42 MW PEM electrolyser and a 13 MWh Li-Ion battery. This will cost an additional ~ £126.8 million over the ten-year transition period of 2025 to 2035, which can be financed through loans, grants or increase in passenger fares. Net zero is achieved by using zero-emissions hydrogen buses and clean renewable energy to power the hydrogen production process, which is made more efficient using the proposed smart electrolyser-battery system. This system benefits the national energy system by exporting excess solar power to the National Grid. Production, storage and distribution needs were also examined to ascertain technical feasibility, while social, legal and financial analysis of the proposal have also been conducted.

9.1 Project limitations

This subsection aims to point out possible limitations which may affect the results of this project proposal. First of all, the COVID-19 pandemic has brought unprecedented change to the world and affected public transport operations deeply. Thus, this report has taken this to be an anomaly and based calculations on pre-COVID levels. However, it is uncertain when or if public transport will return to pre-COVID operation frequencies, especially with the current trend of working from home. This may result in a long-term decrease in public transport demand, thus reducing hydrogen demand.

Secondly, there is room for improvement in terms of availability and suitability of data collected for calculations. Certain specific data is difficult to locate, such as compressor capital cost or ammonia cracker lifetime while mpg data can differ greatly based on a variety of factors such as bus model, driving habits, local topography, etc. As such, these may contribute to slight inaccuracies in the results.

Finally, since hydrogen technology is still an emerging technology in the transportation industry, there is a lack of laws and regulation on hydrogen in the UK. While there are global standards and an ongoing national project to develop hydrogen laws, there will still be slight uncertainty on the outcome.

9.2 Next steps

The framework of the proposed net zero solution can be taken further to all public transport systems including taxi services in Oxford. There are 3 main taxi services in Oxford [9.1, 9.2, 9.3]. These taxi services could become net zero emitters by replacing their current vehicles with hydrogen vehicles. Hydrogen cars typically use a higher 700 bar pressure for storing hydrogen [3.30]. This would require upgraded compressors, refrigeration systems [3.30] and storage vessels for the system.

Additionally, due to the versatility of hydrogen, it is applicable to many sectors. These sectors include food processing, fertilisers and metal treatment industries [9.4]. Future hydrogen pipelines could also be installed to simplify hydrogen distribution. This can provide potential solutions for house heating for example.

Alternative electrolyser power sources may be investigated. There is an ongoing hydroelectric project in Kennington close to Oxford which may provide power for the electrolyser [9.5]. The Gigastack project also aims for cheaper and larger electrolysers [9.6]. Solar farms could also be further integrated into grid electricity networks.

In conclusion, a smart local energy transport system can be extended to many wider applications. The storage, distribution and production infrastructure required for a hydrogen net zero transport system can be extended for other uses. Hydrogen is truly a versatile gas which can be produced from different renewable sources. Developing a zero emission bus network is only the first step of a wide transformation project that will benefit many Oxford industries, households and local businesses.

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The link to the code repository for this report is
https://github.com/akshaypal123/Green-Hydrogen-Public-Mobility-Repository

Section 1

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Appendix A: Bus route data

Bus Route Name [1.15, 1.16, 1.17]	Operator [1.15, 1.16, 1.17]	Weekday Distance (miles) [1.40]	Weekend Distance (miles) [1.40]	Lowest mpg Rating [3.25]
6 - Magdalen Street to Clifford Place	OBC	347.8	310.8	5.3
10 - JR Hospital to Speedwell Street	Stagecoach	1150.2	1107.6	7
X2 - Oxford Railway Station to Orchard Centre, Didcot	Thames Travel	1540	1540	9.1
3A - Westgate to Kassam Stadium	OBC/Stagecoach	130	120	9

This is an example of the data that was collected for bus routes in Oxfordshire. Overall 58 bus routes were analysed, 25 of which were operated by OBC, 17 by Stagecoach, 8 by Thames Travel and 8 were jointly operated by OBC and Stagecoach. Both the weekday and weekend distance was taken into account and the output of this analysis was a hydrogen requirement of 8548.2 kg on a weekday and 6838.6 kg on a weekend. As expected the weekend demand is lower due to the reduced services on the weekend. The Python source code developed for the route modelling can be found in the GitHub repository.

Appendix B: Truck trailer distribution data

Route number	Route description	Distance [1.40, 2.1] (km)	Number of trailer deliveries per day	Distance per day (factor of 2 applied for return journeys) (km)	Diesel required per year for a diesel truck fleet [2.1, 7.16] (gallons)	Hydrogen required per year for a hydrogen truck fleet (kg)
1	Production plant to Cowley OBC	4.7	9	84.0	3,180	2,670
2	Production plant to Cowley Stagecoach	5.3	9	95.6	3,610	3,030
3	Production plant to Didcot Thames Travel	24.6	9	443.1	16,800	14,100
4	Production plant to Witney Stagecoach	25.9	4	207.2	7,840	6,580
5	Production plant to Seacourt Park and Ride	7.2	1	14.5	548	460
Total			32	844.4	32,000	26,800

Data used:

Average truck mpg rating = 6 [7.16]

Fuel economy of a hydrogen vehicle = 8.7 kg per 100km (from Section 4.3 findings)

Appendix C: 10 Year Transition Period Expenditure

Year	1	2	3	4	5	6	7	8	9	10
Business-As-Usual										
Diesel fuel cost	-12281801.73	-12281801.73	-12281801.73	-12281801.73	-12281801.73	-12281801.73	-12281801.73	-12281801.73	-12281801.73	-12281801.73
Diesel fleet maintenance	-3354293.88	-3354293.88	-3354293.88	-3354293.88	-3354293.88	-3354293.88	-3354293.88	-3354293.88	-3354293.88	-3354293.88
Diesel fleet renewal	-11900000	-11900000	-11900000	-11900000	-11900000	-11900000	-11900000	-11900000	-11900000	-11900000
Total Cash Flow for BAU	-27536095.61	-27536095.61	-27536095.61	-27536095.61	-27536095.61	-27536095.61	-27536095.61	-27536095.61	-27536095.61	-27536095.61

Green Hydrogen Public Mobility Project										
Solar Farm Depreciation	-3857142.857	-3636734.694	-3428921.283	-3232982.924	-3048241.042	-2874055.84	-2709824.078	-2554976.988	-2408978.303	-2271322.4
Electrolyser Depreciation	-3024000	-2520000	-2100000	-1750000	-1458333.333	-1215277.778	-1012731.481	-843942.9012	-703285.751	-586071.4592
Battery Depreciation	-232.128	-185.7024	-148.56192	-118.849536	-95.0796288	-76.06370304	-60.85096243	-48.68076995	-38.94461596	-116.064
Solar Farm O&M, Water Costs, Electricity Costs, Solar Energy Sold	-942598.1393	-1885196.279	-2827794.418	-3770392.557	-4712990.697	-5655588.836	-6598186.975	-7540785.115	-8483383.254	-9402416.44
Diesel fuel cost	-11050543.41	-9819285.096	-8588026.776	-7356768.457	-6125510.138	-4894251.819	-3662993.5	-2431735.18	-1200476.861	0
Cracker Depreciation	-391068	-312854.4	-250283.52	-200226.816	-160181.4528	-128145.1622	-102516.1298	-82012.90383	-65610.32307	-52488.25845

Compressor running cost	-314420.9006	-628841.8012	-943262.7018	-1257683.602	-1572104.503	-1886525.404	-2200946.304	-2515367.205	-2829788.106	-3136348.484
Cracker OPEX	-293,518.75	-293,518.75	-293,518.75	-293,518.75	-293,518.75	-293,518.75	-293,518.75	-293,518.75	-293,518.75	-293,518.75
Purchase of Hydrogen Fleet	-13810105.26	-13810105.26	-13810105.26	-13810105.26	-13810105.26	-13810105.26	-13810105.26	-13810105.26	-13810105.26	-13464852.63
Sale of Diesel Fleet	2484000	2484000	2484000	2484000	2484000	2484000	2484000	2779800	3180000	3100500
Hydrogen fleet Maintenance	-846946.5949	-1634606.928	-2366093.528	-3044373.673	-3672275.743	-4252495.311	-4787600.971	-5280039.928	-5732143.347	-6130766.149
Diesel fleet Maintenance	-2912392.983	-2497316.139	-2107726.993	-1742349.875	-1399967.189	-1079416.913	-779590.1961	-499429.0639	-237924.2129	0
Diesel Fleet Renewal	-10332271.93	-8859707.325	-7477565.209	-6181319.899	-4966651.744	-3829438.243	-2765745.539	-1771820.262	-844081.7158	0
Hydrogen Fleet Renewal	0	0	0	0	0	0	0	0	0	0
Total Cash Flow for Green Hydrogen	-45802335.68	-44373840.56	-43057592.19	-41835740.48	-40693435.87	-39618312.87	-38600063.63	-37334285.63	-36005190.55	-34861341.52
Difference between BAU and Green Hydrogen	-18266240.06	-16837744.94	-15521496.58	-14299644.87	-13157340.25	-12082217.26	-11063968.02	-9798190.02	-8469094.934	-7325245.902
Discount Factor	0.965	0.931225	0.898632125	0.8671800006	0.8368287006	0.8075396961	0.7792758067	0.7520011535	0.7256811131	0.7002822742
NPV of dIfference	-17626921.66	-15679729.03	-13948115.45	-12400366.05	-11010439.95	-9756870.051	-8621882.604	-7368250.197	-6145862.239	-5129739.859

Appendix D: 10 Year Transition Period Cash Flow Analysis

Year	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Cash Flow										
Difference in expenditure between BAU and Green Hydrogen (without solar farm)	-10986394.8	-9946250.838	-8979515.669	-8079119.848	-7239129.604	-6454509.4	-5720937.698	-4812221.912	-3887322.735	-3128676.312
Profits	7753710	7753710	7753710	7753710	7753710	7753710	7753710	7753710	7753710	7753710
Annual Cash Flow (without loan)	-3232684.802	-2192540.838	-1225805.669	-325409.8475	514580.3959	1299200.6	2032772.302	2941488.088	3866387.265	4625033.688
Cumulative Cash Flow (without loan)	-3232684.802	-5425225.64	-6651031.309	-6976441.157	-6461860.761	-5162660.161	-3129887.859	-188399.7705	3677987.495	8303021.183
Cash Flow With Loan										
Loan	5000000	0	0	0	0	0	0	0	0	0
Loan Repayment	-728430	-728430	-728430	-728430	-728430	-728430	-728430	-728430	-728430	-728430
Annual Cash Flow (with Loan)	1038885.198	-2920970.838	-1954235.669	-1053839.848	-213849.6041	570770.5999	1304342.302	2213058.088	3137957.265	3896603.688
Cumulative Cash Flow (with Loan)	1038885.198	-1882085.64	-3836321.309	-4890161.157	-5104010.761	-4533240.161	-3228897.859	-1015839.771	2122117.495	6018721.183
Cash Flow with Fare Increase										
Profits after fare increase	15507420	15507420	15507420	15507420	15507420	15507420	15507420	15507420	15507420	15507420
Annual Cash Flow (with fare increase)	4521025.198	5561169.162	6527904.331	7428300.152	8268290.396	9052910.6	9786482.302	10695198.09	11620097.27	12378743.69
Cumulative Cash Flow (with fare increase)	4521025.198	10082194.36	16610098.69	24038398.84	32306689.24	41359599.84	51146082.14	61841280.23	73461377.49	85840121.18