Department of Mechanical and Aerospace Engineering

Feasibility study of wind powered hydrogen generation

Author: Sonal Dsouza

Supervisor: Dr Ioannis Kokkinakis

A thesis submitted in partial fulfilment for the requirement of degree in

Master of Science in

Sustainable Engineering: Renewable Energy Systems & The Environment

August 2021

Copyright Declaration

This thesis is the result of the author's original research. It has been composed by the author and has not been previously submitted for examination which has led to the award of a degree.

The copyright of this thesis belongs to the author under the terms of the United Kingdom Copyright Acts as qualified by University of Strathclyde Regulation 3.50. Due acknowledgement must always be made of the use of any material contained in, or derived from, this thesis.

Signed: Sonal Dsouza Date: 17/08/2021

Abstract

There are plenty of natural resources in Scotland. Wind power is believed to sustain the nation's energy demands into the future. Unfortunately, one of the major drawbacks in renewable wind energy generation is the intermittent and stochastic nature of wind. There is a rising interest in hydrogen with quickly growing demand. Hydrogen can be a clean source of energy when obtained from renewable resources and when it is transformed into electricity, the only emission being water, it enables to utilise renewable energy sources to their full potential.

In this report, a feasibility study to examine the option of hydrogen production by wind powered electrolysis in Scotland is analysed. A detailed review on different energy storage systems, summary of the various technologies to produce hydrogen and the major components of wind powered hydrogen system is covered in this report. From the analysis, it is realised that Scotland is able to produce 100% of its total gross electricity consumption from wind energy by transforming the surplus power generated into hydrogen and storing it to consume it when sources cannot meet demand. The possibilities of Scotland becoming an exporter of hydrogen instead of electricity were discussed briefly by considering the fact that it has a very well-established O&G pipelines which could be used sustainably to transport and distribute hydrogen. In order to decarbonise Scotland by 2045 as per Scottish government's goal, it is estimated that there will be a requirement of an additional 35 to 40 GW capacity of wind farms. It is analysed that eventually offshore wind farms can offer immense energy to produce green hydrogen sustainably and help in reducing emissions in the hard to abate sectors like heating, transport, manufacturing industries, etc., Hydrogen energy as a mainstream fuel or as an energy storage system can help Scotland decrease the need for backup sources of energy, slash transportation losses and earn huge profits by exporting hydrogen energy at peak periods and deliver security of supply which will eliminate the need to import electricity from other nations.

Acknowledgements

First and foremost, I would like to thank the Almighty Lord for His benevolent blessings without which this work wouldn't have been complete. I would like to express my deepest gratitude to my supervisor, Dr Ioannis Kokkinakis, for the continuous guidance he gave me till the last minute and for his encouragement in helping me finish my thesis.

I am also grateful to my mother for her support throughout my master's programme during this COVID-19 pandemic. Thank you for your love and prayers.

This thesis is dedicated to the memory of my father, Albert D'Souza, who always believed in my potential. Although you are no longer with us, your belief in me has made this journey possible.

A big hug to my dearest mascot Micol Laurel Cutinha for always making me smile even at times when I had almost forgotten how to.

I cannot begin to express my heartfelt gratitude to my aunt/friend Teresa Dsouza for her continuous and unparalleled love, help and support, as well as for always being there.

I'm undoubtedly grateful to Christo Tzortzinis and Elli Grigoriadi for their wonderful company throughout this difficult year on a foreign land far from home. I would also like to express my deepest appreciation to Maggie Stewart for continuously testing my knowledge with quirky questions throughout the masters and for being such a lovely friend.

A big thanks to my HP notebook for not giving up on me all through this time, and throughout my master's degree during this pandemic. Although we gave each other some hard time on numerous occasions, I am so glad we made it through together.

Last, but not least, I would like to thank Dr Paul Tuohy for his selfless support throughout the master's program.

Finally, I want to express my sincere thanks to all my dear friends, colleagues, and those who helped me accomplish my dissertation, either directly or indirectly.

Table of Contents

List of Figures

List of Tables

List of Equations

List of Abbreviations

A	Area
AC	Alternative current
AEM	Anion Exchange Membrane
AFC	Alkaline fuel cell
ALWR	Advanced Light Water Reactor
atm	Atmosphere
Avg.	Average
CAES	Compressed air energy storage
CAGR	Compound annual growth rate
CCS	Carbon capture and storage
CH_4	Chemical formula of Methane
CHP	Combined heat and power
CO	Carbon monoxide
CO_2	Carbon dioxide
Cp	Power coefficient
CrO_2	Chromium oxide
CSP	Concentrated solar power system
DC	Direct current
E	Kinetic/Potential energy
EMEC	European Marine Energy Centre
EPRI	Electric Power Research Institute
EU	European Union
EV	Electric vehicles
FCEV	Fuel cell electric vehicles
Fe_2O_3	Ferric oxide
FeO	Ferrous or Iron oxide

FES	Flywheel energy storage
FOWF	Floating offshore wind farms
FOWP	Floating offshore wind platform
GH_2	Gaseous hydrogen
GHG	Greenhouse Gas
GW	gigawatt
GWh	Gigawatt-hour
H^+	Hydrogen ions
H_2	Hydrogen gas
H2O	Chemical formula of Water
HES	Hydrogen energy storage
HTS	High temperature shift
HTSE	High-temperature steam electrolysis
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
km	Kilometre
KOH	Potassium hydroxide
kW	kilowatt
kWh	kilowatt-hour
LH_2	Liquid Hydrogen
Li-ion	Lithium ion
LTS	Low temperature shift
LWRS	Light Water Reactor Sustainability
m	metre
MCFC	Molten carbonate fuel cell
mi	Mile
MW	megawatt

MWh	Megawatt-hour
Mt	Megatonne
NASA	National Aeronautics and Space Administration
NOx	Nitrous oxide
NREL	National Renewable Energy Laboratory
O&G	Oil and Gas
O_2	Oxygen gas
O^{2-}	Oxygen ions
OH	Hydroxide
OH^-	Hydroxyl ions
OWF	Offshore wind farms
P	Power
PEFC	Polymer electrolyte fuel cell
PEM	Proton Exchange Membrane
PHES	Pumped hydro energy storage
PSA	Pressure swing adsorption
PV	Photovoltaic
R&D	Research and Development
RES	Renewable energy system
SAM	System Advisor Model
SDG	Sustainable Development Goals
SMR	Steam methane reforming
SOEC	Solid oxide electrolyser cell
SOFC	Solid oxide fuel cell
TCES	Thermochemical energy storage
TES	Thermal energy storage
ThO_2	Thorium dioxide

TiO_2	Titanium dioxide
TW	Terawatt
TWh	Terawatt-hour
UC	Ultracapacitors
UK	United Kingdom
UN	United Nations
V	Volt
W	Watt
Wh	Watt-hour
WO_3	Tungsten trioxide

Nomenclature

Symbol	**Description**	**Units**
ρ	Density	kg/m^3
A	Area	m^2
m	Measure of distance	metre
km	Measure of distance	Kilometre
mi	Measure of distance	miles
v	Velocity	m/s
η	Efficiency	%
A	Ampere	amps
°C	Temperature unit	Degree Celsius
C_p	Specific heat capacity at constant pressure	J/kgK
C_v	Specific heat capacity at constant volume	J/kgK
kg	Unit of mass	Kilogram
h	Height	metres
I	Electric Current	ampere

Symbol	**Description**	**Units**
K	Thermodynamic temperature	Kelvin
KJ	Measure of energy	Kilo Joule
MJ	Measure of energy	Mega Joule
GJ	Measure of energy	Giga Joule
P	Power	kW
V	Unit of electric potential	Volt
W	Unit of power	Watt
kW	Unit of power	kilowatt
MW	Unit of power	Megawatt
GW	Unit of power	Gigawatt
TW	Unit of power	Terawttt
Wh	Unit of energy	Watt-hour
kWh	Unit of energy	kilowatt-hour
MWh	Unit of energy	Megawatt-hour
GWh	Unit of energy	Gigawatt-hour

Symbol	Description	Units
TWh	Unit of energy	Terawatt-hour
kn	Unit of speed	Knots
E	Energy	Joules
ω	angular velocity	rad/sec
I	moment of inertia	kg.m^2
j	Current density	mA/cm^2
L	wire inductance	Henrys
m	mass	kg
bar	Unit of pressure	bar
g	Earth's gravitational force	m/s^2
atm	Unit of pressure	Pascals
LHV	Lower heating value	MJ/kg
f	flowrate of hydrogen	m^3/s

1.0 Introduction

The world is currently facing an energy crisis. The ever-increasing industrialisation, growing urban population calls for production of more and more energy. The already existing energy methods such as fossil fuels, nuclear, thermal etc., cannot support this ever-increasing demand as the natural resources are depleting day by day and these energy production methods give rise to environmental problems which are of great concern. This gives rise to finding energy producing methods which meet the demands and cause minimum to no harm to the environment. Our planet is witnessing a major shift in the approach energy is generated, converted, accumulated, and consumed in its diverse kinds. Communities are getting more and more aware of the necessity to transition to a civilization in which energy stops making a harmful influence on our climate by switching from carbon-based fuels towards renewable energies [1]. Global challenges such as climate change, volatile energy prices, and energy security concerns have given renewable energy resources, especially wind energy, a positive political backdrop [2]. The main objective of the Paris agreement on climate change is to maintain a global temperature increase below 2°C and to make every effort possible to keep the temperature rise to 1.5 °C [3].

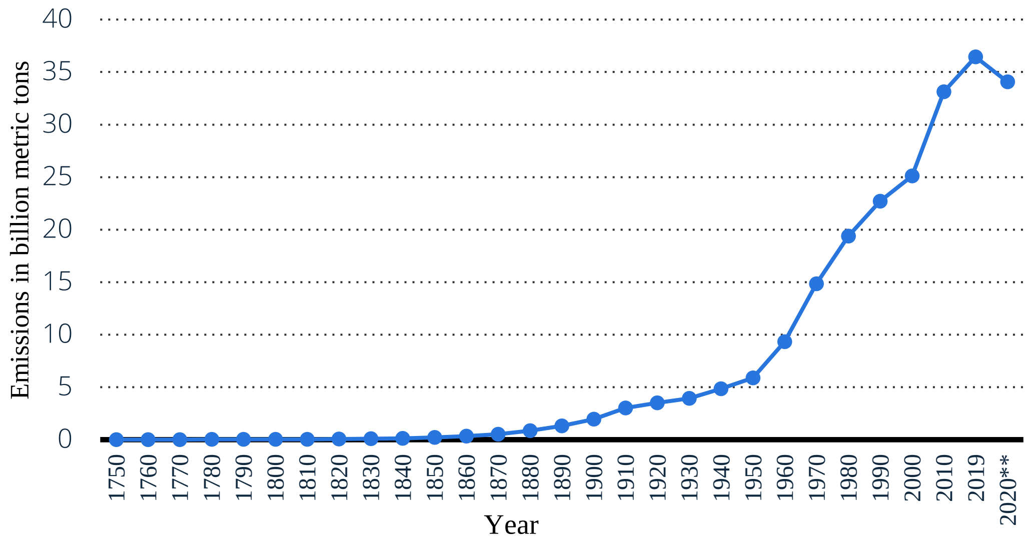

Figure 1: Global CO_2 emissions from fossil fuel combustion and industrial processes from 1758 to 2020 [4]

Since the beginning of the industrial revolution, the carbon dioxide (CO_2) emissions generated via global fossil fuels and the industrial activities have increased dramatically. The world's carbon emissions have most recently been about 36.44 billion tonnes (2019). The United Kingdom (UK) and Europe have agreed on an ambitious objective for Net Zero emissions by

2050, including a shift to zero carbon energy across the economy. Wind energy is (usually) an easy and nearly carbon free resource that may be used by many countries. High wind speed sites in the UK usually coincide with rich ecosystems and rich biodiversity areas, for example, lakes, forests, coastal lands, and mountains. In addition, individual family residential zones are dispersed around the country. These factors should be considered properly before the large-scale deployment of the resource.

Wind is a rich but intermittent source of electricity generation. Electricity generated by wind may be used to make hydrogen from the electrolysis of water to power vehicles or to store electricity, then to generate it during the period when the wind is very low. Hydrogen is an abundant, clean source of energy that has a lot of promise when combined with renewable energy sources. It is light, storable, has very high energy density, and does not create direct pollutants or Greenhouse Gas (GHG) emissions. Hydrogen may have a critical responsibility in reducing emissions particularly in hard to abate operations for e.g., steel industries, space-heating, transportation [5]. It is currently a major business in the world to provide industrial users. Since 1975, requirement of hydrogen has tripled and is still growing, but almost entirely from fossil fuels. About 6% of natural gas and about 2% of worlds coal is used to produce hydrogen [6]. Research on the production of renewable hydrogen energy - so called green hydrogen production technology, has to be done to minimise emissions of GHGs [7].

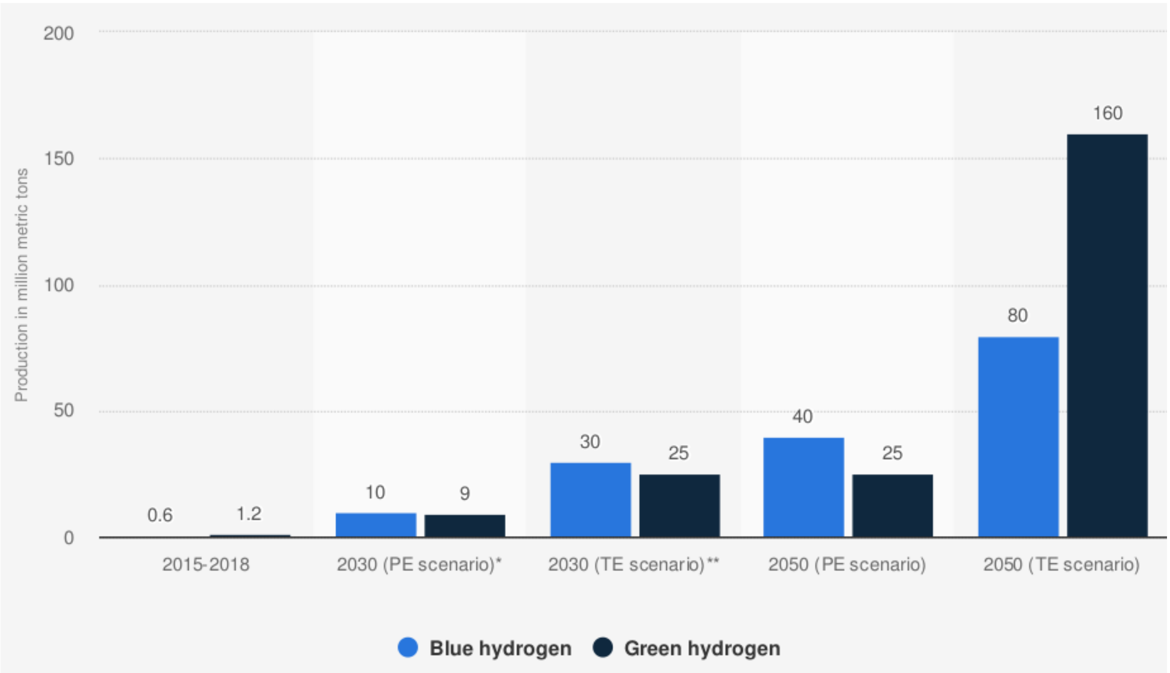

Figure 2: Hydrogen production worldwide (2015-2018), and 2050 prediction (million metric tons) [8]

Recent studies show that green hydrogen is currently gaining impressive push globally and is experiencing exceptional political and corporate support, with a constantly growing number of laws, regulations, and initiatives. Only about 0.1% of worldwide production of hydrogen today is derived from electrolysis, but with falling rates for green energy particularly from solar photovoltaic (PV) panels and wind generation there has been rising interest in hydrogen via electrolysis. This also leads to construction of electrolysers in locations with outstanding renewable energy conditions, and develop an inexpensive source for hydrogen, even after considering transmission and distribution prices for delivering hydrogen from (typically remote) renewable sources to end-users [6]. It is time to scale-up technology, to reduce prices so that hydrogen can be utilised extensively and extract the best out of hydrogen's vital responsibility in a clean, safe, and reasonably priced energy future. Between 2015 and 2018, only about a million tonnes of renewable hydrogen was generated across the world (Figure 2).

Currently, only oil refining and fertiliser manufacturing companies use hydrogen. It also needs to be implemented in areas where it is almost entirely absent on today's date, for instance transportation, homes and energy generation, in order to make an important contribution towards clean energy transitions [6]. A recent research by Aurora Energy Research says that a total of 213.5 gigawatts (GW) of power generation is planned from electrolysers by 2040, 85% of this is within Europe which is more than one thousand times boost from the 0.2 GW (Figure 3) electrolyser capacity operational today [5].

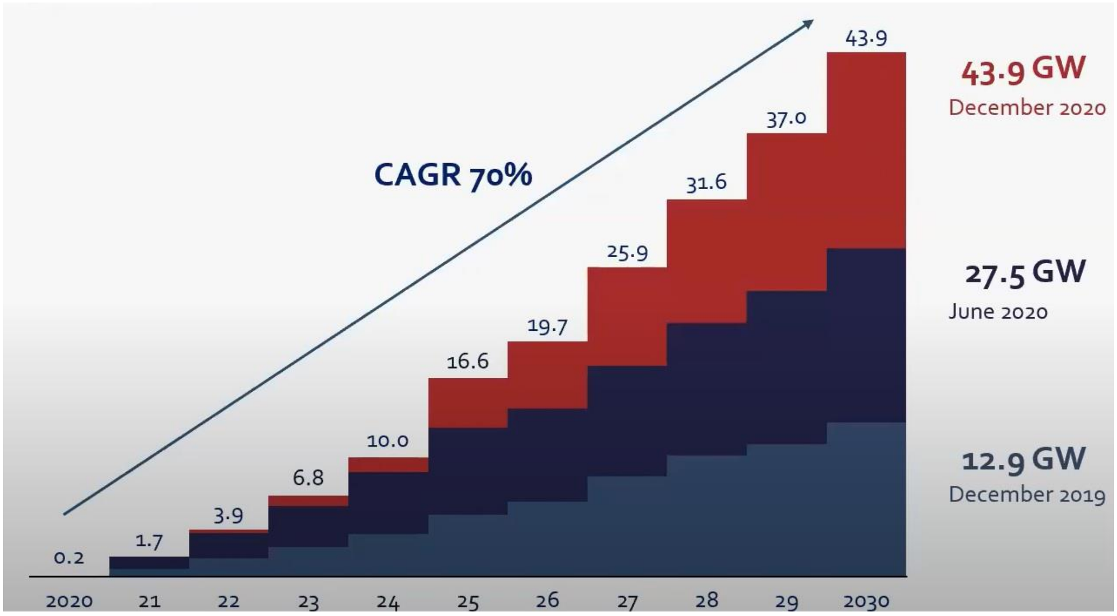

Figure 3: Estimation of electrolyser installation capacity per year (GW) as per McKinsey & company [9]

As the hydrogen industry and technology is expanding fast in a sophisticated system of infrastructure, mitigation policies and energy demand, detailed case studies are essential to evaluate the feasible production process of hydrogen. In this work, feasibility study of using wind-powered hydrogen as a mainstream fuel in Scotland is undertaken, hence ensuring that surplus energy does not go unused and that the negative side of the renewable source (i.e., the intermittent nature of wind energy) is overcome. A quantitative and qualitative analysis is then made based on the findings.

1.1 Aim

The purpose of this dissertation is to evaluate the option for generating hydrogen in Scotland using wind-powered electrolysis when wind energy is in surplus of demand and then utilised to generate electricity during the times of the day when wind resources are low.

1.2 Objectives

This thesis aims to assess the feasibility of providing hydrogen energy storage system to Scotland via wind-powered electrolysis. The main goal would be to generate hydrogen when the wind resource is high and store it so as to be used when the supply is low. The following steps are undertaken in order to accomplish the task.

- Average monthly consumption of electricity for Scotland of a year is studied. This is compared with the average monthly electricity production by wind energy.

- If there is a surplus energy it is then transformed into hydrogen gas for the times when wind energy is scarce.

- If the difference between the above data is negative then the Scotland's export electricity figures are considered for converting into hydrogen. Assuming this was the electricity generated in excess and exported after meeting the Scotland's demand.

- In case if these figures aren't able to produce enough hydrogen to meet the current demand, then a future scenario (2045) is estimated and investigated if this could satisfy the electricity demand

- After meeting the total electricity demand, other hard to abate sectors like heating and transport are considered. The amount of wind energy required to meet the total energy demand of Scotland is evaluated and also the additional wind farm capacity required to meet this demand is also determined.

2.0 Literature Review

This chapter begins with a detailed contextual information of the renewable energy technology, especially wind energy with an aim to gain an understanding of the expertise. A lot of figures and statistics on both wind and renewable energy as a whole are discussed for the Scotland and UK. This section also deals with a thorough literature review on different types of energy storage systems to investigate the most efficient storage system. Various methods of hydrogen production techniques are studied comprehensively for the purpose of giving an insight on why green hydrogen production method was chosen. The different components of the wind powered hydrogen system are discussed in detail with intention of identifying the key points of the system. A broad discussion is involved on various storage methods and distribution of hydrogen with a focus on safety. A brief vision on future techniques of sustainably producing hydrogen is also discussed. The section ends by discussing the environmental impacts of a hydrogen-based energy systems.

2.1 Renewable energy in the UK and Europe

A huge segment of the energy system in Europe still continues to be built on carbon-based fuels today. But with the mass electrification of the energy system powered through the use of renewable energy sources, the European Commission anticipates a drastic transformation. The aim of the European Green Deal, which is a highly ambitious series of proposals which would allow european citizens and corporations to benefit from a lasting green transition and to become the world's first climate-neutral continent by 2050 [10]. All aspects of society and economic sectors from electricity to industry, mobility, buildings, agriculture, and forestry will play a role. Renewable energy sources can help Europe in creating new jobs in green technologies.

Figure 4 illustrates the available statistics on renewable energy share and targets that were set for 2020 in the gross final energy consumption. Renewable energy accounted for about 19.7% of total final power consumption in the Europe, compared with just 9.6% in 2004. Most nations now recognise that there is a need for political assistance to remove restrictions which limit renewable technology from being used more swiftly. These include providing fair and assured access to the electricity markets; financing policies aimed at stimulating investment in renewable energies projects; fiscal measures reflecting external costs and the benefits of renewable energy resources (in particular carbon or energy taxes) [11].

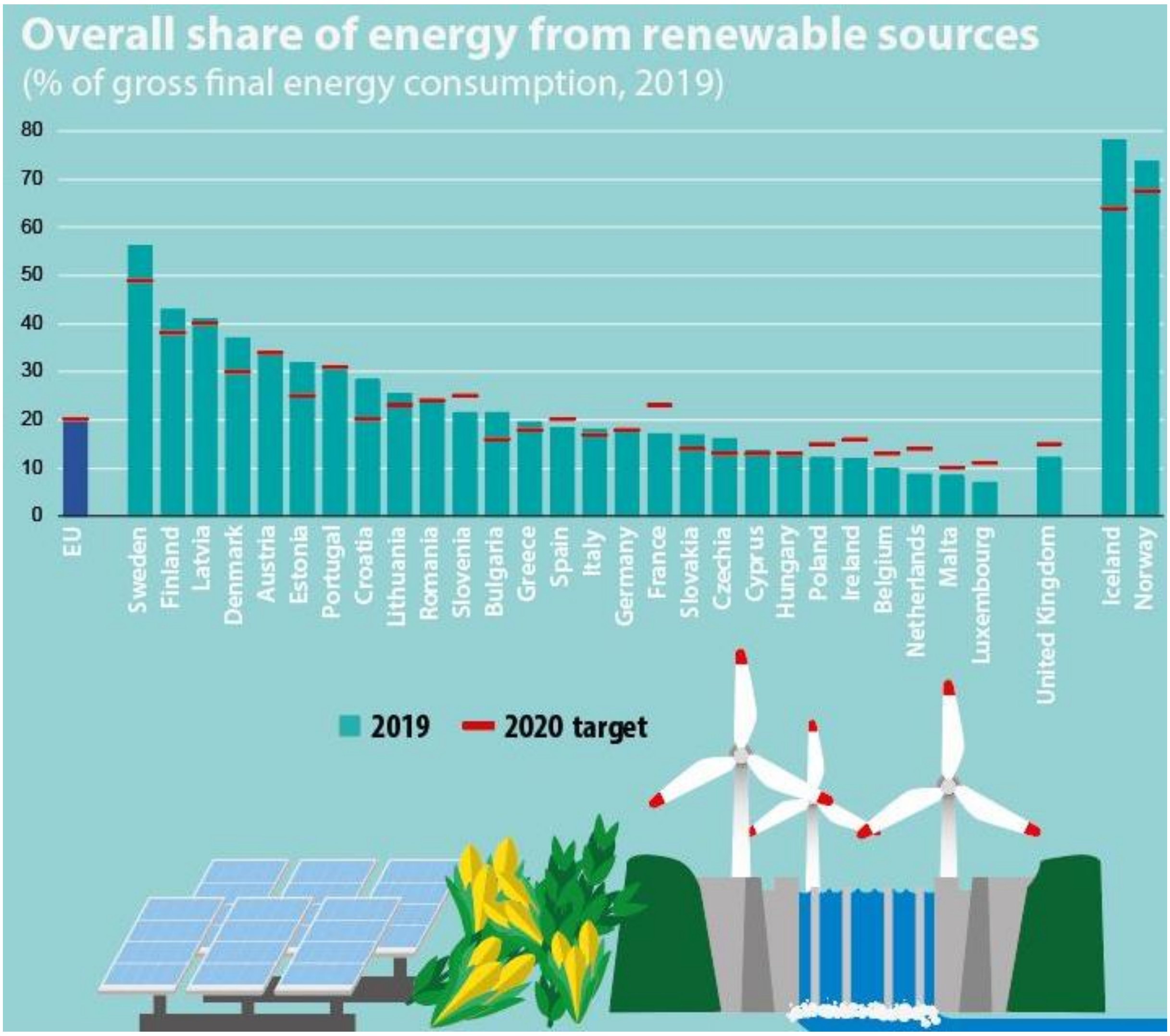

Figure 4: Percentage of gross energy consumption from renewable sources in Europe, 2019 [10]

The figures from the UK government imply that for the first time in the year 2020 renewable electricity generation surpassed fossil fuels, providing 43% of the country's electricity [12] . In Quarter 1 of 2021 renewable energy generation amounted to 34.7 terawatt-hour (TWh) in the UK. Scotland's renewable energy capacity showed consistent expansion between 2009 and 2019, with an average yearly capacity growth since the end of 2009 of more than 800 megawatts (MW) [13]. In 2020, according to preliminary statistics, renewable energy accounted for 97.4% of Scotland's gross electricity consumption [14]. The Scottish Government has made hydrogen an integral part of Scotland's decarbonization goals. In the UK, Scotland became the first country to publish a Hydrogen Policy Statement , which incorporates the aim of producing 5 GW energy from the renewable and low carbon hydrogen in Scotland by 2030 [15].

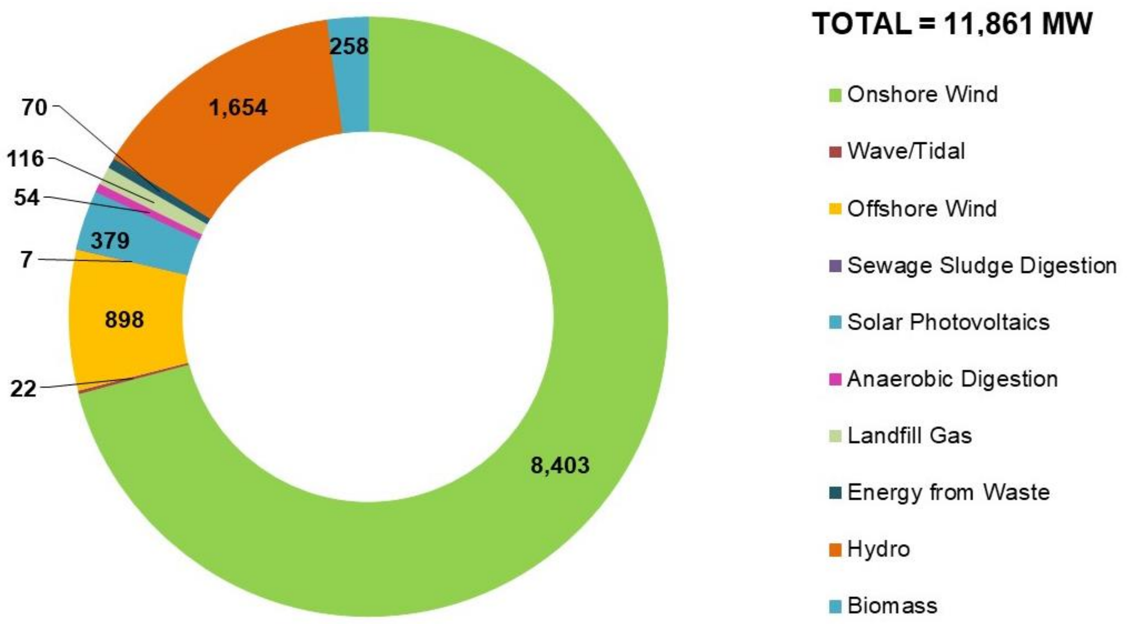

Figure 5: Renewable energy installed capacity (Q1 2021) in Scotland [13]

2.2 Wind energy in the UK and Scotland

In the last few years, the generation of wind energy has increased very fast, and UK is currently the world's sixth-largest wind energy producer, following China, the United States, India and Spain [16]. In the UK, mean wind speeds have been reasonably constant in the previous two decades. In 2019, standard wind speeds were about 8.2 knots. Speeds in 2015 peaked at 9.4 knots, while in the following year it fell to 8.4 knots [17].

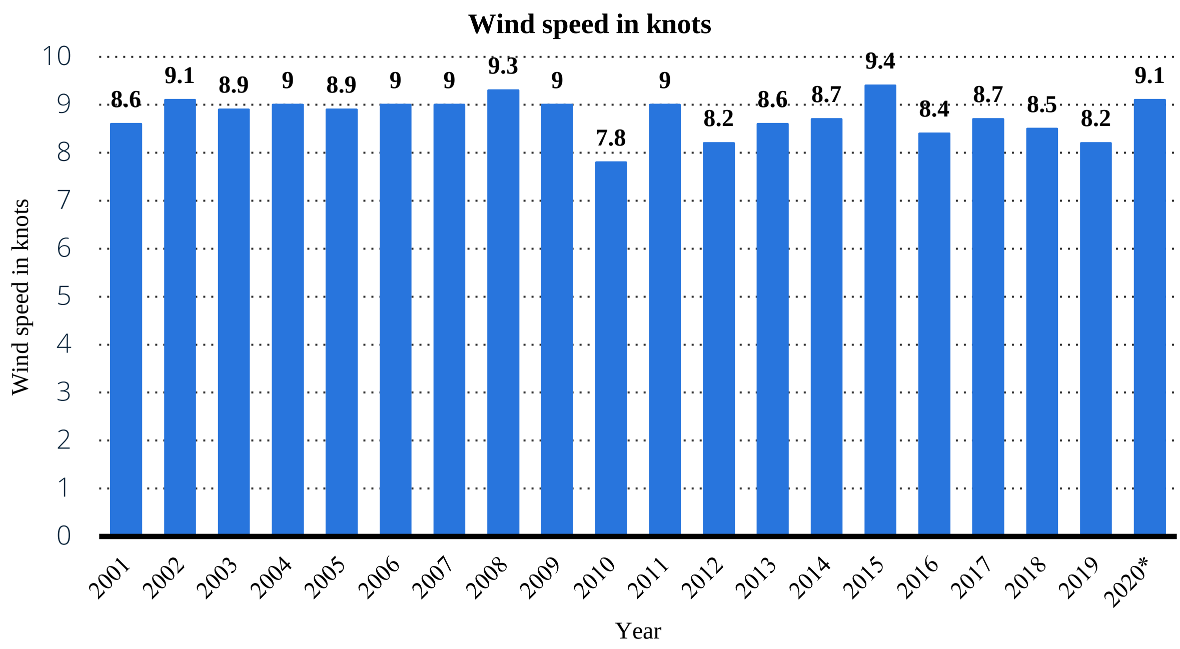

Figure 6: Wind speeds(average speed) in the UK from 2001 to 2020 [17]

Between 2009 and 2020 the UK's wind power generation rose by 715% [16]. In the year 2020, onshore wind farms and offshore wind farms (OWF) together produced more than 50% of UK's renewable energy, generating about 24.2% of the UK's energy demand (approximately 13% came from offshore wind farms and about 11.2% from onshore wind farms) [12]. There are currently around 8,600 onshore wind turbines plus approximately 2,300 more offshore wind turbines in operation across the UK. Wholly a total capacity of over 24.10 gigawatts (GW) of electricity, which is equivalent to about 20% of UK's total electricity generation in 2019 and 54% of green energy [16]. The higher percentage of green energy from wind, in total energy consumption is also an indicator for the Sustainable Development Goals (SDG) set by the United Nations (UN) (7.2.1). The National Grid stated that 2020 was UK's greenest year ever with record high wind generation levels [16].

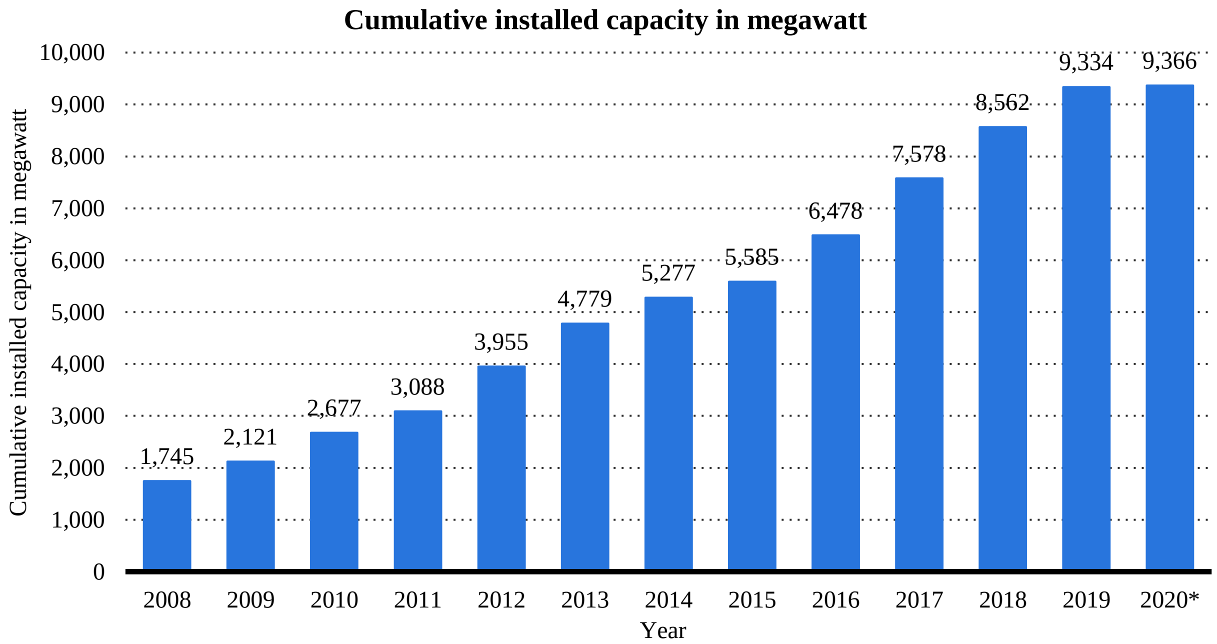

Figure 7: Wind energy capacity in Scotland from 2008 to 2020 [18]

Wind power continues to provide the majority of Scotland's renewable electricity generation (23.2 TWh) [14]. As shown in Figure 8 it contributed to about 73% of total renewable power generation in the year 2020 [13]. Onshore wind farms produced about 19.6 TWh while OWF kept expanding in 2020, about 3.5 TWh generated, which is an increase from 3.2 TWh in 2019 [14]. Figure 7 shows that Scotland has a total wind energy capacity of almost 9.4 GW, with wind turbines up to 8 GW capacity were installed to Scotland's energy sector between 2018 and 2019 [18]. The largest onshore wind farm in Scotland and the UK as a whole is the Whitelee wind farm at Glasgow. When operating at full capacity, the Whitelee wind farm's 215 wind turbines can create 539 megawatts of energy. This production is sufficient to power about 300,000 households in Scotland at any given moment. There is significant additional capacity development in Scotland, with projects in planning or with approximately 14 GW already approved in total. A new project by name Bodinglee wind farm is also in the planning which is about 300 MW capacity and could be the 3rd biggest onshore project in the UK [19].

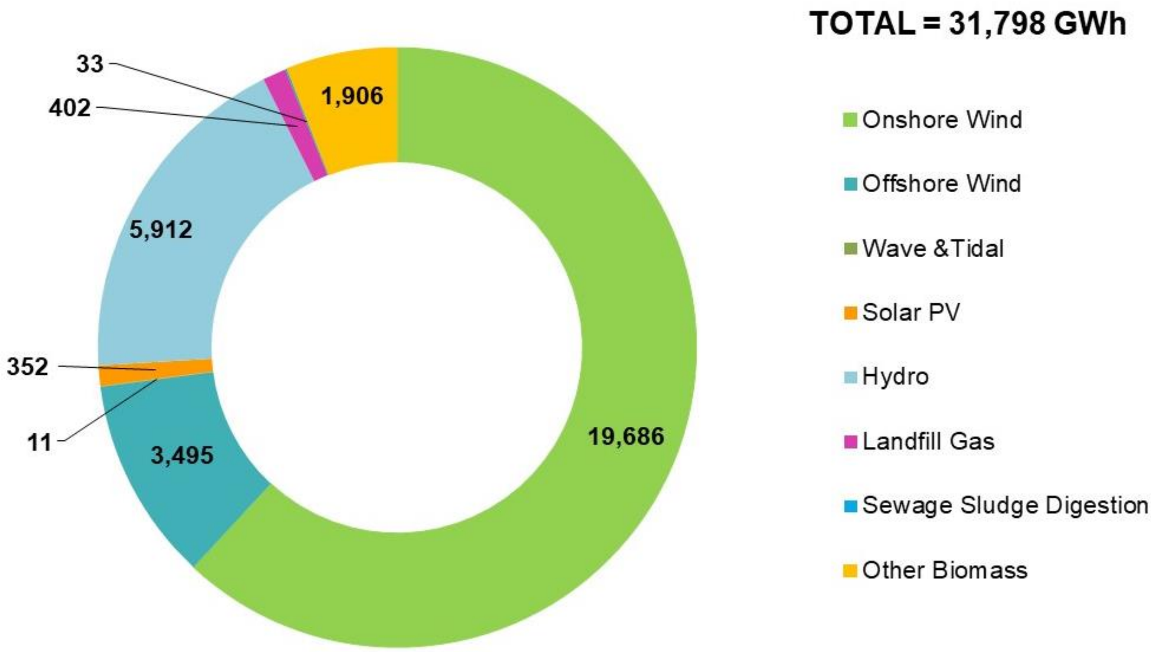

Figure 8: Renewable electricity output by Technology in the year [13]

2.3 Energy storage systems

Energy storage represents the collection of energy generated at once for later usage to eliminate imbalances in supply and demand on the power system due primarily to an increase in renewable power generation [20]. There is supply and demand inconsistencies as renewables are intermittent sources of energy signifying it cannot produce energy when there is no sunshine, or if the wind energy is low. But the consumers still need energy in these renewable downtimes. Today, power grids deliver energy instantaneously implying that electricity is being consistently produced to meet consumer requirements and they are conveniently stored when not essential. However, renewable energy sources – wind energy and solar energy must be harvested whenever it is obtainable and stored until needed [21]. The application of energy storage can present several benefits for power systems, for instance the increased access along with enhanced economic performance of renewable energies. Energy storage provides power suppliers with an option to utilise electricity which would be otherwise unused. This much needed flexibility can transform our energy output and consumption and is thus being studied and tested [22]. Energy storage is also crucial for electrical systems which enables load leveling and peak shaving, frequency control, oscillation of damp energy, improvements in power quality and reliability [21]. Currently the major challenges in implementing electricity storage at the great scale are the cost and the infancy of the technology.

2.3.1 Types of energy storage systems

Energy can be stored in distinct methods (see Figure 9). The popular energy storage methods are: *Electrochemical and battery energy storage system, Superconducting magnetic energy storage system, Thermal energy storage system, Thermochemical energy storage system, Compressed air energy storage system, Flywheel energy storage system, Pumped energy storage system* and *hydrogen energy storage system* [21].

Table 1: Rated installed capacity (GW) and no. of energy storage projects worldwide [23]

Energy storage system	**Active**	**Inactive/under renovation**	**Developed**	**Announced**	**Shutdown/ Withdrawn**	**In production**
Mechanical storage*	166.20 (372)	0.28 (2)	2.31 (11)	11.63 (26)	0.08 (3)	5.95 (7)
Electro-chemical	2.03 (695)	0.05 (3)	0.95 (67)	0.63 (136)	0.09 (40)	0.7 (10)
Chemical storage#	0.01 (7)	–	0.003 (3)	0.001 (1)	0.00007 (1)	–
Thermal storage	3.21(193)	0.21 (1)	0.13 (3)	0.16 (5)	–	0.12 (2)

The value in parentheses corresponds to the no. of projects.

* Involves pumped hydro energy system, compressed air energy system, and flywheel storage energy systems.

Hydrogen storage only.

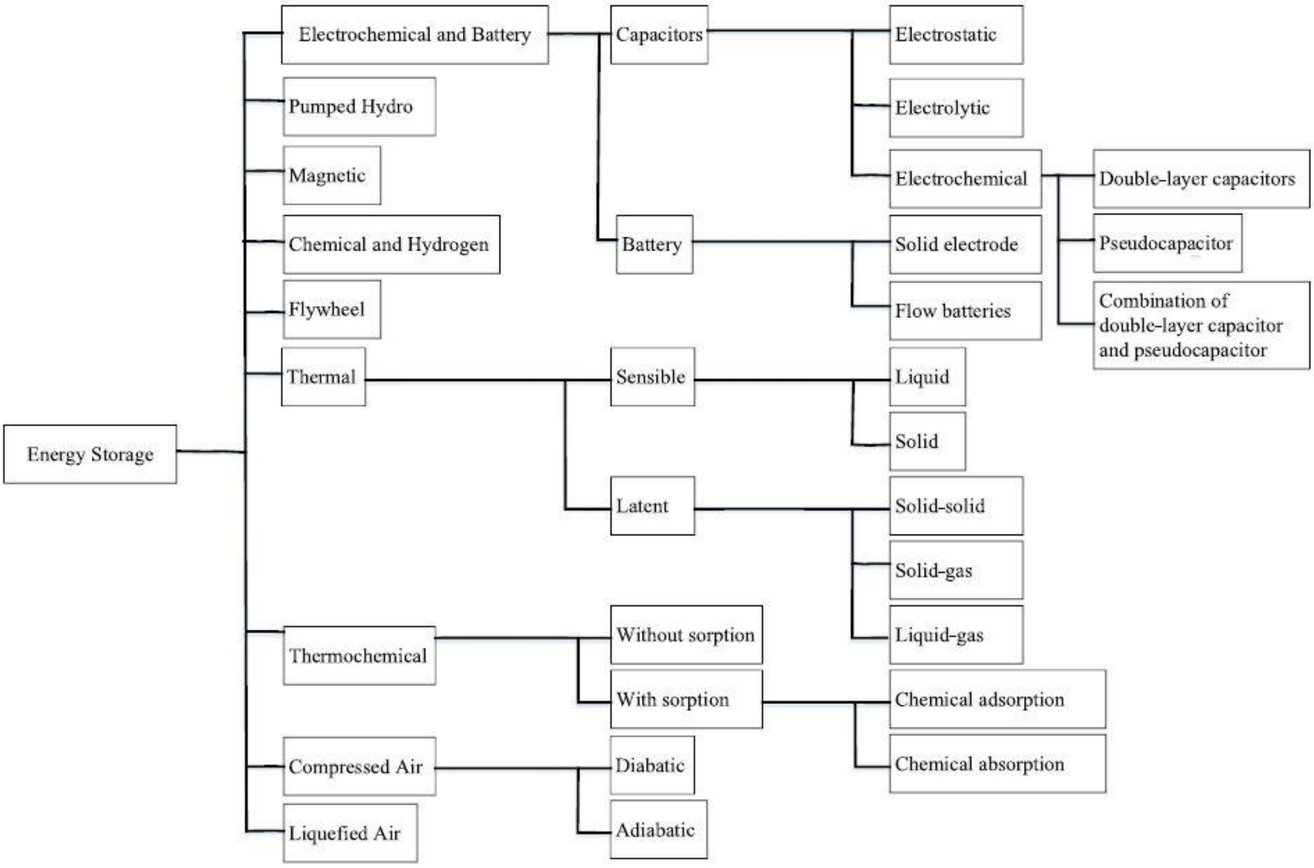

Figure 9: A classification of energy storage types [21]

2.3.1.1 Electrochemical and battery energy storage

Electrochemical and battery energy storage systems can make a significant contribution towards sustainable energy deployment [24]. Batteries and capacitors can store electrical energy electrochemically [21]. Electrical energy is stored in the battery while charged from an external electrical source and may be utilised to power the external charge during the discharge[24]. Batteries are mature, high-energy, and high-voltage energy storage units. Among various batteries, lithium (Li-ion) batteries play an increasingly vital role in energy storage due to improved energy density and specific energy [21]. Capacitors are devices that can store and delivery energy electro-chemically. They are categorized as *Electrostatic*, *Electrolytic*, and *Electrochemical capacitors* [21]. Among these three kinds - Electrochemical capacitors, also known as supercapacitors or ultra-capacitors (UCs), has very much higher capacitance and energy density since it has a porous electrode arrangement. Scotland currently has a battery storage system of about 74 MW [109].

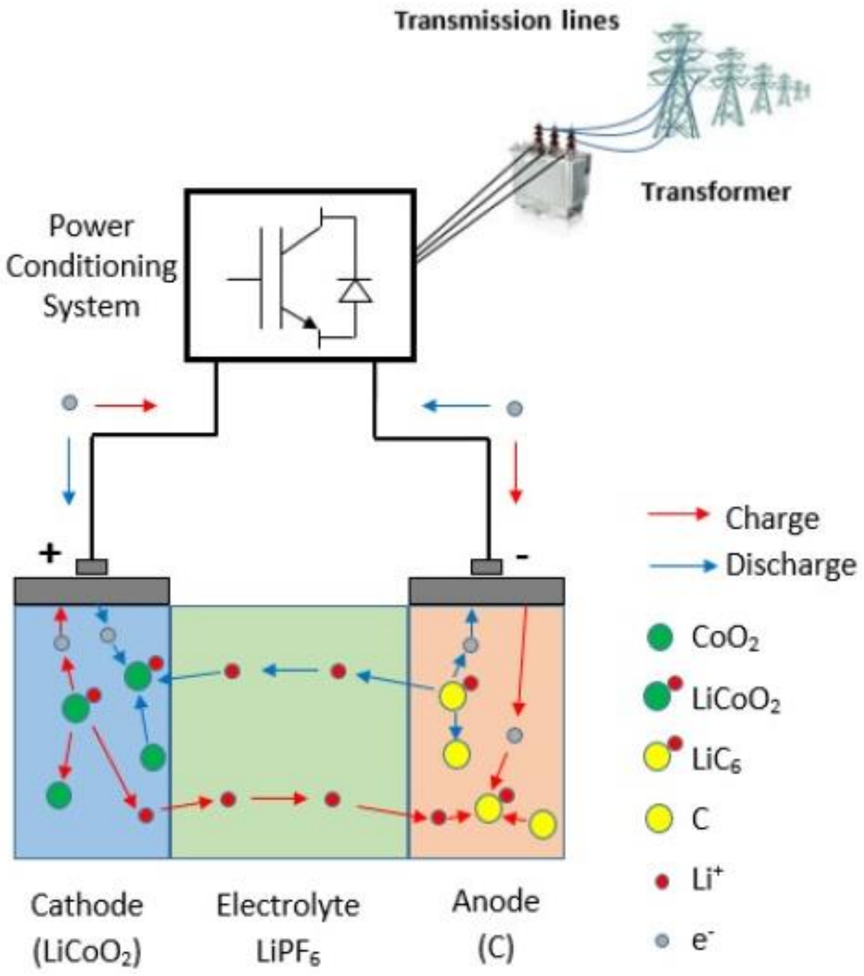

Figure 10: Simple illustration of Li-ion battery energy storage system [26]

2.3.1.2 Thermal energy storage system (TES)

TES is a technique that stores thermal energy by heating or cooling a medium so that the stored energy can be used for heating, cooling and power generation in the future [25]. Usually, thermal storage systems include a storage system and heat infusion and heat withdrawal equipment to or from the system.

Usually, thermal storage systems have a storing system and heat infusion and heat withdrawal equipment to or from the medium. The storing system can be either a natural structure or area (maybe ground) or it might be produced synthetically by using a container that obstructs loss of heat or gain heat from the environment (e.g., water reservoirs) [21]. Thermal energy storage is divided into three kinds according to the thermal mechanism utilised to store energy: *sensible heat system*, *latent heat system* and *thermochemical energy system*. The heat storage system was traditionally done in the form of sensible heat that raised the temperature of the medium. Latent heat thermal storage technology is still under research, which requires the alteration of storage between solid to liquid phases, but variations in solid-gas, liquid-gas and solid-solid phases also available [21].

2.3.1.3 Thermochemical energy storage system (TCES)

Many research carried out in recent years have shown that thermochemical energy storage system is a vital technology for developing short and long-term high efficiency heat storage for diverse applications for example solar thermal or combined heat and power (CHP) [27]. This storage system mainly uses chemical processes that necessitates or discharge heat energy. They have three operational modes: *endothermic dissociation*, *reaction product storage* and *dissociated product exothermic reaction* [21].

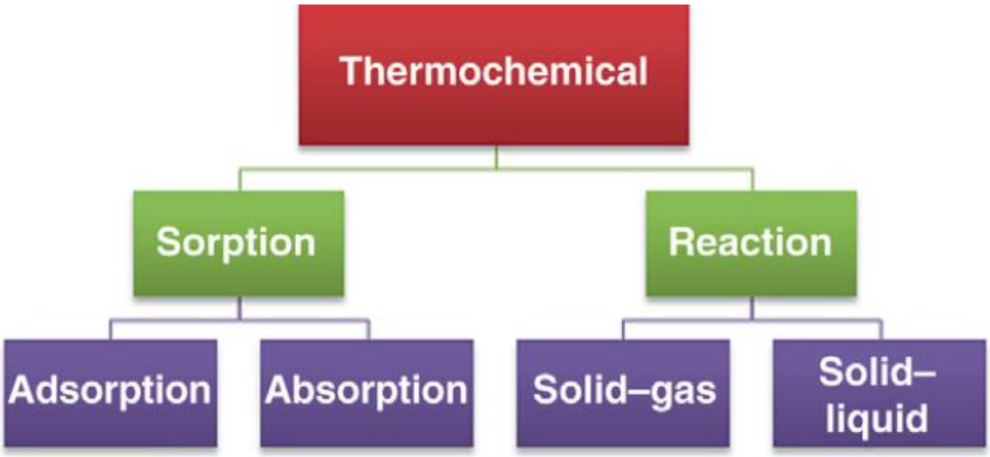

Figure 11: Classification of thermochemical energy storage system [27]

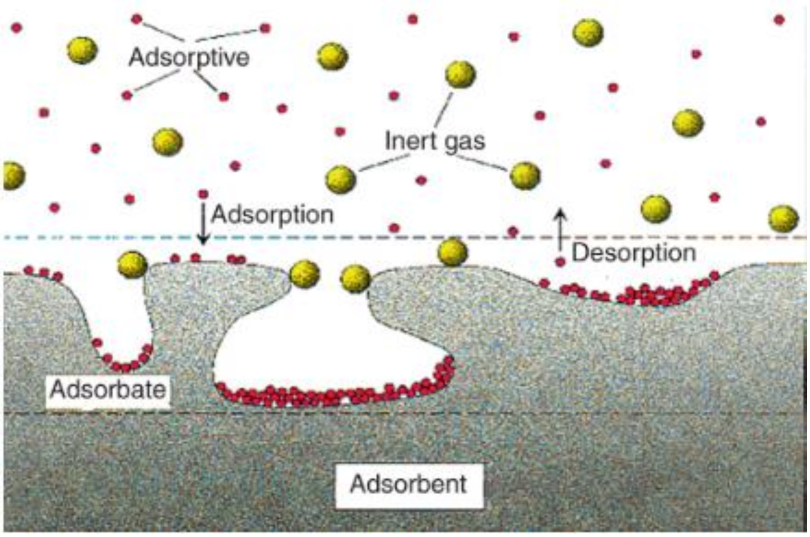

Figure 12: Simple illustration of adsorption and desorption [27]

Thermal energy storage systems offer a greater energy density than other thermal energy storage systems, which means that it allows the storage of significant amounts of energy by means of modest quantities of storage materials. Primarily for long-term storage applications, energy storage relies on chemical processes. For example, solar heat seasonally stored because throughout the storage phase the procedure entails practically little energy loss. Preservation usually takes place at room temperatures [28].

2.3.1.4 Flywheel energy storage system (FES)

It is a form of mechanical energy storage system, also called as kinetic energy storage system, suitable for efficient operation, high energy and high energy density [21].

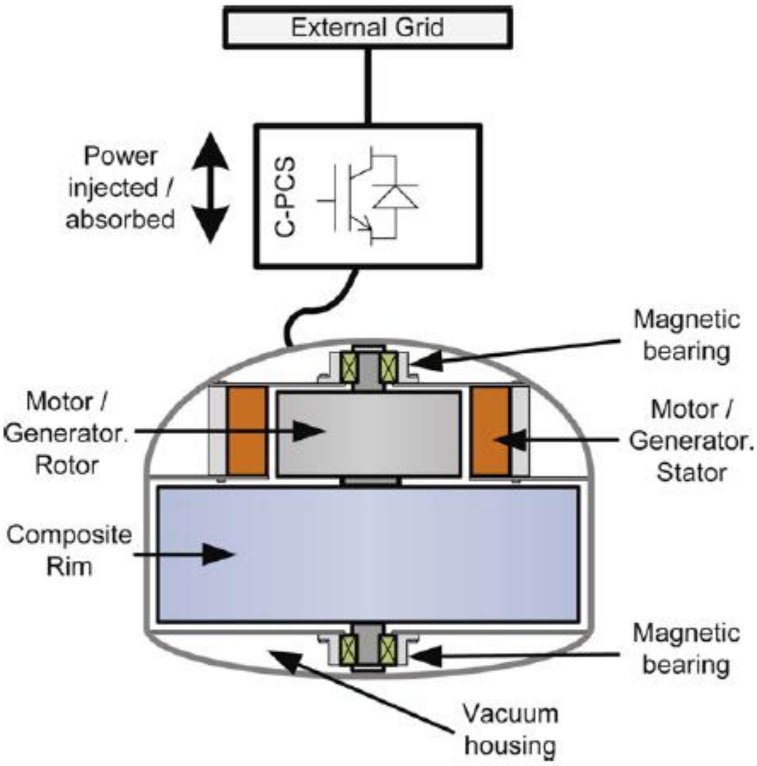

Figure 13: Simple illustration of FES [29]

In this system, energy is captured by the angular momentum of a rotating mass at non-productive hours and release energy at peak hours by the rotating inertia of the flywheel [30]. The overall energy potential is determined by the rotor's size and speed, whereas the power rating depends on the engine-generator [31].

Generally, flywheels are used in frequency stabilization, incorporation of renewable energy systems and hybrid power systems. Their efficiency is quite high (80–90%), short reaction time, low environmental impacts, and long life, which makes them suitable for utilisation.

Besides that, flywheel technology is very costly, large size flywheels are necessary to store up energy in an electric power system, resulting in greater friction losses and lower efficacy. The energy density of this system is expressed in equation 1.

$$E = \frac{1}{2} I \omega^2 \quad \textbf{(1)}$$

Where, *E*= kinetic energy (J),

I = moment of inertia (kg.m^2),

ω = angular velocity (rad/s) [26].

2.3.1.5 Compressed air energy storage system (CAES)

This system stores power at 40-80 bars during off-peak times in the form of the elastic capacity energy of compressed air [30]. The power from the grid during non-productive hours is utilized to pump and compress air into a closed underground cavern to an elevated pressure [32].

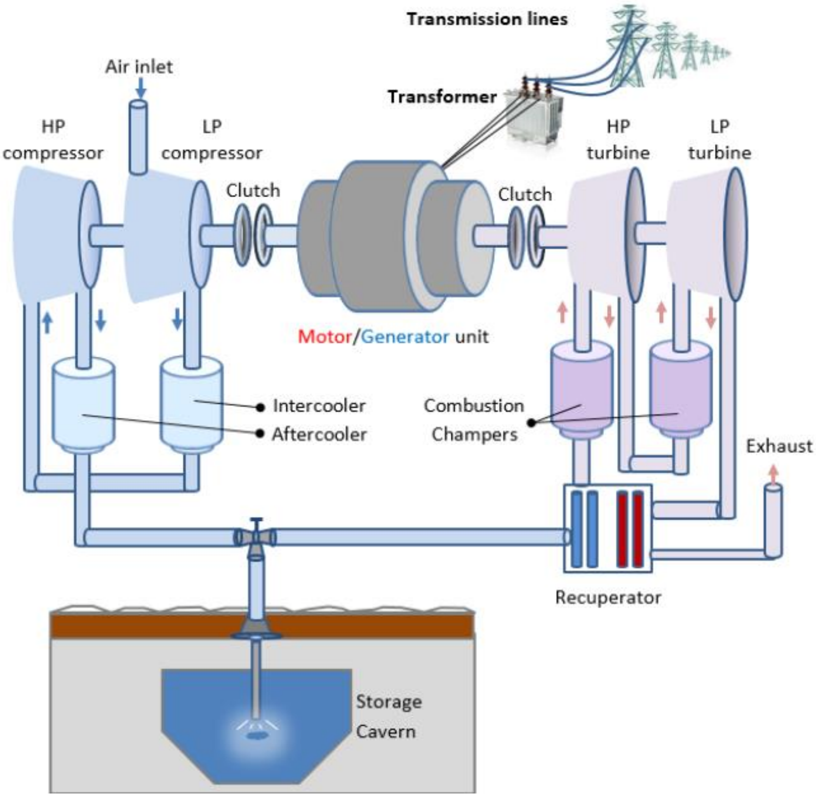

Figure 14: Simple illustration of compressed air storage system [26]

Caverns may be dug into formations of salt or rocks, or existing cavities can be used, for e.g., water strata. These kinds of geographical formations will not be available everywhere and big steel tanks are constructed underground at significant system costs, so that high pressures can be maintained. These systems can be profitable, because they are able to shift energy usage times and more recently because of the requirement to balance intermittent renewable energy into the grid [21]. Along with low environmental effects, this technology offers great dependability, and as the storage is placed below ground so no extra land usage is needed [26].

2.3.1.6 Pumped hydro energy storage system (PHES)

PHES is the only well-known system for the large-scale energy storage which is greater than 100 MW, and is by far, the most widely used storage system in the world accounting for almost 94% of the energy storage systems [26, 23]. PHES is built with an idea of extracting water from a reservoir to another at an elevated location, mostly during non-productive hours and other low power usage intervals. When electricity is needed, a hydroelectric turbine discharges the water from the elevated reservoir to the lower reservoir [31].

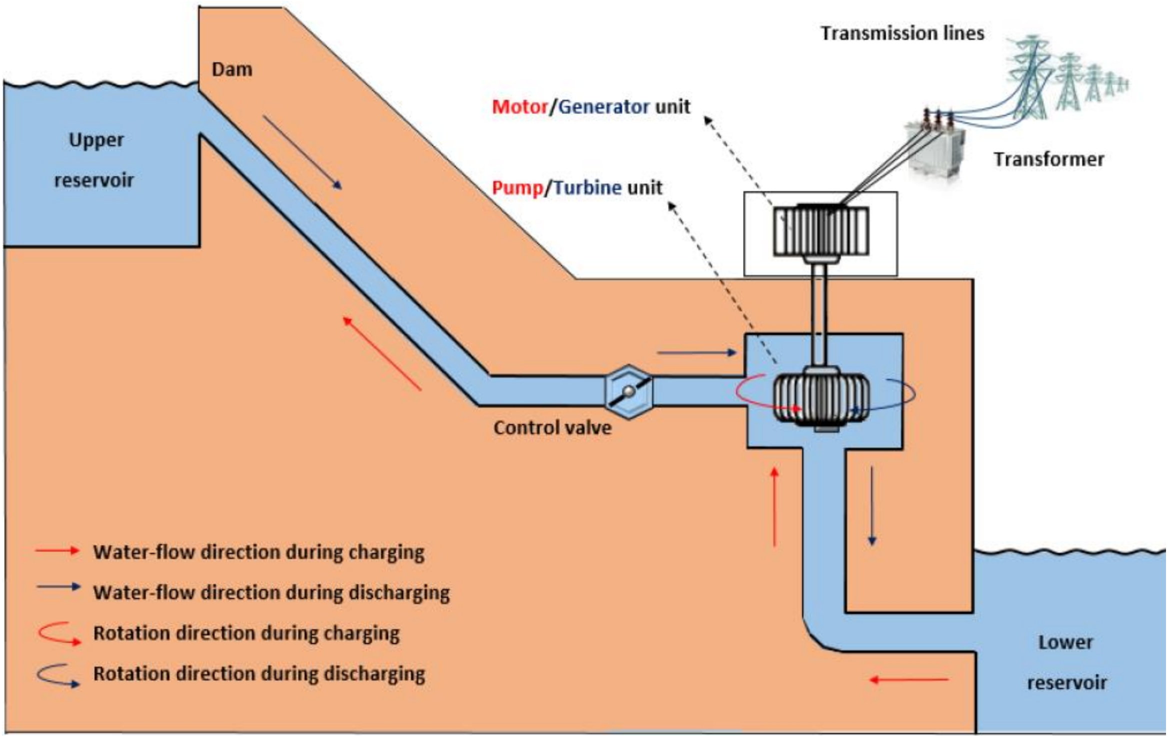

Figure 15: Simple illustration of pumped hydro storage system [26]

The quantity of stored energy depends on the difference in height between the reservoirs and the stored water mass.

$$E = mgh \tag{2}$$

Where, E= potential energy (J),

m =mass(kg),

g = Earth's gravitational force(m/s^2),

h = the head (m).

The turbine is coupled with an electrical generator to produce electricity when power is drawn out of the turbine. The water input may be regulated via gates to the turbine so that a variable power output is possible. Drives with variable speeds can also be utilised to regulate the charging process. PHES systems are 70-80% energy efficient and usually 1000-1500 MW in size. These systems have a lifetime of about 50 to 100 years, and very minimal operating and maintenance costs [21]. Scotland has a PHES system of about 740 MW currently [109].

2.3.1.7 Superconducting magnetic energy storage (SMES)

SMES is a quite brand-new energy storage system and can be achieved using a massive superconducting coil that is virtually free of electrical strength close to absolute zero temperature and capable of storing electrical power by circulating DC current in the magnetic field [21]. The maximum current out of the superconductor is reliant on the temperature. The lower the operating temperature of, the higher the achievable operating current [29]. To retain the superconducting condition, the system must be maintained at lower temperatures (-264°C), which allows the current to pass by the inductor permanently.

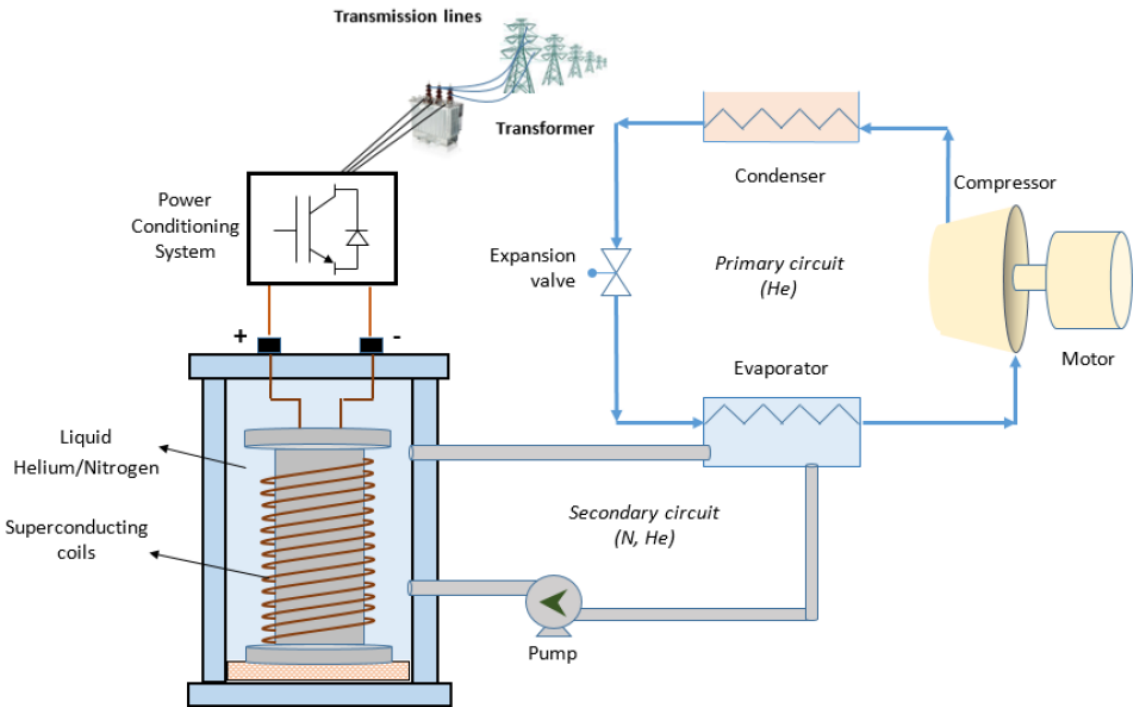

Figure 16: Simple illustration of superconducting magnetic energy storage [26]

Superconductors offer great storage efficiency up to 98% due to their almost non-resistance, which results in low energy losses and rapid reactions compared to conventional energy storage devices, since power can be injected and withdrawn very fast [26].

The energy stored is calculated by below equation:[26].

$$E = \frac{1}{2} L I^2 \quad (3)$$

Where, *E*= Energy (joules, J),

L= wire inductance (henrys, H)

I = Direct current (amps, A)

2.3.1.8 Hydrogen energy storage system (HES)

HES system initially generates hydrogen by photoconverting or electrolysis processes, which may be stored over longer durations and later chemically oxidised or reacted to restore input energy [21]. Electricity has long been a major energy carrier for various energy technologies in civilization [21]. Hydrogen energy has complementary properties to that of electricity. Some have suggested "hydrogen economy" comprising the generation, storage, distribution and use of all hydrogen energy technologies. Water splitting by electrolysis is one of the most popular method of producing hydrogen. Carbon-based fuels, renewable energy or other energy resources can supply energy required for this method. Hydrogen energy storage is significantly different, as it provides a broad storage method and may subsequently be utilised in a number of ways. The gas is beneficial since the energy source is low in carbon because its usage does not contribute to CO_2 emissions during consumption. This is why HES system is one of the most significant storage facilities [33].

As shown in Figure 17, green hydrogen generation system comprises of the following elements: an electrolyser to produce hydrogen, a compressor to compress gas, a hydrogen storage tank, and a power converter (from AC to DC). This system is accountable to generated hydrogen from electrochemical conversions so that energy may be stored as hydrogen and injected into the grid as electricity whenever necessary[29]. Due to the stochastic aspect of the wind resource, wind turbine-produced electricity may have a very inconsistent function, affecting both the quality of electricity and energy planning. In wind energy applications, energy storage systems monitor the wind turbine output and provides backup power systems, when necessary, therefore boosting the penetration of wind turbines. Globally, renewable power sources are expanding with ambitious objectives from nations that support the shift in energy sources. For example, Scotland is aiming to have the equivalent of 100% of their electricity consumption generated from renewables [34].

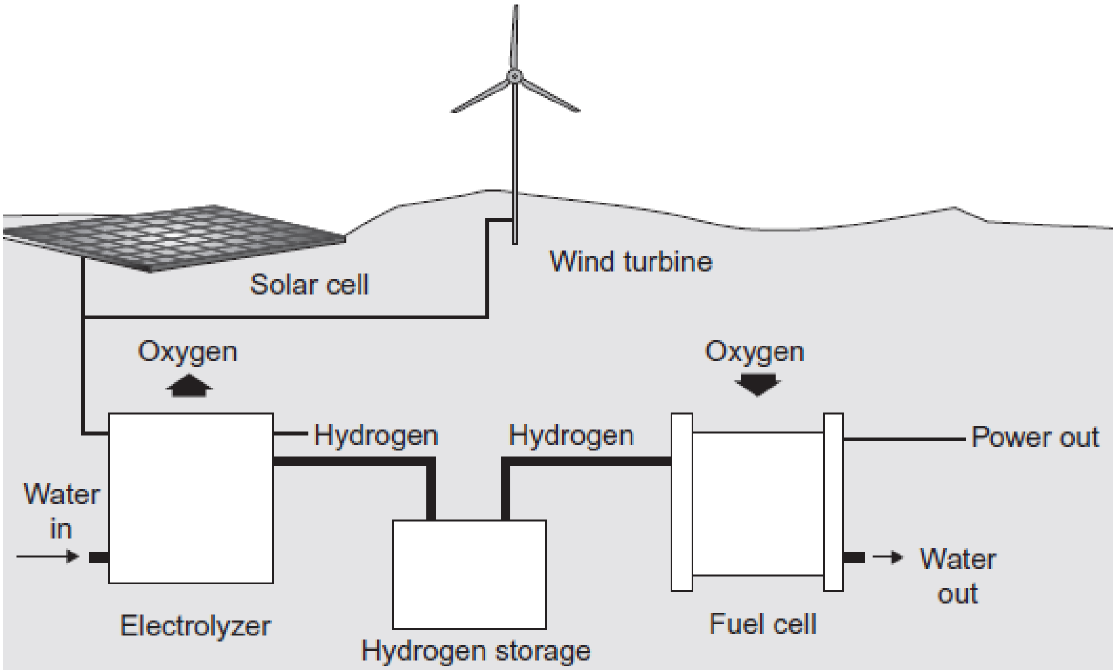

Figure 17: Simple illustration hydrogen energy storage system [33]

Although it is fantastic for countries to push for greener energy, renewable energy has one big flaw, its generation isn't predictable, and it can vary a lot from day to day. This makes it very difficult when planning energy generation to meet demand. Essentially, the hydrogen energy concept is incredibly simple when applied to electrical storage. Hydrogen is produced and is stored when there is excess or non-productive electrical power. When electric power is required this hydrogen is then utilised as to generate electricity using fuel cell [35]. Although the idea is straightforward and technology is available to implement it today, there are certain difficulties are in production, storage and energy generation and must be resolved so that this is a substantial alternative to energy storage and the zero carbon economy [35]. They all have their advantages and disadvantages, where different solutions will be application for different locations depending on the specific location and requirements.

The water electrolysis process method of producing hydrogen has been commercialized since a long time. There are a number of electrolysers nowadays, but all electrolysers work similarly, regardless of their kind. They have two electrodes in electrolysis cell. Namely negative electrode identified as cathode, and positive electrode identified as anode. They are submerged in a highly concentrated electrolyte solution, which is acidic (H^+). When adequate minimum voltage (1.23 volts, V) is supplied through the electrodes (normally a greater voltage is needed) under ideal conditions, positively charged hydrogen ions move towards cathode where it mixes, and with the accumulation of the electrons from the electrode, to form hydrogen gas.

Meanwhile, at the positive electrode, water molecules react to form oxygen while emitting additional hydrogen ions into the electrolyte solution [36].

Hydrogen needs to be stored once produced. The hydrogen storage techniques may be classified into two groups:
(1) Physical storage (gas or liquid)
(2) Material-based storage [37].

The energy density of the gas is higher, but it is relatively light and low in volume. For this reason it needs to be compressed or stored in a concentrated state to reach a high energy density by volume equal to other common fuels. [36]. The storage of the gas phase usually takes place in a 350-700 bar high pressure tank. The boiling point of hydrogen is about −253°C (at one atm) [36]. Therefore, cryogenic cooling techniques are needed to store hydrogen in liquid phase. Storage of material-based hydrogen has indicated an ability to enhance hydrogen density more than twice as much as liquid hydrogen. Materials-based hydrogen storage is possible on metal hydrides, chemically storing hydrogen, and insoluble materials. Adsorption or absorption of hydrogen can be used to store hydrogen on the surfaces of substances. More on Hydrogen storage will be discussed in detail in a subsequent section (*2.5.6 Hydrogen storage*).

Summing up all different technologies that were discussed in this section, battery storage systems might be the most economical choice of energy storage system for applications with less cycle count. Amongst all the technologies, HES systems are perhaps the only technology that can bring a major change to the existing energy system. Energy storage systems are very essential components of energy industry, particularly in systems where energy is generated from renewable energy sources so that they enjoy complete economic advantages. They are simply one among a number of alternatives for delivering flexibility in the energy system. Efficient energy storage systems will give the energy industry and its customers with numerous benefits. In addition to addressing the technological and economic issues, support from governments is also necessary by creating policies that help in boosting energy storage systems [21].

2.3.1.9 Energy storage system using Concrete blocks and cranes

This highly advanced and innovative way of energy storage system is introduced by Energy vault, a Swiss-based start-up company [38]. This has the similar working to PHES system. The basic working principle behind this system is very simple. When any object is lifted against the gravity, the energy is being stored in it and when it is allowed to fall, energy could be recovered. Since concrete is much denser than water, raising concrete blocks needs lot of energy, hence it can also store a lot more energy equal to a tank of water. Initially the cranes use excess energy (generated by solar or wind) from the power grid to stack the concrete blocks. Later when there is energy demand this energy is recovered by letting the concrete blocks fall, which will power the generator to produce electricity [38]. This system uses a slick software to maximise its efficiency, even taking into account the effects of extreme weather conditions. Currently it has an efficiency of about 85-90% and maximum energy that could be stored is about 20,000 MWh. It has very low maintenance and hence a life of about 30+ years [38] .

Figure 18: Schematic diagram of energy storage by concrete blocks [39]

2.4 Hydrogen production technologies

The hydrogen is the consequence of a chemical process but is not the energy source. This implies that the choice of the method for producing hydrogen is therefore crucial in determining how environmentally friendly the hydrogen will be. As shown in Figure 19, hydrogen can be generated with the use of various techniques and energy sources including non-renewable fuels (e.g., natural gas, coal - favourably with carbon capture storage system [CCS]), biomass, non-food yields or using nuclear energy and also renewable energy sources (wind, solar, geothermal, and hydroelectric power) to split water [40]. This range of resource possibilities makes hydrogen, a favourable energy carrier.

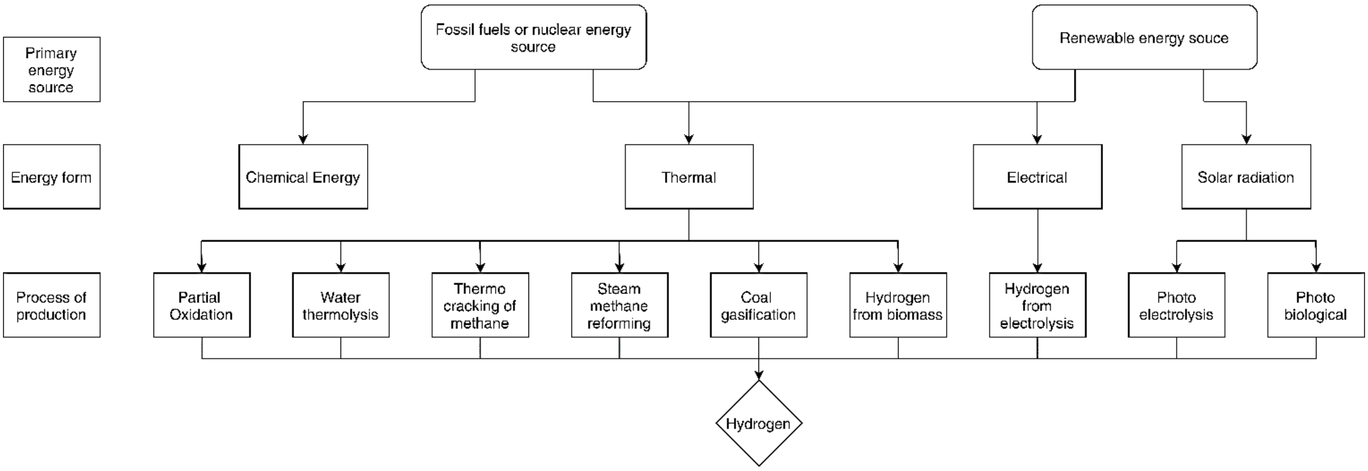

Figure 19: Different methods of hydrogen production[41]

Hydrogen available today is almost entirely (95%) generated from natural gas or coal and a small percentage (5%) is generated through electrolysis [42]. Although the motivation of this research is to produce hydrogen with the goal of carbon free Scotland, but for the sake of understanding the most prominent methods of hydrogen production will be discussed. This gives rise to the different types of hydrogen available in market today. There are different colours of hydrogen (Figure 20) in the present energy world, the most popular ones are– grey, blue, turquoise, and green [43]. Also, the most recent ones are pink, yellow, and white [44].

- **Grey Hydrogen:** When hydrogen is produced using fossil fuels, and hence the process generates carbon emissions, unsuitable for a route toward net-zero emissions [43].
- **Blue Hydrogen:** It is same as grey hydrogen, produced mainly from natural gas. But production takes place using CCS to trap the released emissions [43].
- **Turquoise Hydrogen:** This type is made using a process known as methane pyrolysis to produce hydrogen with no CO_2 emissions. The carbon in methane is made solid

carbon black through the pyrolysis process. This type is still at the experimental stage [43].

- **Green Hydrogen:** When hydrogen is produced using renewable energy system such as wind turbines, solar photovoltaic panels, hydropower, biomass and even waste collection. This is the most suitable one for a fully sustainable energy transition [43].

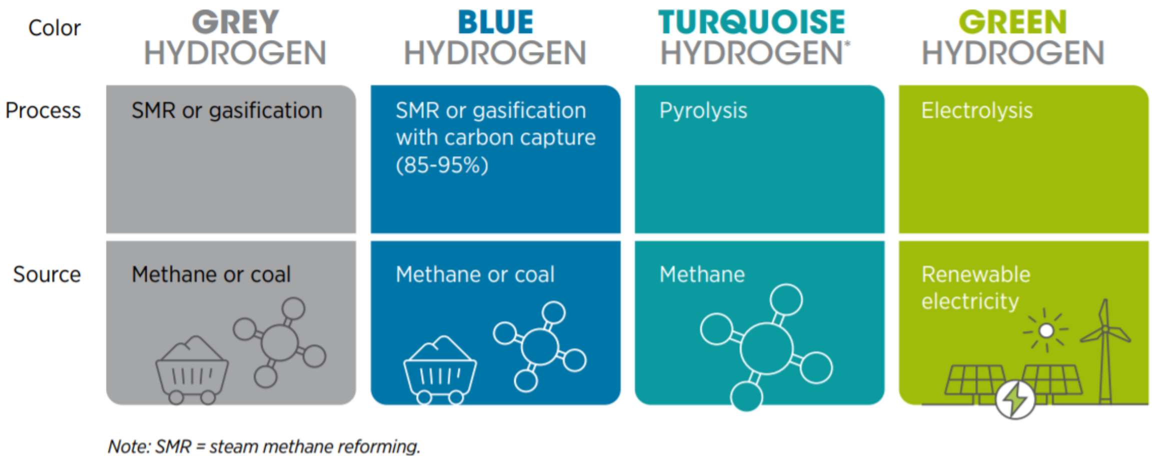

Figure 20: Shades of hydrogen [43]

- **Pink Hydrogen:** This type of hydrogen is produced using electrolysis process powered by nuclear power.
- **Yellow Hydrogen:** This is a very new type and hydrogen is produces using solar power in a photocatalytic or photoelectrolysis process.
- **White Hydrogen:** This type is available naturally in underground deposits of the earth and extracted by fracking process.

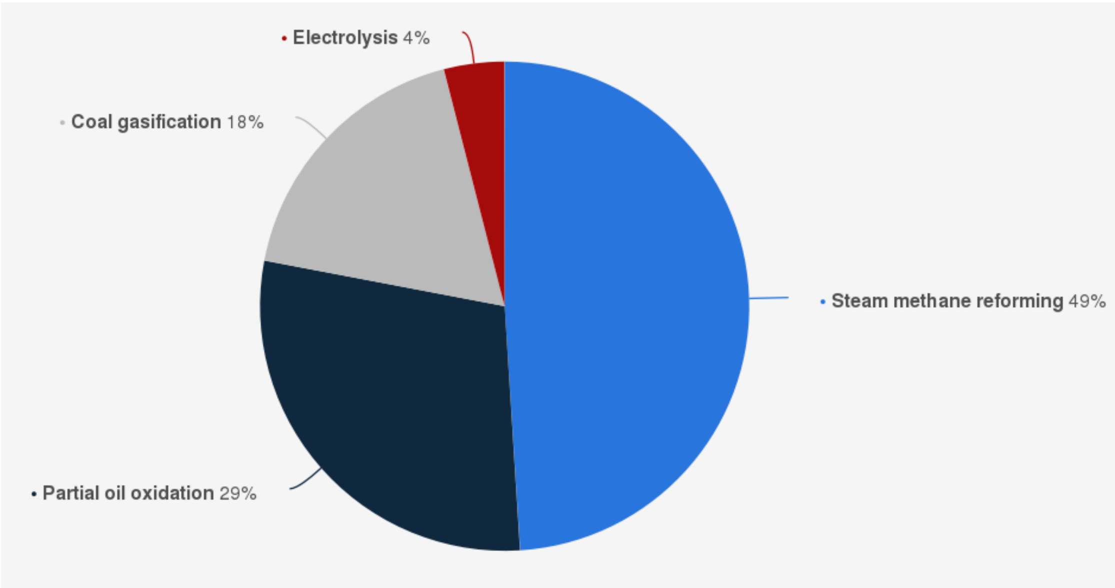

Figure 21: Hydrogen production technology as of 2019 in the UK 2019 [45]

Hydrogen is primarily produced using two methods *Steam reforming* and *Electrolysis* also known as water splitting. In the UK, steam methane reforming from natural gas is the most common method of producing hydrogen [45].

- **Steam reforming:** It is a very high temperature (700°C–1,000°C) process in which steam reacts with hydrocarbon fuel to produce hydrogen. Many hydrocarbon fuels can be reformed to produce hydrogen including natural gas, diesel, renewable liquid fuels, gasified coal, or gasified biomass [40, 46]. During steam methane reforming process, methane reacts with steam under the pressure of 3–25 bar in the presence of a catalyst for the production of a relatively low amount of hydrogen, carbon monoxide and carbon dioxide. Steam reforming is endothermic, which means that heat has to be provided for the reaction process [46].

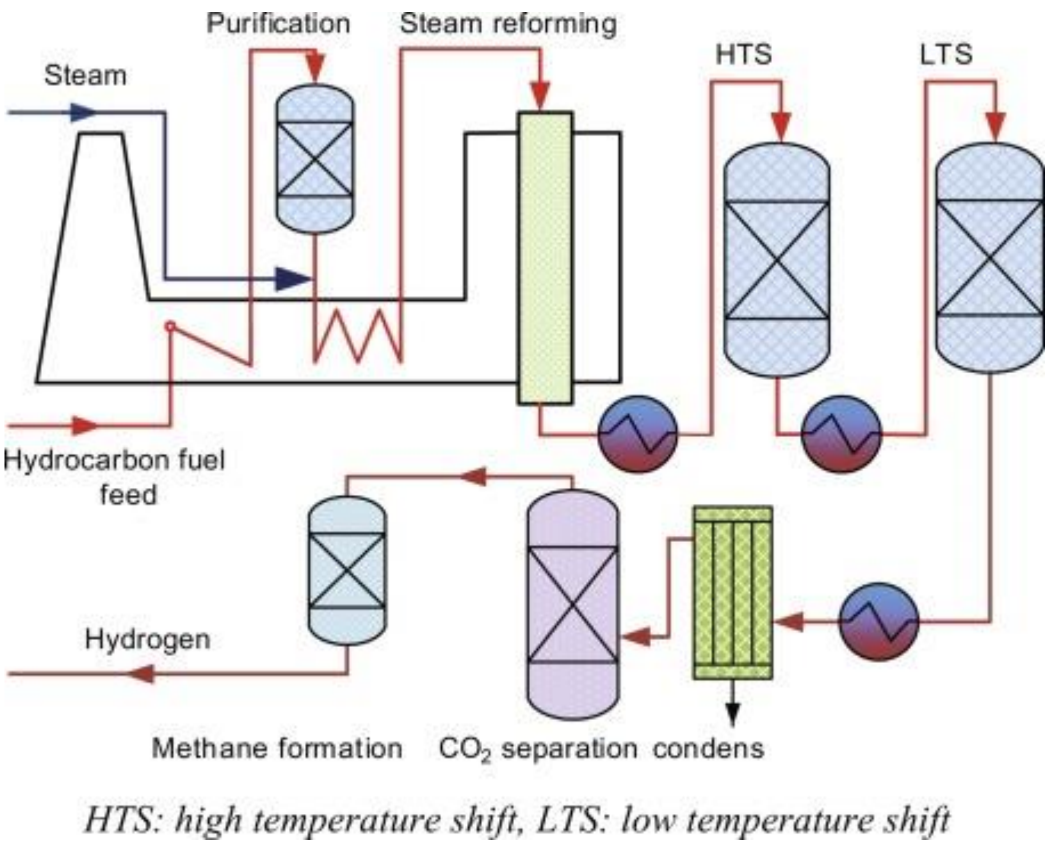

Figure 22: Simple illustration of Steam reforming process [40]

The carbon monoxide and steam are then interacted with the catalyst to create additional carbon dioxide and hydrogen in what is called the "water-gas shift reaction." Carbon dioxide and other impurities are removed from the gas stream in a final process called "pressure swing adsorption" (PSA) which mainly leaves pure hydrogen. Steam reforming may also be used to generate hydrogen from other fuels, including ethanol, propane or petrol [46].

* Steam-methane reforming reaction:

$$CH_4 + H_2O\,(+\,heat) \rightarrow CO + 3H_2 \quad (4)$$

* Water-gas shift reaction:

$$CO + H_2O \rightarrow CO_2 + H_2\,(+\,small\ amount\ of\ heat) \quad (5)$$

- **Coal gasification:** It is the oldest method of obtaining hydrogen through the gasification of coal. This gas, which is generated in older gas plants, includes 60% hydrogen and a lot of carbon monoxide (CO) [40]. This process is also called as partial oxidation. The methane and other hydrocarbons react with a limited amount of oxygen that is not sufficient for the hydrocarbons to fully oxidise to carbon dioxide and water. In this process, the coal is heated to 900°C, converts into a gas, is combined with steam and oxygen, and is typically passed through a nickel-based catalyst, or FeO-CrO_2-ThO_2 at 857°C [40]. The chemical reactions are as follows:

* Partial oxidation of methane reaction

$$CH_4 + ½O_2 \rightarrow CO + 2H_2\,(+\,heat) \quad (6)$$

* Water-gas shift reaction

$$CO + H_2O \rightarrow CO_2 + H_2\,(+\,small\ amount\ of\ heat) \quad (7)$$

Due to the high temperature requirements and the generation of pollutants, this process is less favoured. To generate pure hydrogen, the carbon monoxide (CO) in the syngas can also be transformed to additional hydrogen and carbon dioxide (CO2), by adding steam and reacting through a catalyst in a water-gas-shift reactor to separate a pure hydrogen gas, usually using the PSA process [40].

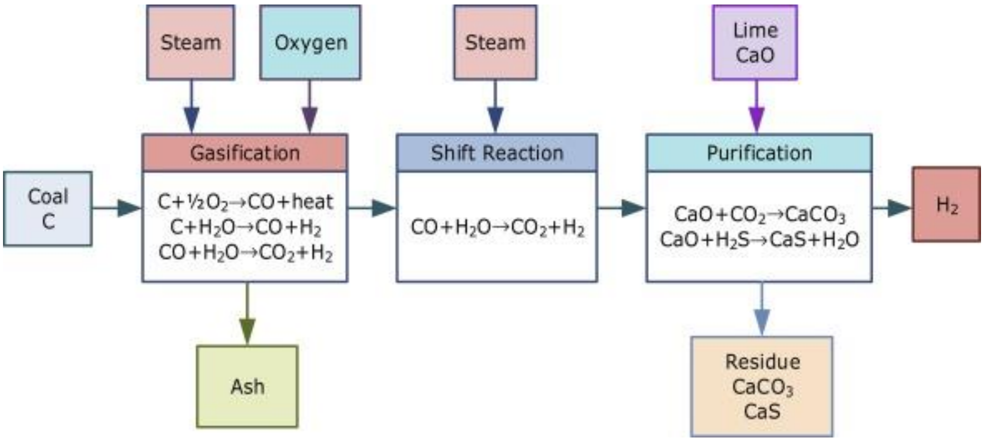

Figure 23: Flow diagram of the coal gasification process[40]

- **Biomass gasification:** Gasification is a potential method in thermochemical technology to convert biomass into gas or syngas for fuel. It typically occurs in partial oxidation of air, steam or oxygen at a high temperature of 800–1000°C [47]. Biomass, a renewable organic resource, which comprises farm crop leftovers (for example, corn stover or wheat straw), forest residues, special crops cultivated particularly for energy consumption, such as switchgrass or willow trees, organic municipal solid trash, and animal waste [48]. Since growing biomass removes carbon dioxide from the atmosphere, this technique can have minimal net emissions of carbon, especially if it is combined with carbon collection, usage and storage in the long term [48].

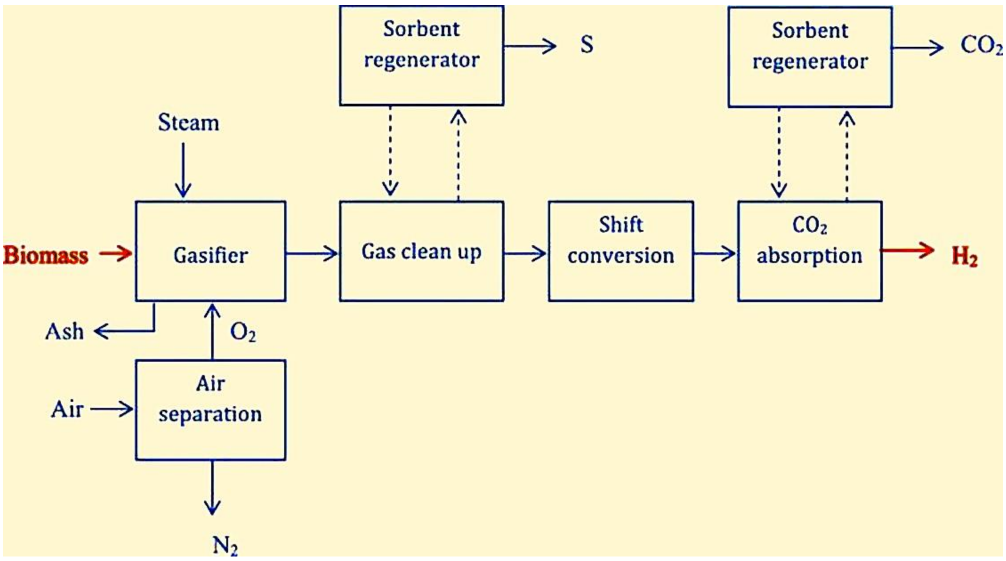

Figure 24: Flow diagram of the biomass gasification process [49]

The gasification process converts organic or fossil-based materials containing carbon into carbon monoxide, hydrogen, and carbon dioxide at high temperatures (>700 °C) using controlled amounts of oxygen and/or steam without burning them. The carbon monoxide then reacts with water to form carbon dioxide and more hydrogen through a water gas shift reaction. Adsorbers or special membranes can separate the hydrogen from the gas stream [48]. The chemical reactions are as follows:

$$C_6H_{12}O_6 + O_2 + H_2O \rightarrow CO + CO_2 + H_2 + other\ species \quad \textbf{(8)}$$

* Water-gas shift reaction:

$$CO + H_2O \rightarrow CO_2 + H_2\ (+\ small\ amount\ of\ heat) \quad \textbf{(9)}$$

- **Water electrolysis:** Water electrolysis is one of the most promising technologies for generating environmentally friendly hydrogen, it is powered by the flow of electrons which constantly circulate through an external circuit [7]. As discussed in earlier section (2.3.1.8) electrolysis is a process that splits water into its basic elements hydrogen and oxygen using an electric current. Electricity used in the process may come from hydrocarbons or renewables. If the electrolysis is powered using renewable resources, it is called green hydrogen. Renewable hydrogen can be used to decarbonise fossil fuel intensive industry and the transport sector.

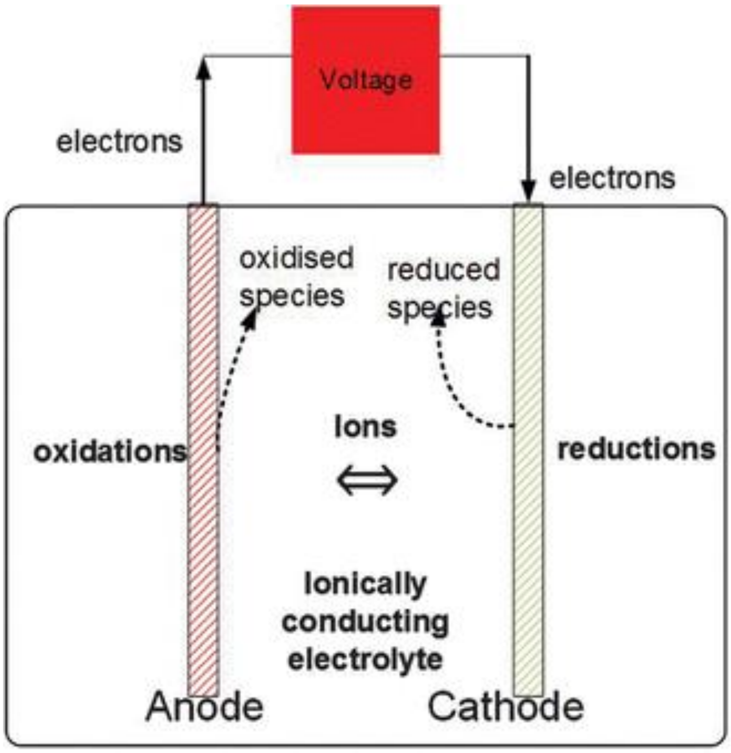

Figure 25: Simple diagram of an Electrochemical cell / Electrolyser [50]

Electrochemical cells are formed by placing two conductive materials (conductors or semiconductors) called electrodes in an ionically conductive electrolyte and electronically connecting them. In the cell two sets of reactions occur at different electrodes. Anodization at anode and reduction at the cathode, both are connected by the flow of an electric current (Figure 25). This current flows from the electrolyte to the ions in the form of electrons at the electrode, separating the electrodes [50].

The chemical reactions are as given below:

* Cathode reaction (reduction):

$$2H_2O + 2e^- \rightarrow H_2 + 2OH^- \quad \textbf{(10)}$$

* Anode reaction (oxidation)

$$2H_2O \rightarrow O_2 + 4H^+ + 4e^- \quad \textbf{(11)}$$

* Water electrolysis summary equation:

$$2H_2O \rightarrow 2H_2 + O_2 \quad \textbf{(12)}$$

These reactions occur in a device called Electrolyser. Electrolysers may range from simple appliance size device to a large-scale equipment. Based on their electrolyte, working conditions and ionic agents, electrolysers may be categorised into four distinct kinds, but the basic operating principles remain the same [1]. They are *Alkaline, Polymer electrolyte membrane (PEM), Anion exchange membrane (AEM)* and *Solid oxide*. These will be discussed in detail in the subsequent section 2.5.3.

In October 2020, Scotland announced to launch the world’s first continuous green hydrogen plant at Orkney. The plant developed by the European Marine Energy Centre (EMEC), will be powered by tides combined with vanadium flow batteries [51]. The most likely technology for manufacturing low carbon hydrogen at near to mid-term volumes is steam-methane reforming and electrolysis, provided that the challenges of high levels of carbon capture (for steam methane reforming) and cost reduction and renewable energy sources (for electrolysis) can be overcome [52].

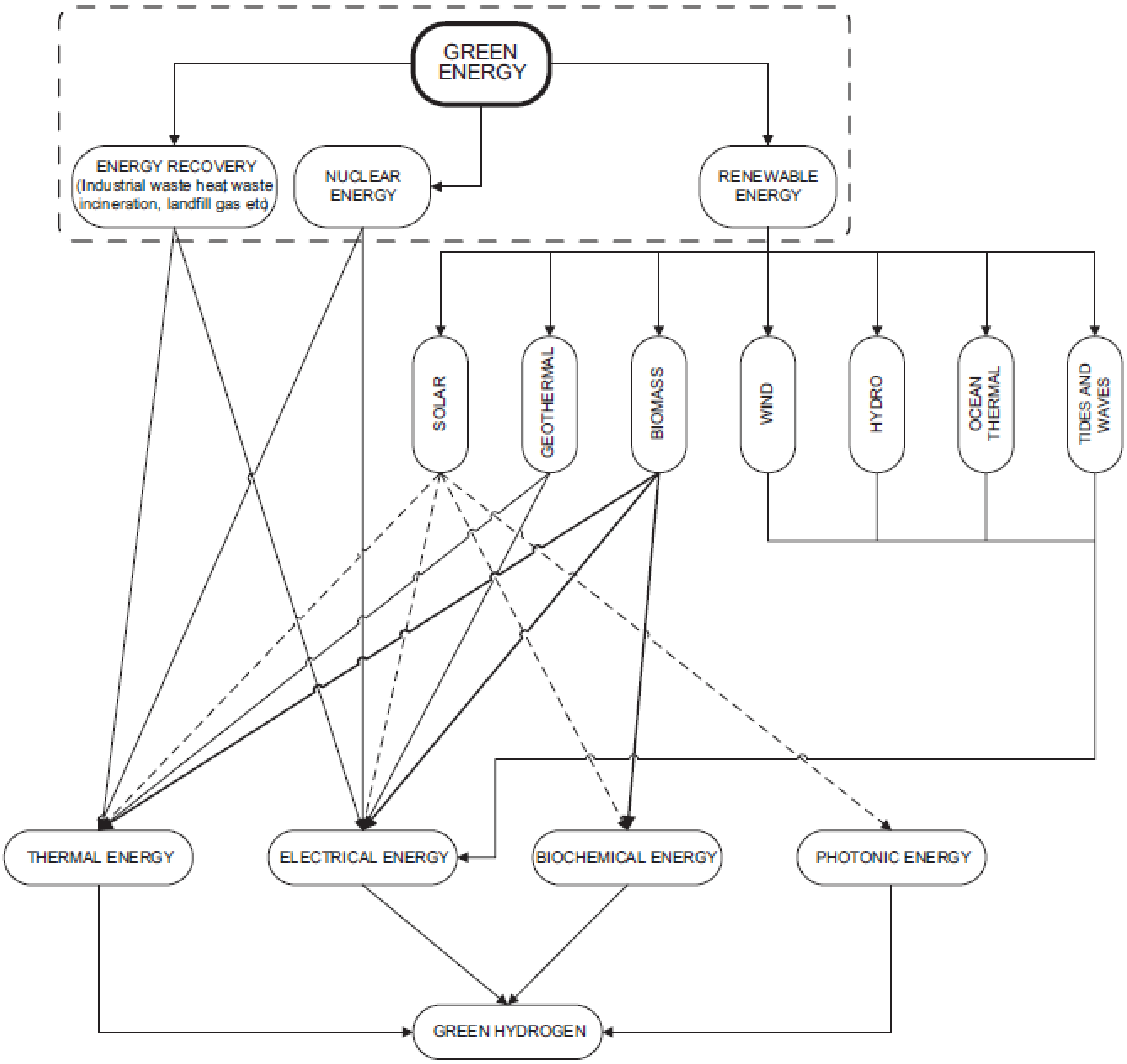

Figure 26: Various paths to generate energy from major green energy sources [7]

The major methods for generating green hydrogen and material resources from which hydrogen may be extracted are diverse, but water, sea water, hydrogen sulphide, biomass and fossil hydrocarbons are of key significance [7]. When fossil fuels are considered, precautions must be taken to extract to extract and conceal the carbon dioxide resulting from the reactions. Naturally, every method of production has its own positives and negatives. For this reason when selecting a method various criteria needs to be considered, including environmental impact assessment, efficiency, cost efficiency, usage of resources, commercial availability and feasibility, and alternatives for system integration also needs to be examined [7].

2.5 Wind powered hydrogen energy system components

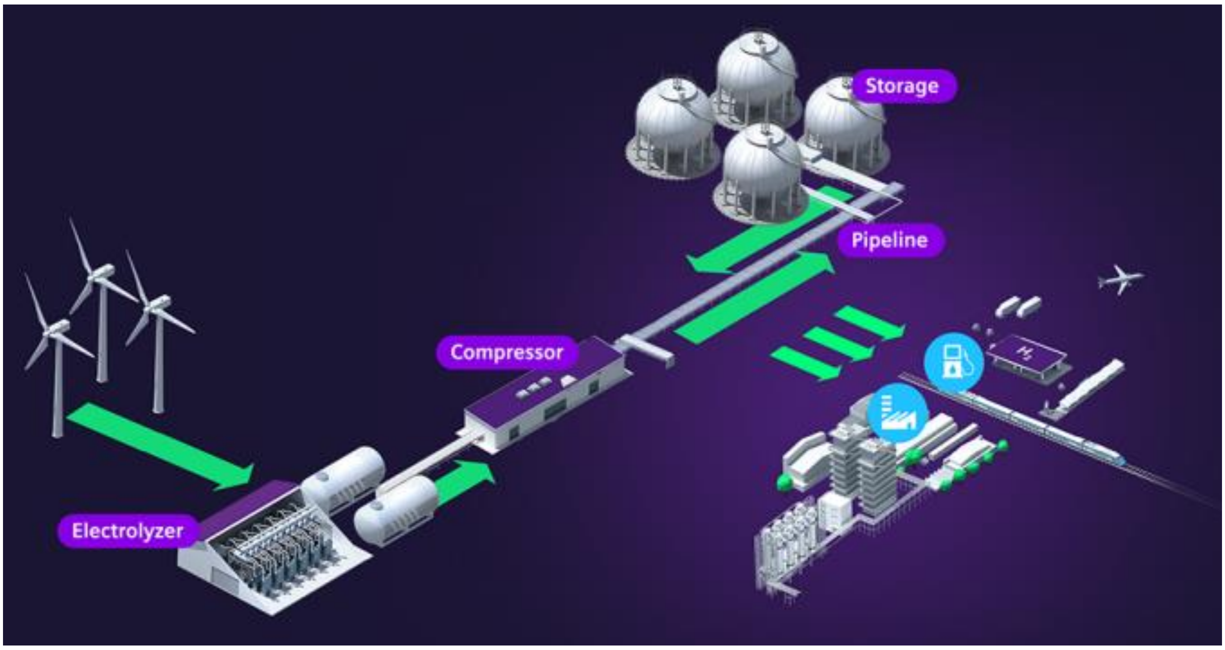

Figure 27: Wind-powered hydrogen energy system

The wind powered hydrogen energy system includes wind turbines, converters, electrolysers, compressors, and either pipelines or storage mediums. The different components are discussed below in detail.

2.5.1 Wind turbine

Wind power is harnessed by wind turbines, which converts the kinetic power provided by wind into usable mechanical energy and convert it into electric power to supply electricity. In terms of power production, wind energy is most rapidly growing renewable energy today. It is one of the cheapest technology with an actual wind energy cost of 5 to 6 pence per kilowatt-hour [53]. The majority of wind turbines are grouped into two types [54]:

1. *Horizontal axis turbines*
2. *Vertical axis turbines*

The most common wind turbine for electricity generation is the horizontal-axis wind turbine. The major parts of the turbine system are the rotor and the generator. The blades, which are placed in the rotor, are an extremely essential element of the system since they carry out the function of harnessing the wind. Because of aerodynamic forces, the blades have different pressure on each side, and they function on the concept of 'lift' and 'drag,' increasing the lift force and driving the rotor to spin [55]. Either the rotor is connected directly with the generator or through a shaft that drives the transmission system.

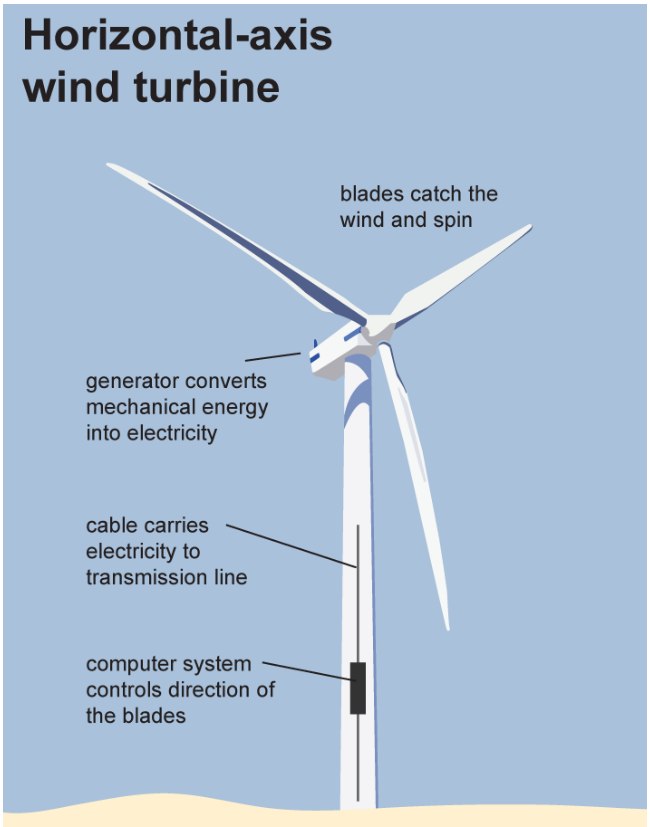

Figure 28: Standard horizontal-axis wind turbine [56]

Modern wind turbines are classified according to where they are erected and how they are linked to the grid [54]:

1. **Onshore or Land based wind turbines** are turbines are most cost-effective and usually located in areas where there is low conservation or habitat value.

2. **Offshore wind turbines** are very massive and taller in size. These turbines are capable of capturing powerful ocean winds and generate electricity.

3. **Distributed wind turbines** use wind energy to deliver clean, zero carbon energy for homes, farms, schools, and small enterprises.

Modern wind turbines require at least Class 3 winds to function. Table 2 shows the standard wind classification, which demonstrates that class 3 winds begin at 6.393 m/s. Below that, the available wind power is negligible on a utility scale. The turbines are to function between two speeds known as the cut-in speed and the cut-out speed which poses the limits. Any speed below the cut-in speed would be too low to produce any reasonable power and over the cut-off speed, the turbine is shut as it needs to be protected from damage [57].

Table 2: Wind power classification at 50 m [58]

Wind Power Class		Wind energy density (W/m²)	Avg. wind speed (m/s) *	Source potential
1	1-	0-100	0-4.381	Very poor
	1+	100-200	4.381-5.588	
2	2-	200-250	5.588-6.035	Poor
	2+	250-300	6.035-6.393	
3	3-	300-350	6.393-6.706	Marginal
	3+	350-400	6.706-7.018	
4	4-	400-450	7.018-7.287	Good
	4+	450-500	7.287-7.510	
5	5-	500-550	7.510-7.778	Very good
	5+	550-600	7.778-8.002	
6	6-	600-700	8.002-8.404	Excellent
	6+	700-800	8.404-8.807	

*Mean wind speed is based on Weibull shape parameter value of 2.

The amount of power produced is directly related to how much area is being swept by the blades, and the amount of wind reaching the blades depends on the tower height [59]. The hourly power produced by the wind turbine is calculated by the formula given below [59]:

$$P = \frac{1}{2}\rho . A . v^3 . C_p \tag{13}$$

Where, P =power produced, kilowatt (kW),

ρ =density of air, kg/m^3,

A = the swept area, m^2,

C_p = power co-efficient,

v = the wind speed perpendicular to turbine, m/s.

2.5.1.1 Floating offshore wind farms (FOWF)

The most emerging technology of modern day which has been making a lot of buzz is the Floating offshore wind energy that offers accessibility to additional wind generation locations allowing for an expanded wind supply in upcoming zero-carbon energy systems [60]. Renewable energy is presently responsible for 25% of the overall UK energy generation, with wind energy and solar energy producing 14%, but as stated earlier wind power alone in Scotland accounted for about 73% (23.5 TWh) of total renewable energy generation (in 2020), of which 14% (3.5 TWh) was derived from offshore wind resources [14]. At present, OWF are mostly placed in near-surface (up to 60 metres deep) and far off from the coastline, the maritime route, in strategical naval facilities and in ecologically sensitive areas [61]. This implies that it cannot be constructed further than 30 kms from the coast in most places.

FOWF epitomizes the future of energy source from offshore winds, expanding access to depths up to 0.7 km–1.3 km [60]. They are based on floating structures instead of fixed structures (as in conventional offshore turbines), extends new prospects and alternatives. This technology might allow wind farms to be constructed well beyond the waters, where wind is generally stronger. In addition to higher wind speeds, access to locations dispersed across a broad region can offer more spatial diversity possibilities [60]. A floating offshore wind platform (FOWP) is a concrete, steel, or hybrid substructure that houses the wind turbine and provides buoyancy and stability. Floating platforms are anchored and moored to the seabed. The remainder of the operation is identical to a conventional wind turbine [62].

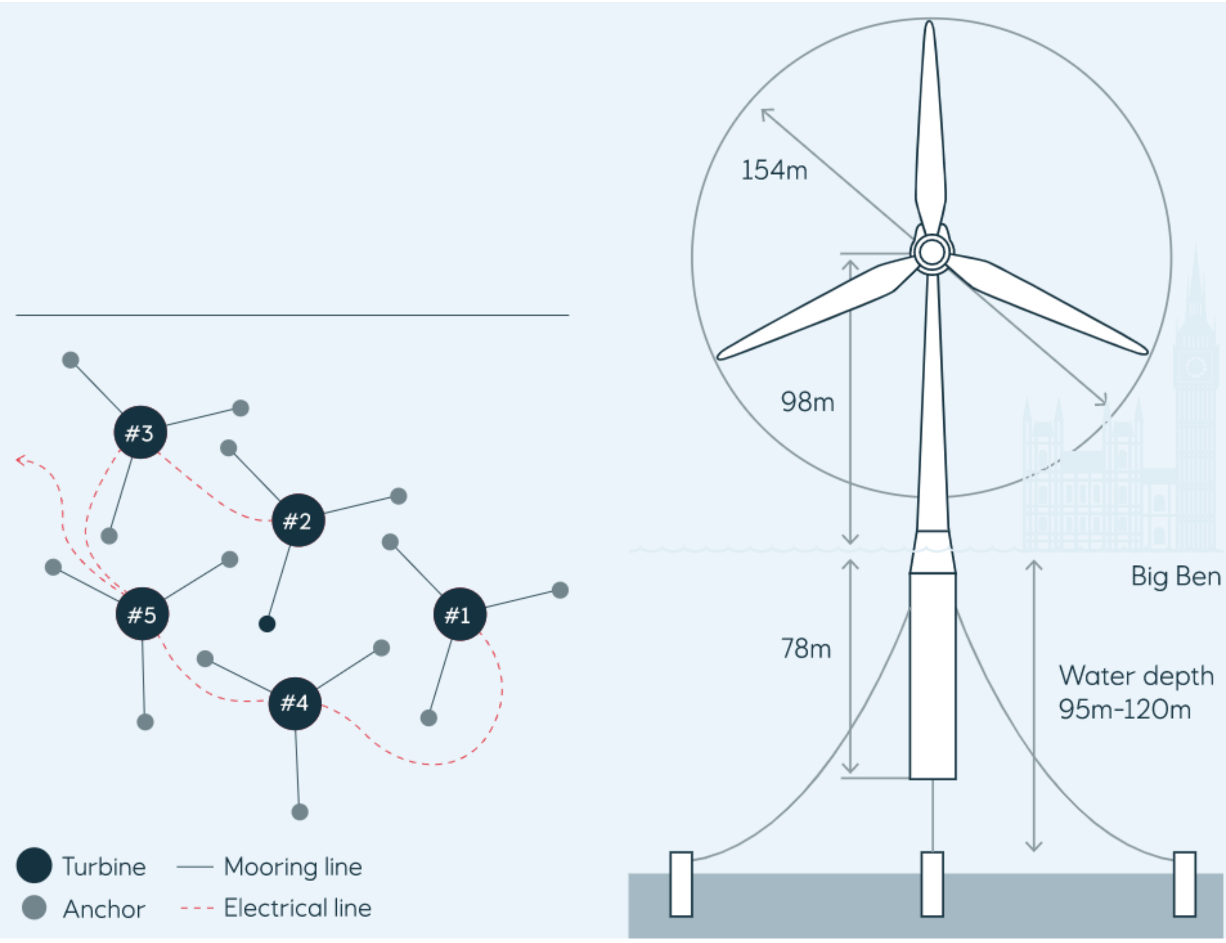

Figure 29: Schematic diagram of Hywind Scotland [63]

At the Hywind wind farm which is a new major project (world's first) in north-east Scotland (25 kms off the shore of Peterhead), the modern offshore floating wind turbines currently being installed can operate in water up to 1 km deep [64]. The 30 MW Hywind project consists of five 6 MW turbines weighing 11,500 tonnes and this is built by Statoil, along with Masdar [64].

2.5.2 Converter

The power generated from the wind turbine varies greatly in frequency and amplitude. In turn, the power grid has rigorous input power requirements in terms of frequency, phase shift and sinusoidal shape. Therefore, power converters are frequently employed in wind power. AC-DC-AC converter is used to convert three-phase alternating current (AC) power, generated from wind turbines to direct current (DC) power, required for electrolyser. AC-DC converter is also called rectifier, which rectifies the AC voltage to DC voltage [65]. Moreover, DC-DC converters transform the DC source from voltage level to voltage level by momentarily saving the input energy and releasing this power to the output at a different voltage [66]. The AC-DC rectifier has an efficiency of 95-99% whereas DC-DC converter efficiency is about 95% [65].

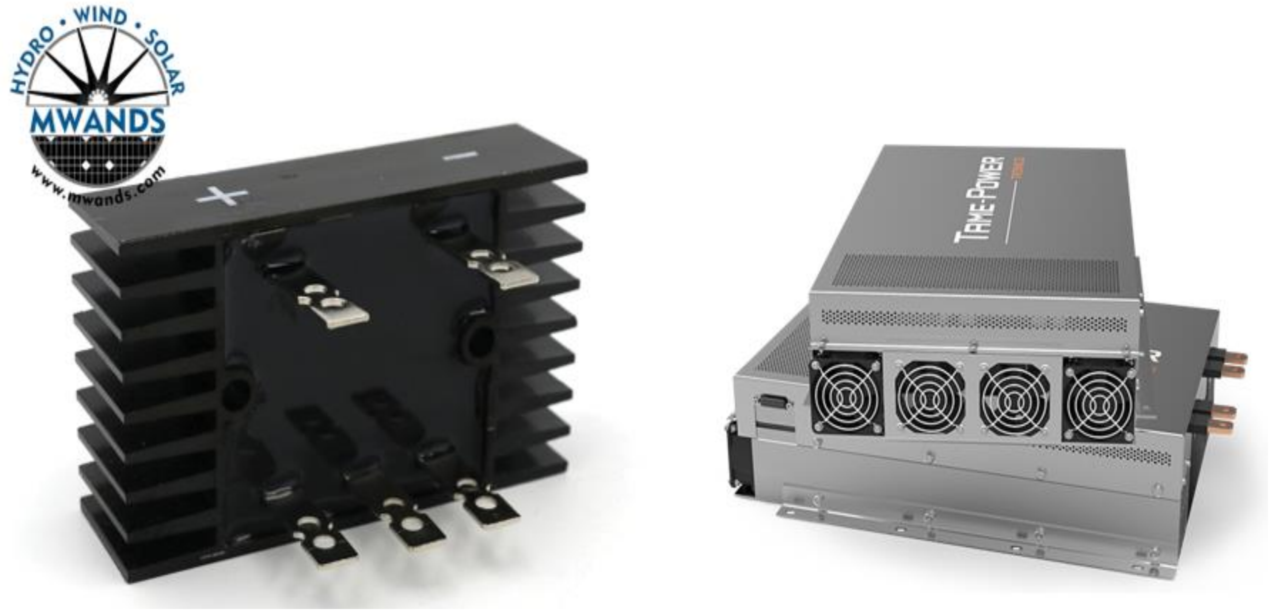

Figure 30: AC-DC Converter (left) [67], DC/DC converter (right)[68]

2.5.3 Electrolyser

With more than 95% of the current world's hydrogen source derived from fossil fuels, the possibility for vast capacity electrolyser systems to produce zero-carbon hydrogen is tremendous [69]. Scotland has in its pipeline to reach about 0.2 GW installed capacity by 2025 and about 2 GW electrolyser capacity by 2032 and 5 GW by 2045 to achieve the decarbonising goals set by Scottish government [69]. Scottish power launched a plan to build the biggest electrolyser in the UK in Glasgow, Scotland. The electrolyser will be installed at Whitelee wind farm of Scottish Power, it will be coupled with 50 MW of a battery-storage system [70]. Silyzer 300, a Proton Exchange Membrane (PEM) electrolyser by Seimens energy has the highest level of overall plant efficiency of 75.5% with lower maintenance requirements producing high quality pure hydrogen from 100-2000 kilograms (kgs) per hour [76]. As discussed earlier in section 2.4 an electrolyser is a system that splits water into oxygen and hydrogen. The cell contains a layer called membrane that divides the electrochemical cell into cathode (positive pole) and an anode (negative pole). It does not involve any peripheral components or moving components. It is a critical component of hydrogen systems for renewable energies and represents a large part of the expenses. When current is supplied to the electrodes, electrolysis takes place. The electrolyser consists of the stack and the rest of the plant, which comprises of electric power system, supplying the water, compressor, probably electricity and gas processing unit [1]. The reactions in an electrolyser are identical to the reactions in fuel cells but reversed. Hydrogen gas is produced at cathode in an electrolyser whereas in a fuel cell hydrogen gas is created at the anode [71].

The electrolysers can be divided into three levels as shown in Figure 31 below. The cell is the electrolyser's core or hub and here the chemical reactions are carried out. As mentioned earlier, here the two electrodes are immersed in an electrolyte solution adjoining to the membrane, two permeable passage, and the bipolar plates that support mechanically and dispense the movement [1]. Stack is collection of a number of cells with insertions or spacers to separate each cell. It has seals and frames to support mechanically and end plates to avoid leakages. System level is the compressors, dryers, water and electrical power supply, rectifier hydrogen gas processor, purifier, and storage tank [1].

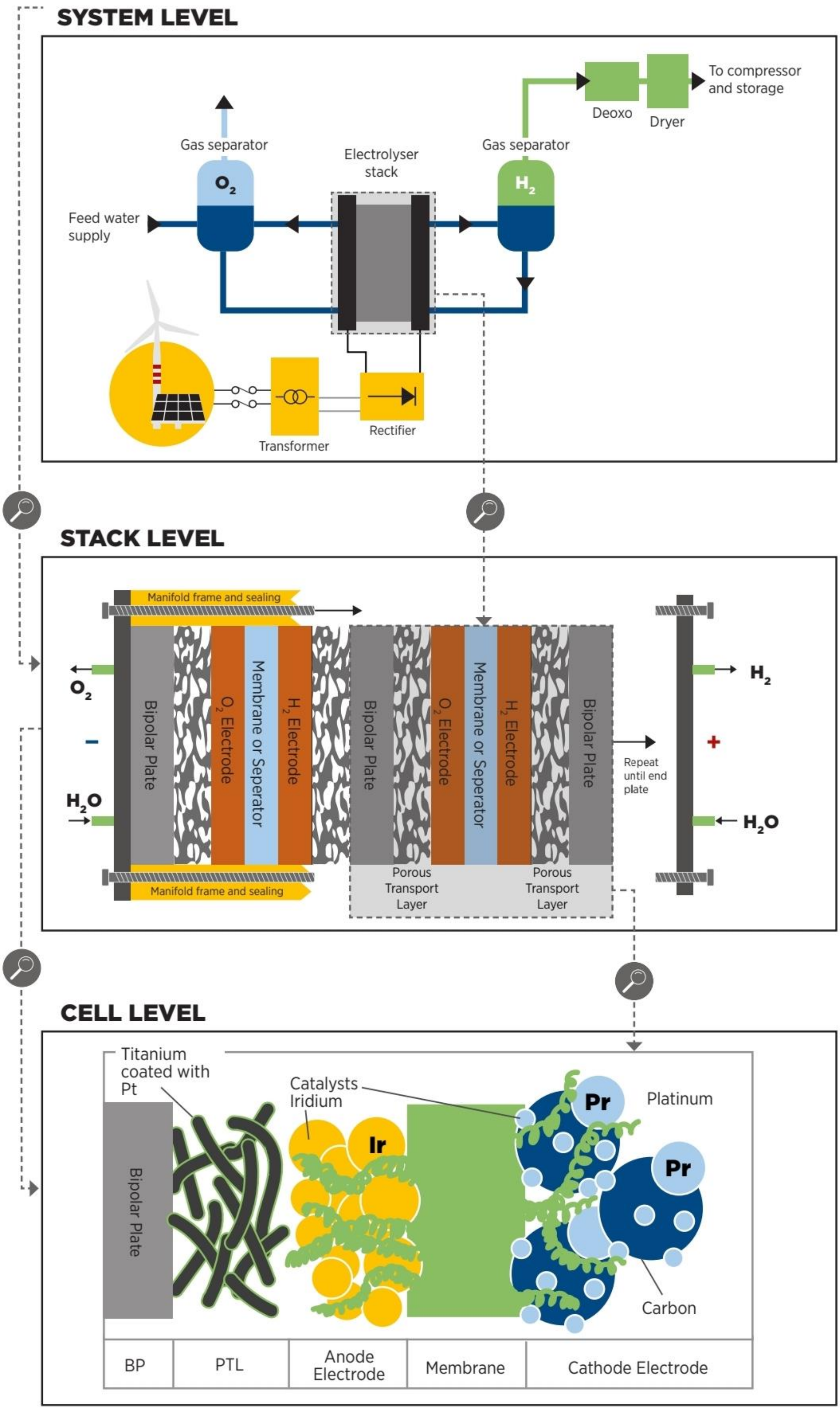

Figure 31: Different parts of electrolysers at different levels [1]

Electrolysers have existed since a century now. But most of the underlying process or technical aspects have stayed same (Figure 32), the emergence of diverse trends has influenced the time split into around five generations [1].

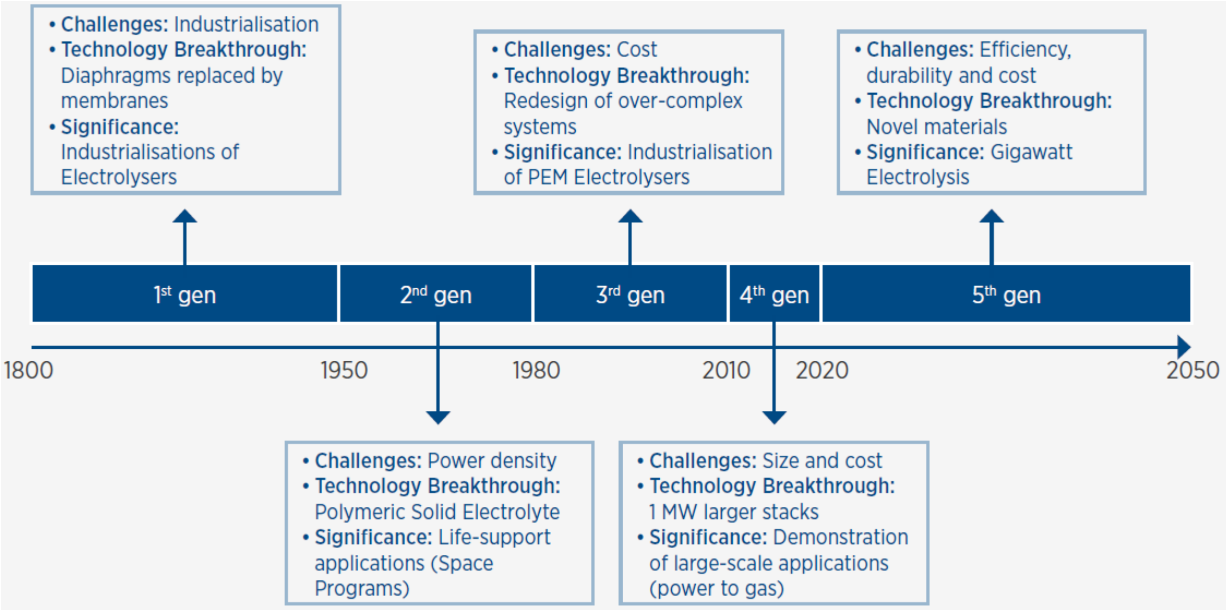

Figure 32: The challenges and advances in each electrolyser since its invention[1]

Hydrogen electrolysis is prominently undertaken with Alkaline electrolysers or Proton Exchange Membrane electrolysers (PEM), whilst Anion Exchange Membrane (AEM) and Solid oxide electrolyser cell (SOEC) are still at research stage, promising a key breakthrough [1].

- **Alkaline electrolyser:** Alkaline electrolyser works by immersing two electrodes in an electrolyte solution like potassium hydroxide (KOH), with water. When a voltage is applied the product gases - oxygen and hydrogen are released. Alkaline electrolysis operates at lower temperatures such as 70-90°C [1]. The concentration of the liquid electrolyte is ~20% to 30%. However, it causes some problems. It is unable make most use of irregular power supplies denoting it is not well-suited with renewable power. Alkaline powered by wind energy should have a battery storage, otherwise the system cannot really run effectively, since it needs a stable power source. Else impure hydrogen will be produced which won't be useful. Hydrogen produced in Alkaline electrolyser needs to be compressed in order to be used or stored. Alkaline electrolytic cell systems have the lowest cost of capital, limited current densities (below 400 mA/cm^2), the lowest efficiency, low operating pressure, and the cost of electrical energy is too high

[72]. The generation of hydrogen from alkaline water electrolysers is well established technology throughout the globe up to the megawatt market range.

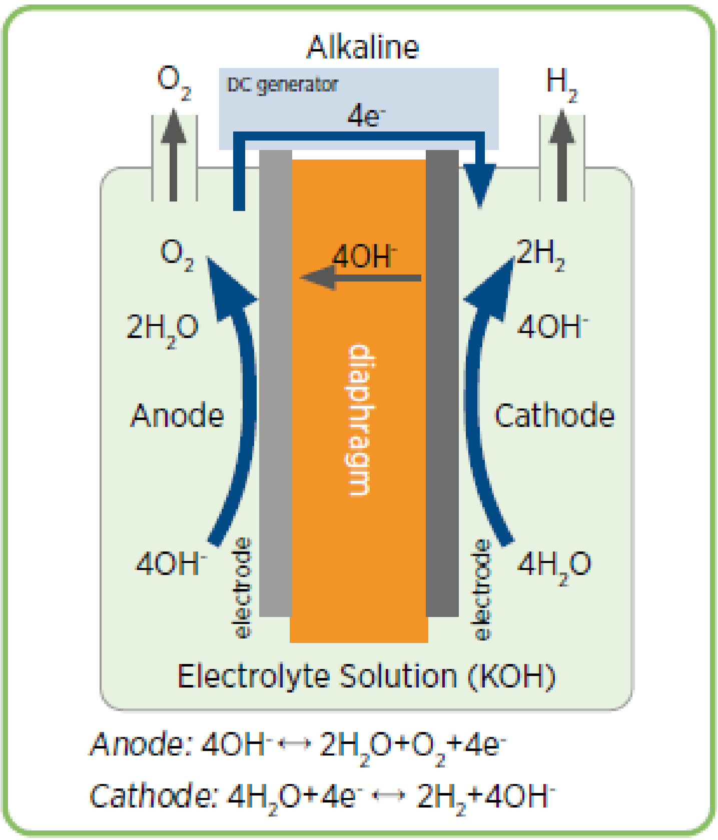

Figure 33: Schematic diagram of Alkaline electrolysis process with chemical reactions[1]

The amount of hydrogen mass produced from wind energy is given by:

$$M_{H_2} = \frac{\eta_{el} \times E}{LHV_{H_2}} \tag{14}$$

Where, M_{H_2} = Mass of hydrogen, kg

η_{el} = Efficiency of electrolyser, %

E = Amount of electricity supplied, kW

LHV_{H_2} = Lower heating value of hydrogen, MJ/kg

- **Proton Exchange Membrane electrolysers (PEM):** The PEM electrolyser overcomes some of the issues of alkaline electrolyser by using a solid polymer electrolyte which is the membrane responsible for the conduction of protons - the separation of hydrogen and oxygen and the electrical insulation of the electrodes [73]. At the anode water reacts to release oxygen and hydrogen ions that are charged positive. The electrons pass via external circuit and the hydrogen ions pass through the PEM preferentially toward the cathode. At the cathode, the hydrogen ions and the hydrogen gas are combined with electrons from the outside circuit [74]. PEM is able to make use of the fluctuating power supply from renewables and results in the pure hydrogen due to the solid structure of the electrolyte. It is easy and more efficient. However, it has a prohibitively high cost due to its required use of gold, iridium and platinum [72].

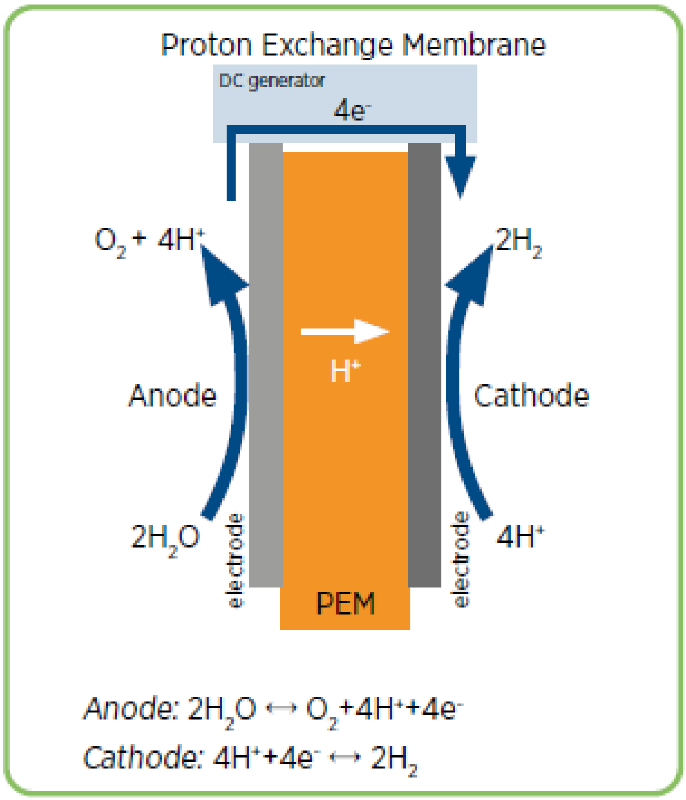

Figure 34: Schematic of PEM water electrolysis process with chemical reactions[1]

- **Solid oxide (SOEC):** The SOEC is used to perform electrolysis of water steam at very high temperatures (500-900°C). The water breaks down to Hydrogen at this temperature. This decreases electricity demand by around 16% [75]. Hydrogen is generated significantly differently from solid oxide electrolytes which utilises a solid ceramic material as an electrolyte, preferentially conducts negatively charged oxygen ions (O^{2-}) at higher temperatures. Steam at cathode reacts with electrons from external circuits in order to generate negatively charged oxygen ions with hydrogen gas. The oxygen ions pass through the solid ceramic membrane and react at the anode to form oxygen gas and generate electrons for the external circuit[74]. This technique has the benefit of being able to work reversibly: in an electrolyser or in the fuel cell, it should be combined with the concentrated solar power system (CSP). SOEC electrolysis is at the laboratory research stage with an efficiency of up to 90% [75].

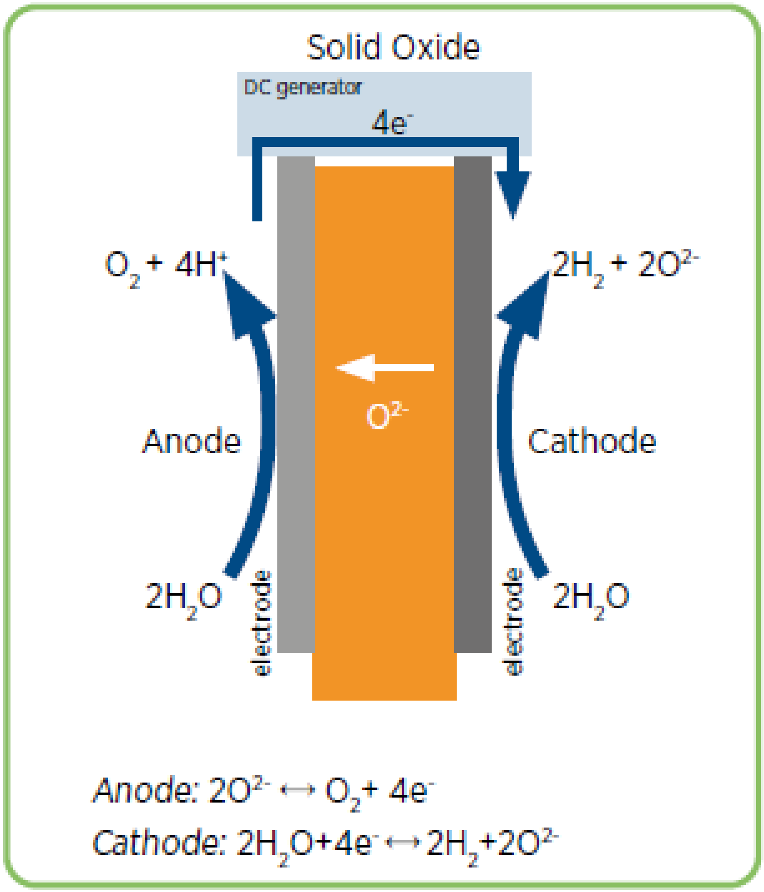

Figure 35: Schematic of Solid oxide electrolysis process with chemical reactions [1]

- **Anion Exchange Membrane (AEM):** AEM electrolyser provides a solution to all of the above problems faced in different electrolysers. It uses an alkaline solid polymeric membrane eliminating the need for rare and expensive noble metal catalysts. It is a simpler and more efficient system that produces directly compressed hydrogen, hence eliminating the need of a compressor. The AEM electrolysers can provide hydrogen at a pressure of 30 bar [76]. It is the key technology that enables lower overall costs. The AEM electrolyser combines the benefits of the PEM electrolyser with the cost of an alkaline system. It is an import breakthrough which will enable the economical adoption of hydrogen energy storage systems all over the world. However, the fact is it has certain issues with the membrane, also chemical stability is low, mechanical performance isn't great, resulting in unstable lifetime patterns. Currently this electrolyser is at lab phase [76].

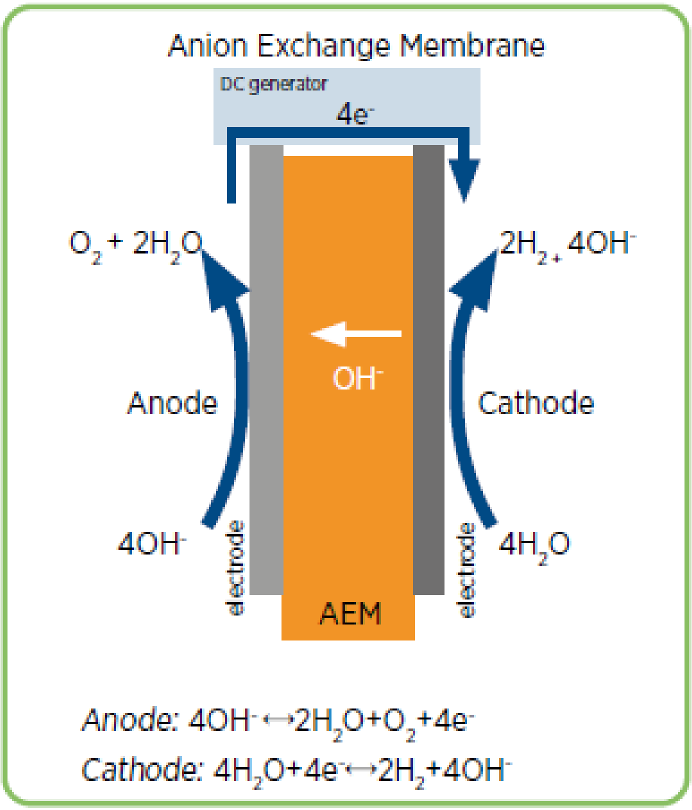

Figure 36: Schematic of AEM electrolysis process with chemical reactions [1]

Electrolyser efficiency:

The performance of electrolysers is influenced by several factors. The general design, the materials utilised, the operating temperature and pressure are some of these. Working at high temperatures increases efficiency but also increases the corrosion rate of the materials used for the electrolysers. Electrolyser electrical efficiency is calculated using the formula [71]:

$$\eta_{EL} = \frac{1.48}{V_{el\_cell}} \tag{15}$$

Commercial electrolyser units typically have a operating efficiency between 60 to 70% [71]. Most modern electrolysers consume 3.8-4.0 kilowatt-hour (kWh) per cubic meter of hydrogen gas. To produce 1 kg of hydrogen an 100% efficient electrolyser may need 39 kWh of electricity and modern-day electrolysers may need about 48 kWh/kg of electricity [69]. A 1 GW offshore windfarm facility, having a capacity factor of 58% can generate about 5.1 TWh electrical energy which is input to a linked 1 GW electrolyser with an efficiency of about 69% can generated 3.5 TWh of green hydrogen (92,000 tonnes) [69]. Table 3 below summarizes the four discussed electrolysers for the operating conditions and the most important components.

Table 3: Important characterisation of the discussed electrolysers[1]

	Alkaline electrolyser	**PEM electrolyser**	**AEM electrolyser**	**Solid oxide electrolyser**
Operational temperature	70 to 90°C	50 to 80°C	40 to 60°C	700 to 850°C
Operational pressure	1 to 30 bars	< 70 bars	< 35 bars	1 bar
Electrolyte	Potassium hydroxide (KOH) 5-7 $molL^{-1}$	PFSA membranes	DVB polymer support with KOH or $NaHCO_3$ 1$molL^{-1}$	Yttria-stabilized Zirconia (YSZ)
Separator	ZrO_2 stabilized with PPS mesh	Solid electrolyte (above)	Solid electrolyte (above)	Solid electrolyte (above)
Electrode / catalyst (oxygen side)	Nickel coated perforated stainless steel	Iridium oxide	High surface area Nickel or NiFeCo alloys	Perovskite-type (e.g., LSCF, LSM)
Electrode / catalyst (hydrogen side)	Nickel coated perforated stainless steel	Platinum nanoparticles on carbon black	High surface area nickel	Ni/YSZ
Porous transport layer anode	Nickel mesh (not always present)	Platinum coated sintered porous titanium	Nickel foam	Coarse Nickel-mesh or foam
Porous transport layer cathode	Nickel mesh	Sintered porous titanium or carbon cloth	Nickel foam or carbon Cloth	None
Bipolar plate anode	Nickel-coated stainless steel	Platinum-coated titanium	Nickel-coated stainless steel	None
Bipolar plate cathode	Nickel-coated stainless steel	Gold-coated titanium	Nickel-coated stainless steel	Cobalt-coated stainless steel
Frames and sealing	PSU, PTFE, EPDM	PTFE, PSU, ETFE	PTFE, Silicon	Ceramic glass

2.5.4 Compressor

The hydrogen generated from electrolyser is at low pressure. So, compression is required to minimise the volume of storage tank to store the hydrogen. Compressors are used to increase pressure of gaseous hydrogen. However, liquid hydrogen is not often considered compressible. Thus, pumps are used to enhance liquid hydrogen (LH_2) pressure at the site of application by delivering a steady flow [77]. There are two categories of compressors required for hydrogen compression- positive displacement compressors (reciprocating or rotatory type) and centrifugal compressors. The compressor is supplied with a suction pressure between 3 bar and 15 bar from the electrolysers and when fully filled, it comprises gas into tanks up to 350 bar.

Power consumed by compressor is calculated by the formula given below:

$$P = f c_p T_1 [\left(\frac{P_2}{P_1}\right)^{\left(\frac{\gamma-1}{\gamma}\right)} - 1] \quad (16)$$

Where, P is power required in kW,

f = flowrate of hydrogen(m^3/s),

c_p= specific heat in constant pressure (kJ/kgK),

c_v= specific heat in constant volume (kJ/kgK),

$\gamma = c_p/c_v$,

P_2 = pressure of the gas after compression, Bars,

P_1 = pressure of the gas before compression, Bars.

Figure 37: A typical hydrogen compressor [78]

2.5.5 Fuel cell

A fuel cell is a system that utilises hydrogen and oxygen to generate energy while also producing heat and water as by-products [79]. Fuel cells have the potential to replace combustion-based technologies in a variety of applications, most significantly transportation. A fuel cell also features a very basic operating mechanism that does not utilise moving parts (apart from ancillary devices such as pumps and fans). Their electrical efficiency is about 40% when compared to other resources like PV or wind energy [80]. The advantages are fuel flexibility, base load, and off grid applications. The noise-free operation and integrated design are added to enable additional use in tiny residential, automotive, mobile electronic devices, as well as off-grid electricity generation in remote areas, maritime and spaces [80]. A combined heat and power system can be used for heating or cooling applications using the cell's waste heat in order to push the efficiency even higher [81].

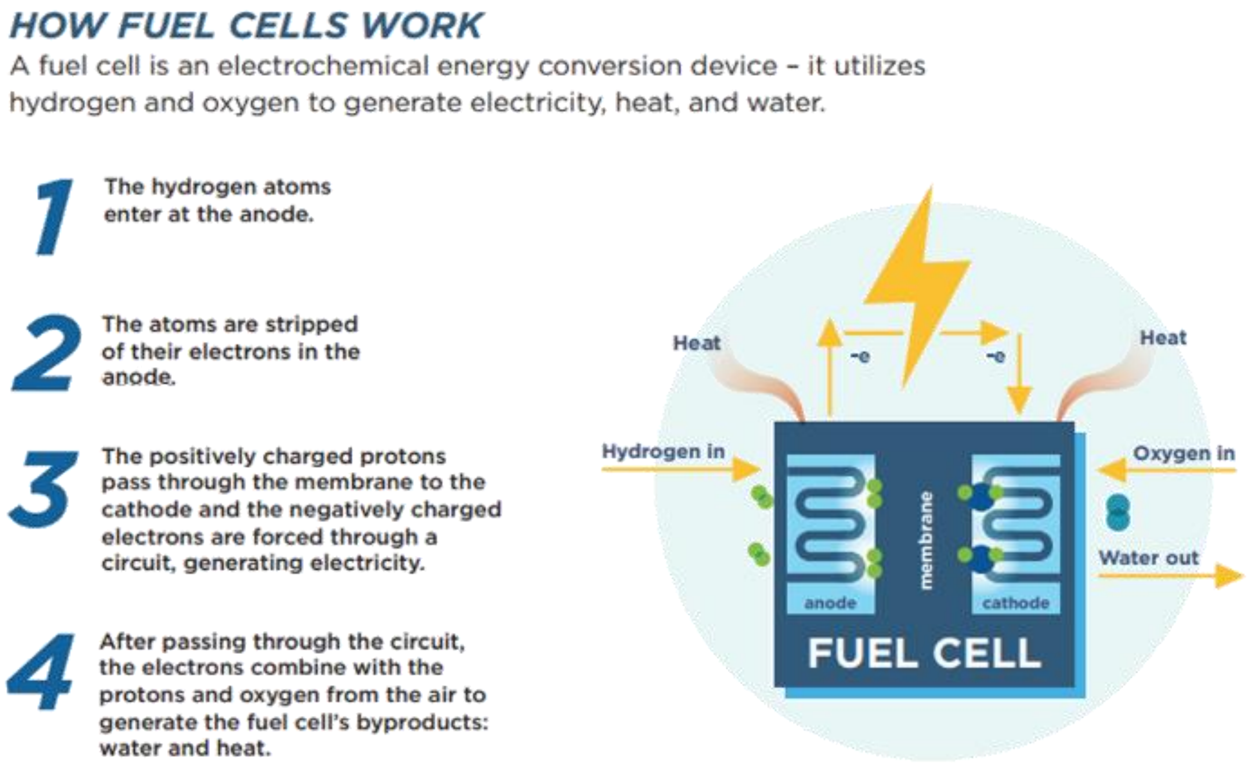

Figure 38: Working of a typical fuel cell [81]

The processes in a fuel cell are the same as the electrolyser reaction, except the reactions that occur in the anode and cathode are reversed. In a fuel cell, the hydrogen gas is consumed at anode and in an electrolyser hydrogen gas is produced at the cathode [71]. Fuel cells are categorised depending on the materials of construction and operating temperature. They are mainly divided into five groups: *polymer electrolyte fuel cell (PEFC), alkaline fuel cell (AFC),* *phosphoric acid fuel cell (PAFC)*, *molten carbonate fuel cell (MCFC)* and *solid oxide fuel cell* (SOFC) [80]. Fuel cells are extremely promising energy conversion technology for an area dominated by outdated technologies, such as the internal combustion machine and a gas turbine to replace in order for the energy industry to decarbonize.

2.5.6 Hydrogen storage

Hydrogen storage poses a major challenge, particularly for transport functions. Hydrogen, as a gas, provides considerable benefits versus electricity while storing, especially in the long term, when electricity needs to be stored from summer to winter seasons. If natural gas in the global economy today was entirely replaced by hydrogen, overall storage infrastructure would have to be increased 3-4 times [69]. The energy density of hydrogen is less than other fuels, which actively demonstrates that it takes a far bigger fuel tank than petrol and diesel to operate a vehicle [21]. Due of its low density and smaller molecular size it may leak from confined vessels. As discussed in the earlier section (*2.3.1.8 Hydrogen energy storage*) hydrogen storage methods can be divided in two categories as gas, liquid and material-based storage. In its pure state, it can be stored by compressing into a gas or as a liquid by cooling it or in a combined phase in pure form. Condensation and compression of hydrogen both demand a lot of energy and a big, specialised infrastructure to produce greater concentration in a liquid or mixed form [21]. The most established hydrogen storage technique is physical storage [82]. The particular reason for this is due to its ability to rapidly refuel the vehicles, easy interfacing with fuel cells and the high tank efficiencies involved.

Gaseous hydrogen (GH_2) in metal tanks (or other composite materials like carbon fibre or polymer) at pressures up to 350 bar. Also, they offer a specific volume of 5.6 times more than the volume of liquid hydrogen, if stored at 164 bar and 288.15K [83]. Furthermore, the thickness of tank walls for the necessary internal pressure increases enormously, at least two orders larger than the cryogenic storage method. The proportion of hydrogen mass per composite tank mass is between 7.5% and 8.5%, whereas steel cylinders are between 1% and 3%. Gaseous hydrogen can further be stored in metal hydrides. This technique, however, provides around 5% mass of hydrogen capacity. While in more recent research on unmanned aerial vehicles metal borohydrides store mass percentages of hydrogen beyond 10%, those storage densities with accompanying problems in the rate of fuel retention do not seem to represent a favourite storage choice [83]. At the moment, hydrogen energy storage systems are one of the highly preferred storage technologies to set up renewable energy integration issue. Price and overall efficiency are its major constraints.

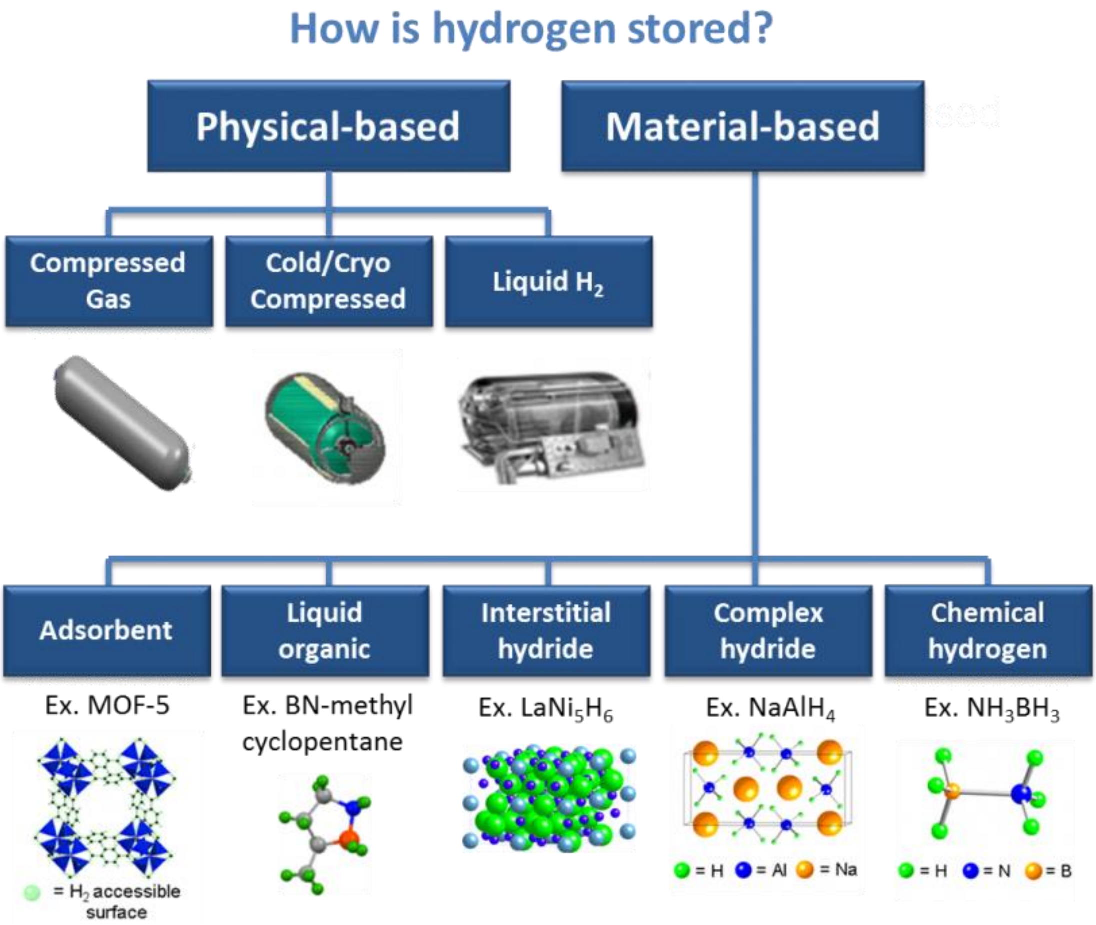

Figure 39: Types of hydrogen storage [84]

2.5.6.1 Comparison of main hydrogen storage techniques:

Hydrogen can be compressed into high-pressure tanks in a gas form. In order to do this, the particular procedure requires energy. The space in the compressed gas is large and the energy density is reduced automatically. The major expense of compressed hydrogen technology is the capital cost of the construction and acquisition of the pressure vessel. In this respect, there are no extra charges to be incurred except the cost of power to operate the compressor. In comparison with the costs for storage of Liquid Hydrogen, the Compressed Hydrogen storage technology may readily be justified to be less cost efficient, and it also includes a lower infrastructure [35]. Gaseous hydrogen in significant quantities is typically not held at pressures exceeding 100 bar in aboveground storages and 200 bar in underground storages because of material characteristics and operational expenses [85]. Gaseous hydrogen compressed at 700bar is mostly preferred due to the easy interfacing with fuel cells.

One of the qualities of the hydrogen is that it has lower density. Actually, it is denser than gasoline. This implies it must be liquid-compressed and kept at low temperatures in the same way to guarantee its efficiency as a source of energy. Hence hydrogen should always be stored and transported at higher pressure. This makes transporting hydrogen difficult and limits its usage. Storing hydrogen as compressed gas is more costly than storing hydrogen on a kilogram basis in caverns or other subsurface structure [69]. But the high initial costs of subsurface structure implies that it is possible only once the generation of hydrogen is large enough to merit such an expenditure [69]. The major possibility for this type of storage within Scotland is the re-use of existing on-shore and offshore Oil & Gas (O&G) infrastructure [69].

Table 4: Common hydrogen storage options [69]

	**Compressed Gas in Pipeline transmission systems:** In this type, hydrogen from daily or weekly variations can be stored. Linepacking is not as effective as natural gas in case of hydrogen because it has lower density
	**Highly compressed in pressurised containers:** For short-term storage at a small scale, hydrogen can be stored by compressing. For instance, to be utilised at hydrogen refuelling stations. This form of storage may be utilised modularly to achieve considerably greater amounts, but it is costly.
	**Hydrogen in liquid form in cooled pressurised vessels:** Liquification requires energy and therefore storing hydrogen in liquid form is very costly medium of storage. It may be utilised for much higher energy densities, either when the space is concern or for relatively long-distance transits.
	**Large underground storage facilities:** High capacity and thus reduced unit costs benefit from geological storage systems. But to make the first investment it takes substantial quantities of generated hydrogen.

Hydrogen is stored in liquid form when area of storage is a major problem for example in case of transporting hydrogen. Liquid hydrogen storage method involves high cost, estimated from raw material prices, capital equipment, labour, and other operating costs. The least costly method for supplying huge quantities of hydrogen is pipelines. They have been used for more than 50 years and they are currently being utilised in various countries across the world. Current pipelines run on 10-20 bar pressures; however, pressures may be deployed up to 100 bar. Over long distances, transporting hydrogen in liquid form is cheaper than as a hydrogen gas, since liquid tanker truck can contain significantly more hydrogen than a gas tube trailer [35]. Also, transportation of gas via railway or trucks leads to substantially greater operating costs than pipelines; nevertheless, it does give smaller consumers far more flexibility when construction expenses for pipes are not feasible. The Scotland and the UK has a moderately very well established gas network if contrasted with other nations, the possible use of these existing gas lines will be one of the primary benefits of hydrogen economy [69].

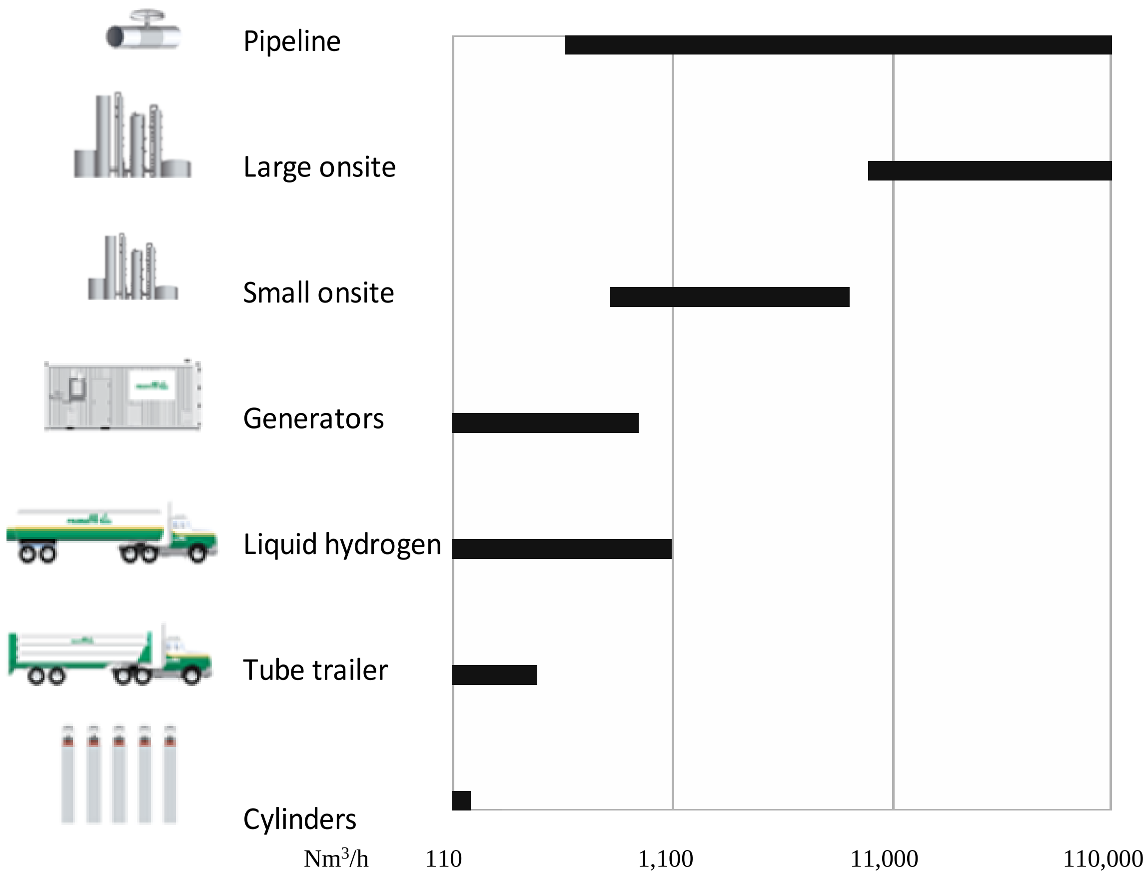

Figure 40: Methods of hydrogen transportation and distribution [86]

As an alternative to high-pressure storage systems, metal hydrides are a safe and controlled technique for the storage of hydrogen in small spaces at lower pressures. This low-pressure method works because the hydrogen molecules stay chemically linked inside the structure of the metal complex and stable and unsafe at atmospheric pressure [87]. Typically, metal hydride storage systems operate at 10-40 bars, 20 times lower than standard high-pressure systems. The desorption process begins with feeding heat (45 - 65°C), when the hydrogen is necessary, and the gas starts flowing outside (1-2 bars). Their operating life corresponds directly to the purity of the stored hydrogen. The alloy serves as a sponge during the absorption process, which can readily absorb contaminants and also stores hydrogen. Thus, hydrogen is finally expelled from the tank very purely, but the impurity is kept in the metal area that the hydrogen formerly occupied decreasing the tank's lifetime. Metal hydrides storage systems comes with a high estimated cost for its implementation.

Table 5: Brief table of advantages and disadvantages of common storage techniques.

	Advantages	Disadvantages
Compressed Hydrogen	Low weight	It has large volume
	Some already present infrastructure	Energy loss due to compressibility factor at high pressures
	Easy interfacing with fuel cells	Hydrogen penetration through walls
		Hydrogen embrittlement in the wall
		High cost of materials
		Required factor of safety is more than 2.25
Liquid Hydrogen	Low weight	Boil-off losses
	It has small volume	Hydrogen embrittlement in the wall
		Very low operating temperature
		Hydrogen permeation through walls
		High energy needs for liquefaction
		Infrastructure not yet developed
		Harder interfacing with fuel cells
		High cost of materials
Metal hydrides	Low operating pressure	Large weight
	Very small volume	High operating temperatures
	Low operating pressure	Hysteresis losses
		Slow charging /decharging
		Volume changes upon charging/ decharging
		No existing infrastructure
		Harder interfacing with fuel cells
		High cost of materials

A thorough comparison of hydrogen storage alternatives yielded the following suggestions for the various storage techniques' uses [88]:

- For seasonal stationary energy storage, underground tanks and moderate-pressure chambers are preferred.
- Composite high-pressure cylinders are the ideal choice for big transit capacity applications (buses, camions, ferries).
- In smaller applications of transport (cars, tractors), the cryogenic high-pressure containers and methanol reformers are recommended.
- The ideal solution for usage in aviation and space applications are cryogenic low-pressure containers.
- For application in low-scale hydrogen storage systems the metal hydrides are recommended.

The prospects may alter significantly if the hydrogen economy comes into use. Hydrogen would then be readily available and storage facilities would be available all over the place. The generation and storage of hydrogen from power stations would therefore be considerably cheaper and easier to incorporate into the larger network functioning.

2.6 Future techniques of producing hydrogen

Siemens Energy is incorporating its unique system with a combination of gas and steam turbines, electrolysers as well as heat pumps and transforms it in one operating system into a single optimised plant solution also called as hydrogen power plant [89]. There are various benefits of hydrogen integration with gas turbine operations [89]:

- Energy storage, electricity, and heat generation.
- Improving overall hydrogen production plant efficiency by use of waste heat. The combination of power and heat generation provides an excellent total efficiency of 70%.
- Lower emissions of power per kWh.
- Renewable energy integration into heating and sustainable energy supply.
- 100% future proof power plant.

Nuclear power can be used to generate hydrogen without CO_2 emissions using reactors (minimising the energy needs associated) to split water molecules either by electrolysis or thermochemical methods or steam reforming of natural gas [90]. A substantial more efficient hydrogen production can be achieved by increase in the water temperature before its molecules are divided using thermochemistry or electrolysis. Such solutions demand temperatures between 700°C and 1000°C. The Light Water Reactor Sustainability (LWRS) and short-term water-cooled Advanced Light Water Reactor (ALWR) produce temperatures below 350°C and cannot be used for this purpose. However, different reactor coolants of numerous generation IV concepts (above 700°C) are suggested to reach such high temperatures and can be combined with thermochemical plants. A recent Electric Power Research Institute (EPRI) analysis has pointed out that nuclear reactors to produce the heat needed in the process of steam methane reforming (SMR) are more cost effective than their use for water splitting. Nuclear-assisted SMR would lower the use of natural gas and carbon dioxide emissions in the process [90]. Advanced reactors are anticipated to operate at significantly higher temperatures and to enable nuclear power stations to generate hydrogen more effectively to significantly scale up the sector [91]. U.S department of energy analysed High-temperature steam electrolysis (HTSE, at 550 to 750°C or more) in solid oxide electrolysis (SOEC) to use both heat and electricity. It utilises about one-third less energy than low-temperature electrolysis but is not yet commercialised as ceramic elements are unsustainable in a hot hydrogen environment [92].

Hydrogen can also be produced from the photonic process by utilizing the photon energy. These are divided into two methods the photocatalytic and the photoelectrolysis water splitting [93]. The photocatalytic splitting of water for producing hydrogen is a direct technique for producing hydrogen from water by the use of ordinary light. This technique has produced poor efficiency. Another method is Photoelectrolysis process. In this method, sunlight is used to directly decompose water into hydrogen and oxygen. Photoelectrolysis systems are similar to photovoltaic systems; both technologies use semiconductor materials [93]. The p-type and n-type semiconductor materials are used in photovoltaic system. The electric current is generated, due to the forced movement in the opposite direction of the electron and hole. In photoelectrolysis the electric current water is decomposed into hydrogen and oxygen instead of generation. The performance of the photoelectrolysis systems largely is reliant on the photoelectrode and semiconductor materials used [94]. Various materials from photoelectrodes, such WO_3, Fe_2O_3, and TiO_2, for usage in photoelectrolysis as a thin film are being analysed [93].

Another latest industry buzz is the safer and more efficient storage and distribution of Hydrogen through a very well-established infrastructure that is already being used worldwide [95]. However, hydrogen must be first converted into ammonia in order to benefit from this infrastructure. There is a significant lot of interest in the potential advantages of delivering and storing ammonia as a long-term energy carrier across all energy industries [96]. As compared to hydrogen, ammonia is relatively easy to transport and to store. It liquifies at only -3°C and it only needs to be compressed to ten times atmospheric pressure to make it practically transportable. In addition, unlike hydrogen it does not react with steel.

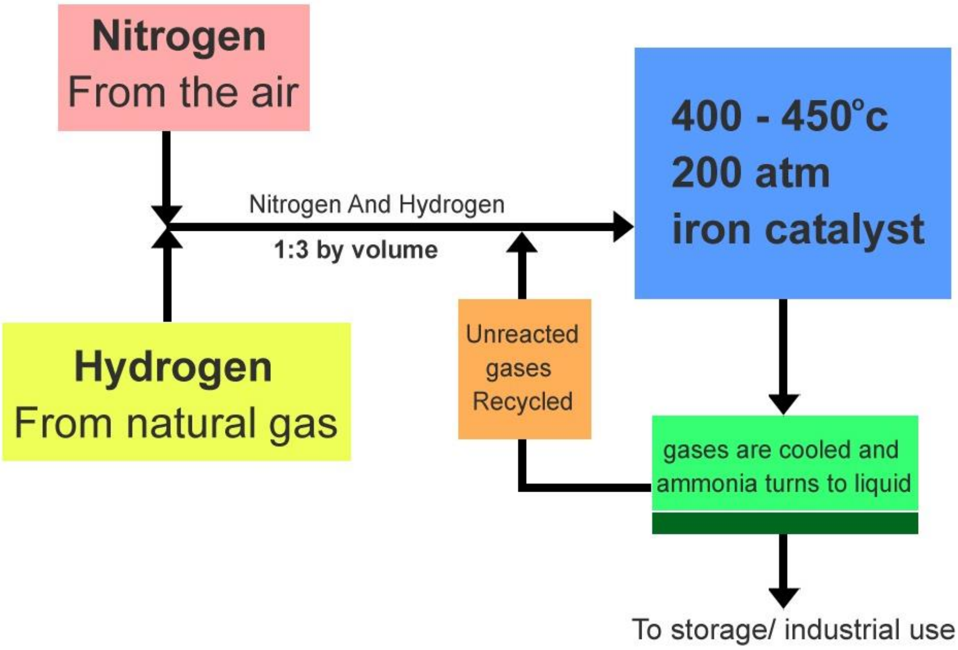

Figure 41: The Haber-Bosch process flow diagram [95]

In fact, it is actually a better hydrogen carrier than hydrogen itself. For the same volume, ammonia contains 50% more hydrogen than hydrogen does. The naturally available nitrogen and hydrogen can be combined using a process called Haber-Bosch (see Figure 41). The process consumes an enormous amount of energy, currently supplied by fossil fuels, which presumably indicates that more CO2 is being released into the environment. But if it were possible to employ renewable energy for power supplies, that would be a major breakthrough [97]. R&D efforts continue internationally to produce renewable hydrogen in order to ensure our future global portfolio is a renewable, sustainable, and green transportation alternative, and this will be accomplished in the near future.

2.7 Environmental impacts of hydrogen-based energy system.

All energy storage technologies can be considered as an opportunity for economic and greener operation of electricity system [98]. Green hydrogen—while it surely is greener than gas, it is highly inflammable. Steam methane production leaves behind harmful emissions. This method of production results in grey hydrogen as well as 830 million metric tons of CO_2 emissions each year [99]. Electrolysis has an environmental impact depending on the fuels and technologies that are utilised to produce the energy needed in the process. Using traditional grid electricity would lead to greater global warming than natural gas steam methane reforming. Using energy from renewables enable a really low or zero carbon cycle. Hydrogen is an important, yet rarely researched, trace component of the atmosphere. Currently it is present at a mixing ratio of around 510ppb with significant human and natural sources. Its atmospheric lifetime is about 2.5 years and there is a global load of about 180Tg in the atmosphere [100]. Because hydrogen interacts with tropospheric OH radicals in the atmosphere, the emission of hydrogen into the atmosphere would alter the distribution of methane and ozone and hence to an increase in global warming. Hydrogen can therefore be considered an indirect GHG that could enhance global warming [100].

The estimations show that the potential effects of hydrogen-based energy system would be of course much lower when compared with the traditional fossil fuel-based energy systems. However, the extent of impact will depend on the rate of hydrogen leakage during the production, storage, and distribution or at use. Higher levels of hydrogen can reduce the natural atmospheric oxidising capacity and thus increasing the lifetime of air pollutant and GHGs. Also, it can raise atmospheric water vapour concentration, resulting in cloud formation, increase stratospheric temperatures and ozone loss [101]. The estimates indicate that a worldwide hydrogen economy with a 1% leakage rate would have climate impact of 0.6% of the fossil fuel system it replaces. If the rate of leakage was 10%, the climatic impact would be 6% of the rate of fossil fuel [101]. Sustainable sources of hydrogen would minimise carbon monoxide and nitrous oxide (NO_x) emissions by reducing tropospheric ozone levels. This would enhance air quality in many parts of the world [101]. The new analysis shows that a future hydrogen economy is not devoid of climatic turmoil, but it may be far less pronounced than the existing system of fossil fuels. If the potential climatic benefit of the future global hydrogen economy is to be achieved, thorough attention should be committed to the reduction of hydrogen leakage to a bare minimum [100].

3.0 Methodology

This chapter describes the research method of this thesis. It outlines the research strategy, approach, the methods of data collection and its analysis. A quantitative research was conducted to fulfil the goals of this dissertation.

- The preliminary step of this study was to set an aim for this project. After the aim was determined, an extensive literature review was conducted. The literature review involved studying background information and known statistics of the renewable energy sector, in particular wind energy statistics were studied.

- A detailed background research was conducted on various energy storage techniques in order to understand the most efficient and useful storge techniques. To gain more understanding of the subject, detailed research was carried out on different methods of hydrogen production. This helped to draw a clear picture between different types of hydrogen available in market. Green methods of hydrogen production were studied.

- In order to obtain a better comprehension into the subject matter, background information on wind powered hydrogen system components was undertaken. In this section the wind power classification in order to select wind turbines was realized. The working and necessity of converter was explored. A detailed research on working of electrolyser and different types of electrolysers was undertaken. It was very necessary as part of this study to research on different methods of storing hydrogen. To understand the benefits and drawbacks of storage methods thorough comparison of various methods of storing and distributing hydrogen was undertaken.

- In order to gain a better insight into the possibilities for improvement, future techniques of hydrogen production were examined. At the end of the literature review the environmental impacts of hydrogen-based energy system was analysed.

- For meeting the goal of this project an extensive statistical analysis was done energy system of Scotland. The initial step was to decide a year to evaluate. Upon research it was evaluated that the year 2020 was massively effected by the lockdowns due to the covid-19 pandemic, therefore it was decided to conduct analysis on the years before the pandemic. The various statistics of wind energy and energy sector as a whole were evaluated for the year 2019 and earlier.

- The major task was to find average monthly electricity consumption of Scotland. This data was then to be analysed along with average monthly electricity generation by wind. The goal of this project was to completely meet the consumption demand of electricity by just using wind energy. The data for average monthly wind energy was not available accurately. Hence the quarterly wind energy generation values were converted into average monthly by using Newton Polynomial interpolation method. This calculation was carried out on an online calculator [102]. The equation used to generate the average monthly numbers is given below (equation 17). The quarterly electricity generation data was divided by three (i.e., 1 quarter = 3 months). The divided value was considered for the middle month of the quarter. In the online calculator, the data points were input as one point per line, as *x values* separated by spaces. In order to get a polynomial dipping curve, the point -1 was considered and given the divided value of the 3rd quarter and another extra point was considered at the end with a value of 1st quarter. The values were inputted as follows:

Table 6: Values inputted in online polynomial calculator

-1	2117
2	2243
5	1470
8	1613
11	2117
14	2243

Newton Polynomial after simplification

$$0.07x^5 - 3.09x^4 + 43.64x^3 - 222.45x^2 + 148.17x + 2534.43 \quad (17)$$

- The estimated average monthly electricity generation values were then analysed against average monthly electricity consumption. The idea was to find a gap in supply and demand of wind energy. The months when the supply was lower than demand was calculated. The months with excessive supply was also calculated. This was the initial task of this thesis. To use the excess electricity and convert it hydrogen. This hydrogen is saved so that it can be used later to generate electricity. The efficiency of the hydrogen powerplant was considered as 75.5% [89]. In this analysis, the powerplant will first convert excess electricity into hydrogen using Siemens Silyzer 300 as the electrolyser which is a PEM, it produces pure high-quality hydrogen at required pressure to be stored. This hydrogen gas is then converted back into electricity using gas/steam turbines. This electricity is then used in various applications as per the demand.

- If the demand was not met by using the excess electricity then the Scotland's export electricity figures were considered to convert it into hydrogen and stored for times when the demand is higher. If excess hydrogen was produced this could be either stored for later usage or it could be exported and the wholesale value of hydrogen gas was to be evaluated against the current wholesale value of electricity exports.

The formula to calculate amount of hydrogen gas produced is given by:

$$Amount\ of\ H_2 = \frac{Energy\ input \times conversion\ factor\ (kWh\ to\ MJ)}{LHV\ of\ H_2\ (MJ/kg)} \tag{18}$$

Where, *Amount of* H_2 = mass of hydrogen in kg,

Energy = The energy input to producing hydrogen, kWh

Conversion factor = The value used for conversion of energy [1 kWh =3.6 Megajoules (MJ)][103]

Lower heating value (LHV) of H_2 = 120.10 MJ/kg [103]

- Hydrogen was converted to volume by using the volume of hydrogen at 700 bars, which is equal to 42 kg/m^3 [104]. In electrical terms the energy density of 1 kg of hydrogen is equivalent to 33.6 kWh [105]. This is how the energy generated by 1 kg of hydrogen was calculated. The current price of hydrogen was considered as £7, an average value between £5 and £8. The profit or the wholesale export value of hydrogen is calculated.

- The alternative scenario of electricity demand in 2045 (five years ahead of the Scotland's actual goal-2050) was considered to find out if the demand could be met with the proposed wind energy plans of Scottish government. For this scenario it was assumed that at least 50% vehicles would be electrified, and electricity consumption rose by 1% from the 2019 figures.

- To get the wind energy estimations of 2045, simulations were carried out to determine the wind power output of the wind turbines. These were carried out in three different softwares- *System Advisor Model (SAM)* developed by National Renewable Energy Laboratory (NREL) [106], *RETScreen* clean energy management software developed by government of Canada [107] and *Energypro* by EMD international [108]. Similar capacity turbine models were used in all the simulations. The offshore wind turbine model SWT-6MW-154 by Siemens was used for the sake of simulation. The power curve was obtained from the company's website. The wind speed of 10.15 m/s was considered at a reference height of 100m for SAM model. RETscreen model took the coordinates of the proposed windfarm location. All three simulation results were compiled and compared, and an average was taken for the analysis purpose. The amount of hydrogen required was calculated by using the wind power input from the simulations in order to meet the electricity demand projections. If the demand was not met, what would be the additional capacity of wind power required was determined.

- After the primary need of gross electricity consumption for Scotland was satisfied, heating and transportation sectors were analysed. Research was undertaken to find the share of each sector in the total gross energy consumption. This was considered in line to meet the GHG targets set by the Climate change act of Scotland in order to decarbonise Scotland completely by 2045. It was assumed that natural gas would be replaced completely by hydrogen gas or heating would be electrified (assumed same efficiencies) and investigation was undertaken to analyse the amount of hydrogen required for 2019 and 2045. The energy density of natural gas was obtained from literature review (1 kg =55 MJ/kg and equivalent to 13.1 kWh energy). A thorough research was conducted to understand the existing O&G pipelines of Scotland. This was done in order to discuss the possibilities of cheaper distribution of hydrogen and quick switching of natural gas to hydrogen. For the 2045 scenario, the amount of hydrogen gas required, and the amount of energy required was calculated. The mass of hydrogen required was obtained and then the volume of fuel required in 2045 i.e., hydrogen and gas were compared. Based on the calculations conclusions were drawn.

- It was understood from literature review that the transport sector was the hardest to mitigate sector. Despite that with an ambitious goal of decarbonised system and a total renewable energy usage in all the sectors by 2045 (five years ahead of Scotland's actual goal), a scenario with complete hydrogen powered vehicles was assumed. The amount of hydrogen gas required was calculated. In order to understand why hydrogen gas cannot mitigate transport sector, a detailed discussion on hydrogen car and battery cars with the figures, efficiencies and important characteristics involved were discussed. The volume of hydrogen required against petrol for the 2045 scenario was calculated. 1 kg of unleaded petrol is equal to 12.06 kWh with an energy density of 46 MJ/kg [103]. And hydrogen had an energy density almost thrice to petrol.

- Finally, the share of renewable energy in the total energy consumption in order to decarbonise the complete system was discussed. The total wind energy capacity required by 2045 to meet the complete energy demand from renewables was calculated. In the end, the baseline of how the costing of hydrogen would be determined was discussed briefly. The cost analysis was not considered in the scope of project due to the reason that the green hydrogen is a latest technology, and it would be difficult to predict the prices which will definitely alter so much over the next few years. All the results obtained are discussed in detail in the next chapter.

4.0 Analysis and Discussion

The Scottish government plans to produce 100% of the nation's electricity demand by using renewable energy technologies to help fight climate change. The government is aiming to generate at least 50% of the total Scottish energy utilization (heat, transport, and electricity) from renewable energy sources by 2030, and to have a 100% decarbonised energy system by 2050 [34]. Based on a study of several figures, good results have been achieved to date, with renewable energy sources attaining 19.3% of the total energy demand in 2019 [109]. In 2019, renewable electricity generation amounted to over 30.5 TWh which is equivalent to 90.1% gross electricity consumption, up by about 13.4% from 2018 [110].

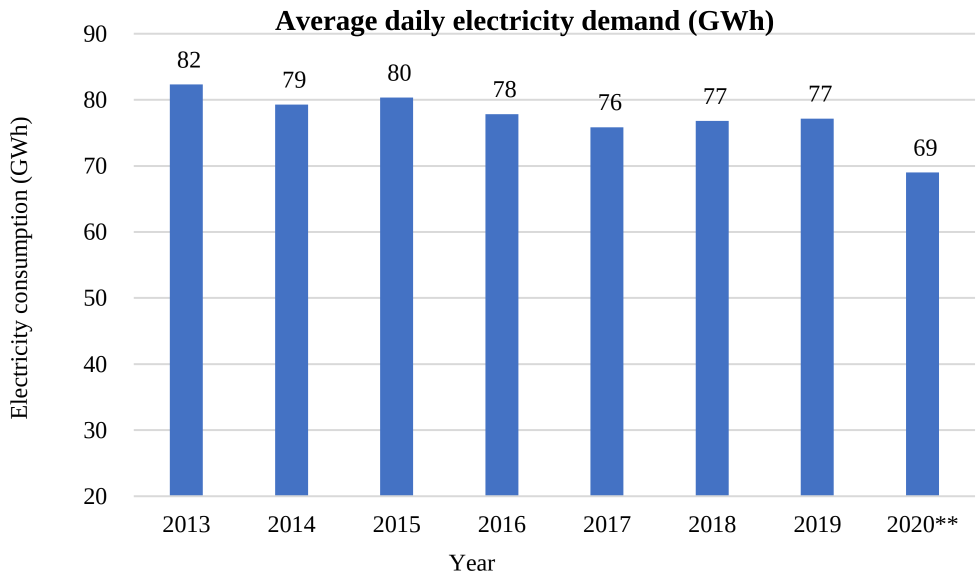

Figure 42: Average daily electricity demand (2013 to 2020) [110]

The year 2019 has been considered as a part of this study, the year 2020 is ignored due to the effect of the pandemic. The Covid-19 lockdowns caused a considerable decrease in the usage of energy in Scotland and as shown in Figure 42 the average daily demand for electricity in Scotland was 16% lower when compared to earlier years. Also, it is noted from the graph that over the years the average daily electricity consumption has seen a downtrend.

As mentioned earlier in section 2.2, between 2009 and 2020 the UK's wind power generation rose by 715%. As shown in Figure 43, the share of Scotland's wind power in whole of UK is 35% which is a very high percentage for a small nation. Table 7 shows that in the year 2019, over 44.68% of the Scotland's total electricity production was generated from the onshore wind farms and OWF i.e., amounting to 22.3 TWh with a total wind energy capacity of 9.4 GW [109].

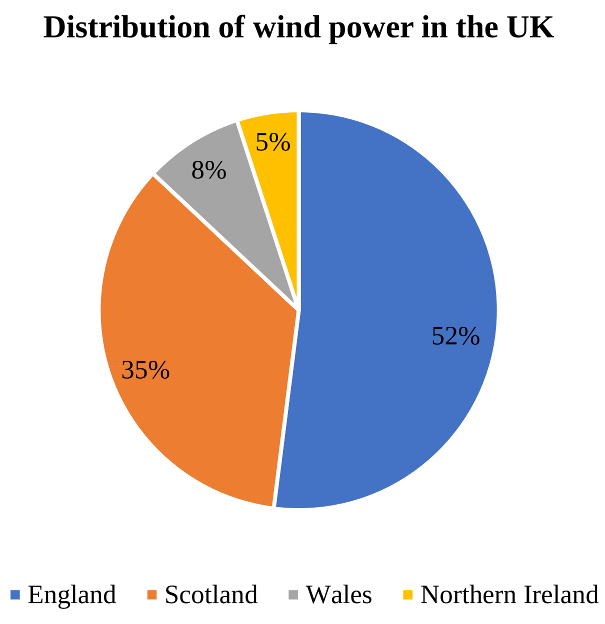

Figure 43: Share of Scotland's wind power generation in UK [111]

A CNBC report in 2019 explicitly stated that Scotland produced adequate wind energy to power all of its households twice, which highlights the fact that Scotland could easily produce sufficient energy to meet 100% electricity demand if an efficient storage system was introduced [112]. In this study, hydrogen-based energy system is considered to demonstrate how Scotland could meet the total demand by just using wind power.

Table 7: Annual wind energy figures for Scotland [109]

Year	Electricity generated from wind (GWh)	Electricity generated from renewables (GWh)	% of wind energy in total energy generated from renewables	Total electricity generation (GWh)	% of wind energy in total electricity generation
2013	11,151.19	16,989.64	65.64%	53,024.11	21.03%
2014	11,700.01	19,045.05	61.43%	50,042.05	23.38%
2015	13,878.00	21,742.83	63.83%	51,335.07	27.03%
2016	12,415.70	19,475.59	63.75%	45,679.12	27.18%
2017	17,201.14	25,301.38	67.98%	48,841.22	35.22%
2018	19,383.13	26,864.66	72.15%	48,770.14	39.74%
2019	22,325.92	30,521.33	73.15%	49,969.45	44.68%

It is estimated that in order to meet the current annual electricity demand (34 TWh), about 14-16 GW wind power capacity is required. Else if the surplus energy which is generated at times when the demand is low should be converted to hydrogen gas and stored. Normally the demand is lower at night-time and wind blows little faster at night. The clouds are usually cooler in the night than in the daytime, while the sea surface temperature remains more or less the same as the day. This leads in a rise of the temperature between the cloud top and the surface of the sea, leading to increased air mixing and hence higher wind speeds. The excess energy generated during the night-time or when generated during the off-peak seasons when demand was lower, could be stored as hydrogen gas and used later during peak hours. This could help Scotland meet 100% of the electricity demands.

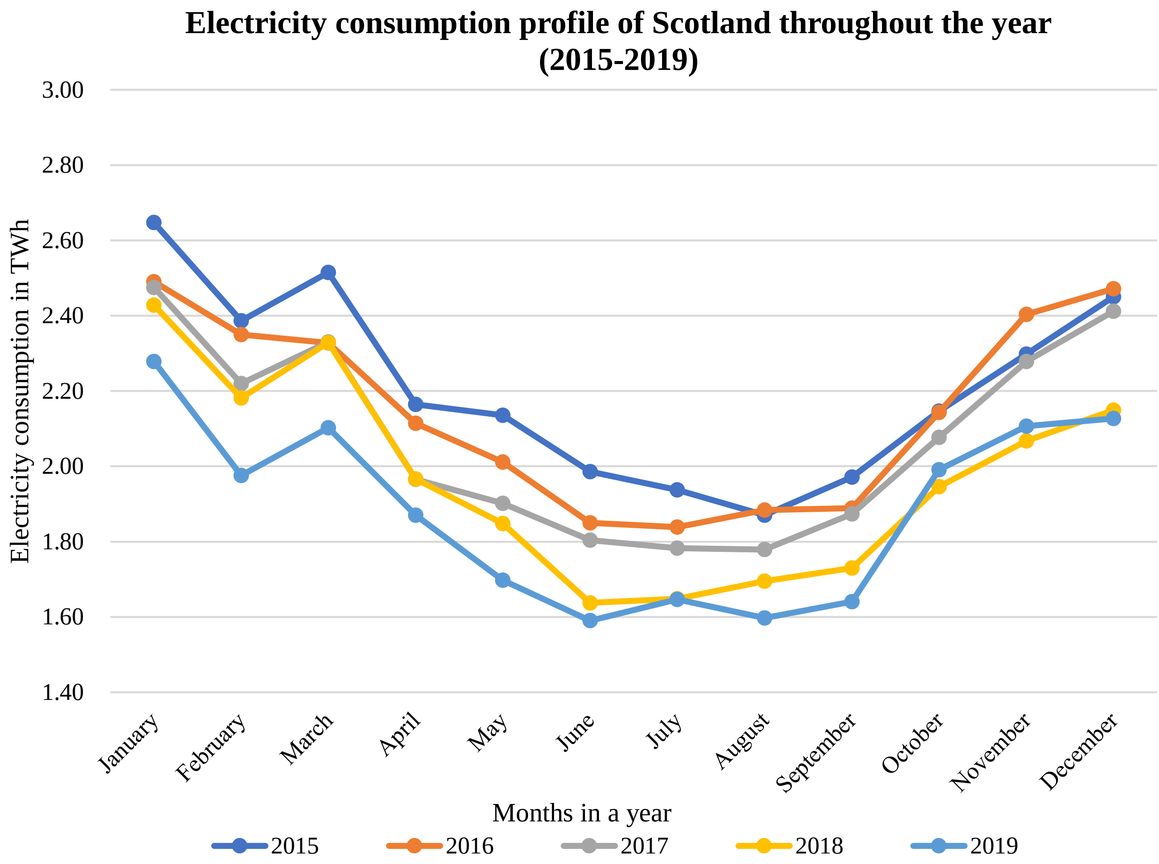

Figure 44: Scotland's electricity consumption figures from the past few years [113]

Figure 44 shows the actual electricity utilization for Scotland throughout the year from 2015 to 2019. From the above graph it was understood that the Scotland's average electricity consumption for 2019 was around 2.26 TWh per month between January to April and November to December. In the research period between 2015 and 2019, Scotland consumed on an average about 2.05 TWh of electricity every month. It was also learned that the Scotland's consumption was higher during colder months than during summer. The initial task of this report was to meet 100% of the total electricity demands by using wind power. For the sake of this study, average monthly electricity consumption figures were analysed against average electricity generated by wind for the year 2019. The accurate data for average monthly electricity generation was not available hence quarterly electricity generation data was converted to monthly average electricity generation using Newton's polynomial interpolation method (Equation 17).

Table 8: Monthly electricity generation and consumption analysis for the year 2019

Month of the year	Average electricity generated from wind energy (TWh)	Average electricity consumption (TWh) [113]	Supply-Demand difference (TWh)
January	2.50	2.28	0.22
February	2.24	1.98	0.27
March	1.92	2.10	-0.18
April	1.65	1.87	-0.22
May	1.47	1.70	-0.23
June	1.42	1.59	-0.17
July	1.47	1.65	-0.17
August	1.61	1.60	0.01
September	1.79	1.64	0.15
October	1.97	1.99	-0.02
November	2.12	2.11	0.01
December	2.20	2.13	0.07
Surplus energy			0.74
Energy shortage			-1.00

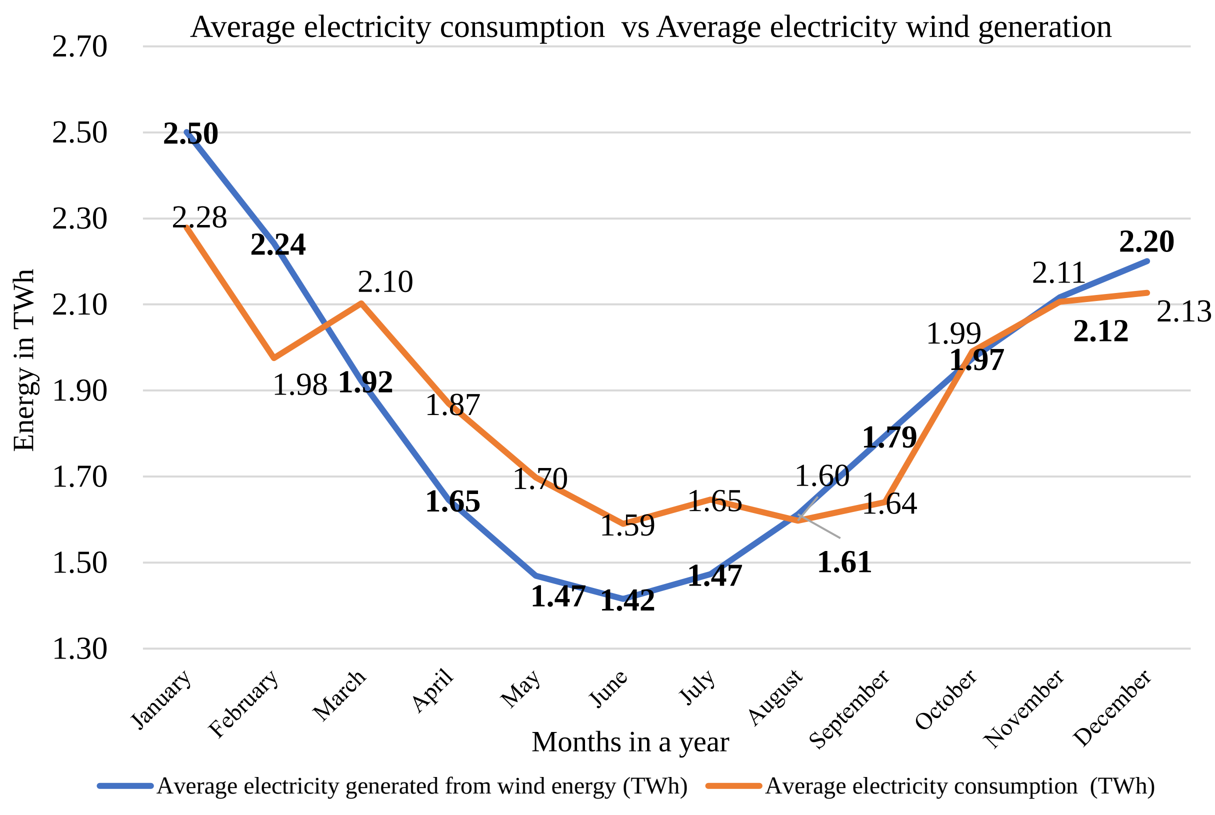

Figure 45: Average electricity consumption against average electricity generated by wind [109]

From the above graph (Figure 45) it is evident that seasonal variation is therefore essential as winter demand is larger than summer and so is the wind energy production. To calculate the amount of hydrogen energy required to meet 100% demand at all times, Scotland's power consumption was compared to the electricity produced by wind on monthly basis as shown in Table 8. Also, the above graph (Figure 45) clearly depicts the months with shortage of electricity which is also highlighted in red in the above table, this shortage accounts up to 1 TWh. The surplus energy amount was about 0.74 TWh. Thus, in the year 2019, a deficit of around 1 TWh occurred and hence this will be the hydrogen energy required for demand to be met at all times. The surplus electrical energy was converted to hydrogen gas amounting to about 16,747tonnes. Assuming that Siemens Silyzer 300 PEM electrolyser was used to generate hydrogen with an efficiency of 75.5%. The energy density of 1 kg of hydrogen equals about 33.6 kWh of useful electrical energy [105,103]. Therefore, if the hydrogen was burnt in a hydrogen powerplant and converted back to electricity it would be equal to 0.56 TWh of energy. This energy is still unable to meet the shortage of 1 TWh. In such a scenario, electricity which Scotland exports was taken into account in other words if Scotland wasn't exporting that electricity, and instead produced hydrogen gas, the total electricity demand of Scotland could be met easily.

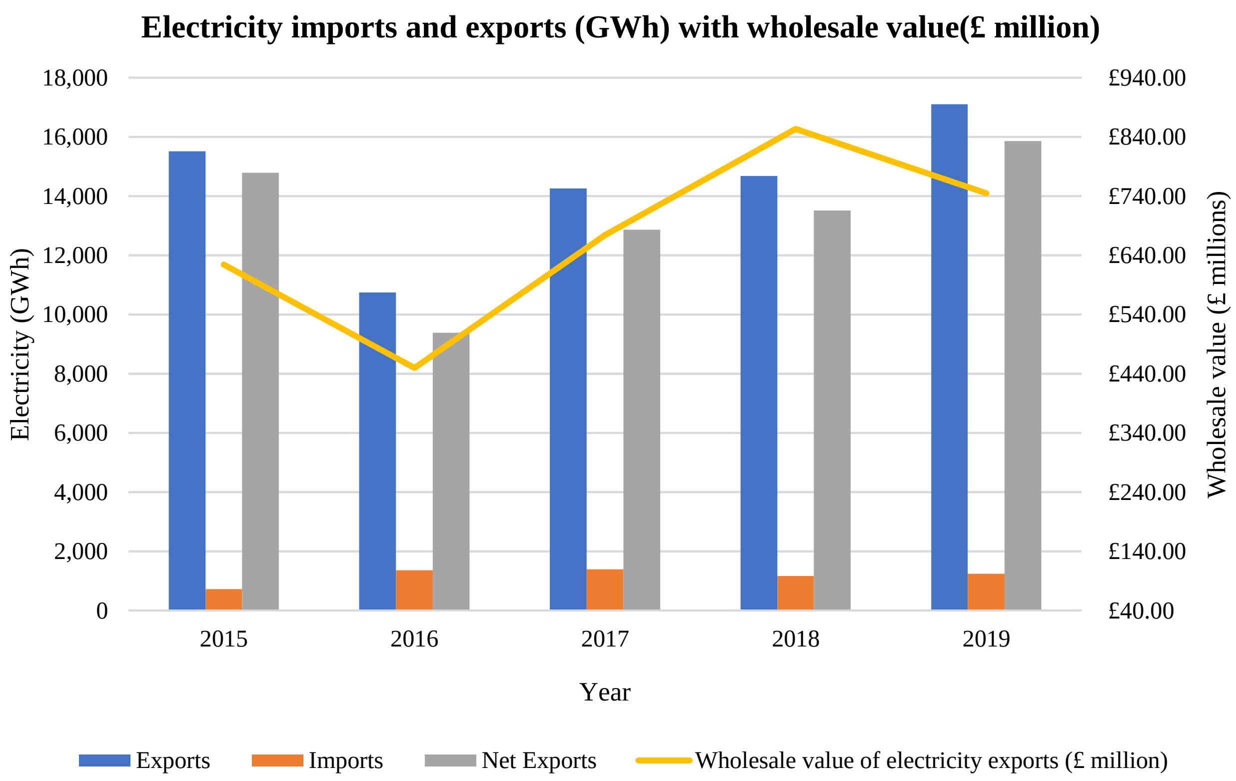

Figure 46: Energy exports and imports by Scotland from 2015 to 2019 with wholesale value [109].

Scotland exports electricity all through the year when electricity is above Scottish demand. Similarly, electricity is also imported if the demand exceeds generation. Approximately 17.09 TWh of electricity was exported in the year 2019 and about 1.2 TWh was imported during the shortage hours [109]. The wholesale value of this was anticipated to be about £746 million [109]. Assuming that this exported energy was the electricity generated during off-peak hours and after meeting 100% electricty demand. The amount of hydrogen produced from 17.09 TWh equals to approximately 386,766.19 tonnes of hydrogen gas. This energy can be stored and used when the demand for electricity is higher. This amount of hydrogen gas could produce electricity amounting to 13 TWh which is enough to power about 15,000 households twice. In this way if hydrogen was generated from excess electricity instead of exporting electricity Scotland could successfully meet its electricity demand by using wind power.

It is also worth noting that Scotland could also become exporter of hydrogen instead of electricity. Green hydrogen is priced currently at about £5 to £8 per kg. If the produced hydrogen (386,766.19 tonnes) was traded after meeting 100% electricity demand of scotland, it would be worth £2.5 to £3 billion. Scotland could make profit upto four times more by selling green hydrogen rather than electricity.

The second task of this study was to consider a scenario of 2045, assuming electricity demand rose by about 1% from current figures. This ambitious rise in electricity demand is assumed with the fact that there would be mass adoption of Electric vehicles(EV) and hence assuming a majority of the vehicles would be electrified, perhaps the figures could even be doubling by 2050 if heating is electrified [122]. Currently the transport sector is consuming a total energy of about 38 TWh. Assuming for the sake of this study that about 50% of the vehicels would be electrified. That would give us an estimated electricity demand of about 45 TWh (25 TWh electricity + 19 TWh EVs). With this in mind and considering the climate change effects the government of Scotland has put forth many proposals and several are under construction and many more awaiting approval. Wind power projects with a capacity of 13.4 GW are in the planning. About 2 GW are under development, most of which are OWFs [109]. If all these windfarms come into existence and underway producing energy it is estimated it could produce more than double the current level of production. However, it should be kept in mind a number of factors might affect the final generation value. For a better approach the wind power produced was estimated by simulations from three different softwares namely *SAM* [106], *RETScreen* [107], and *Energypro* [108]. All three model simulations gave similar values with approximate differences averaging 20%. These variations could be accounted towards various factors. Energypro doesn't take into account the factors like elevation, roughness, turbines losses, wake effect, and the predominant wind direction which are actually considered in both RETscreen and SAM. RETscreen uses accurate location details which are obtained from NASA (National Aeronautics and Space Administration) database whereas SAM takes average windspeed for the particular location. The monthly wind power estimated values for the year 2045 are obtained as per Table 9 and projected on the below graph (Figure 47).

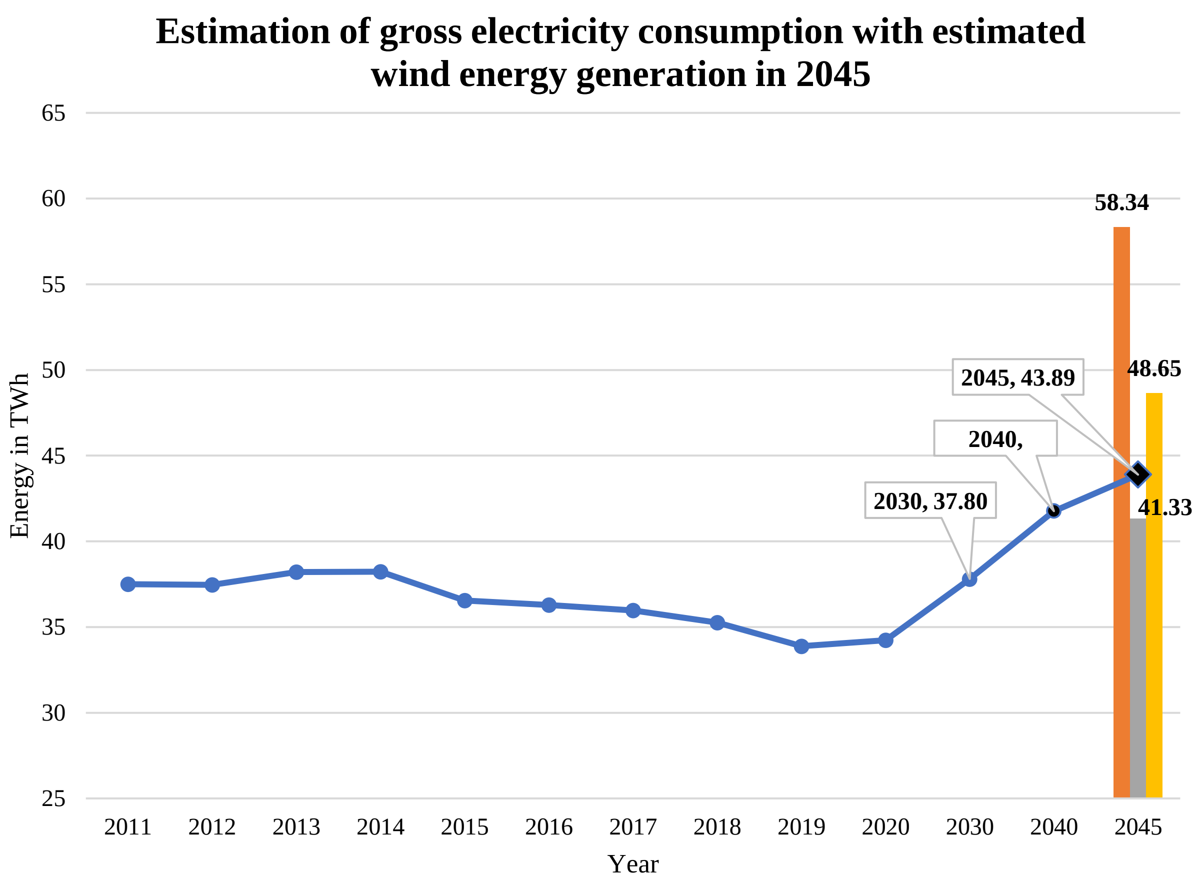

Figure 47: Gross electricity consumption and wind energy prediction for the year 2045 with 1% increase

Based on the above estimated consumption and wind energy generation (taking an average of the three values, 49.44 TWh), it is found that there could be a surplus of about 5.55TWh. Scotland could produce 125,602.83 tonnes of hydrogen (75.5% efficiency) which is equivalent to 4.22 TWh of electricity. This implies that with the current installed wind capacity (9.4 GW) and an additional planned 13.4 GW plants Scotland could meet the total electricity demand. But hydrogen energy storage system will play a key role in storing energy when wind is surplus so as to Scotland could make full potential of the renewable source. The surplus electricity could be traded to UK or Europe for huge revenue.

Table 9: Wind power estimations using the softwares for the year 2045

Months in a year	Monthly electricity production from SAM model (TWh) *	Monthly electricity production from EnergyPro model (TWh)*	Electricity production from RETScreen model (TWh)
January	4.95	3.43	4.86
February	4.48	4.12	
March	4.95	4.60	
April	4.79	3.33	
May	4.95	2.18	
June	4.79	2.93	
July	4.95	2.73	
August	4.95	3.39	
September	4.79	3.30	
October	4.95	3.87	
November	4.79	2.84	
December	4.95	4.60	
Total	**58.34**	**41.33**	**48.65**

*The models were created for a size of 300MW (because of software limitations) and upscaled.

The third task of this study was to estimate the wind capacity required to meet the total energy demand of Scotland. As discussed earlier, Scotland has already taken steps to produce at least 50% of Scotland's overall energy consumption from renewable sources by 2030, and a completely decarbonised energy system by 2050. After covering the primary need i.e., electricity, the next hard to mitigate sectors are heating and transport. Scotland's energy demand can be divided by sector as shown in the Table 10 below.

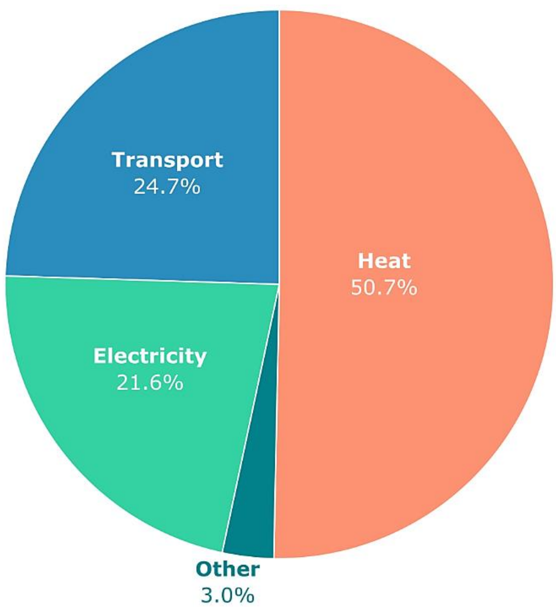

Figure 48: Percentage energy demand of Scotland's major sectors for the year 2019 [109]

Table 10: Breakdown of energy demand in Scotland (2019) [109]

Major sectors	Energy (GWh)
Heating	79,634.00
Transport	38,793.00
Electricity	33,874.58
Others	4,705.00
Total Energy demand	**157,006.58**

The overall energy strategies of the Scottish government are motivated by the requirement for a decarbonised energy system, in accordance with the emissions levels established by the Climate Change (Scotland) Act, hence the need for renewable energies is substantial [114]. This Act set targets to reduce all GHG emissions in Scotland to net nil by 2045 no later than five years before the whole of UK.

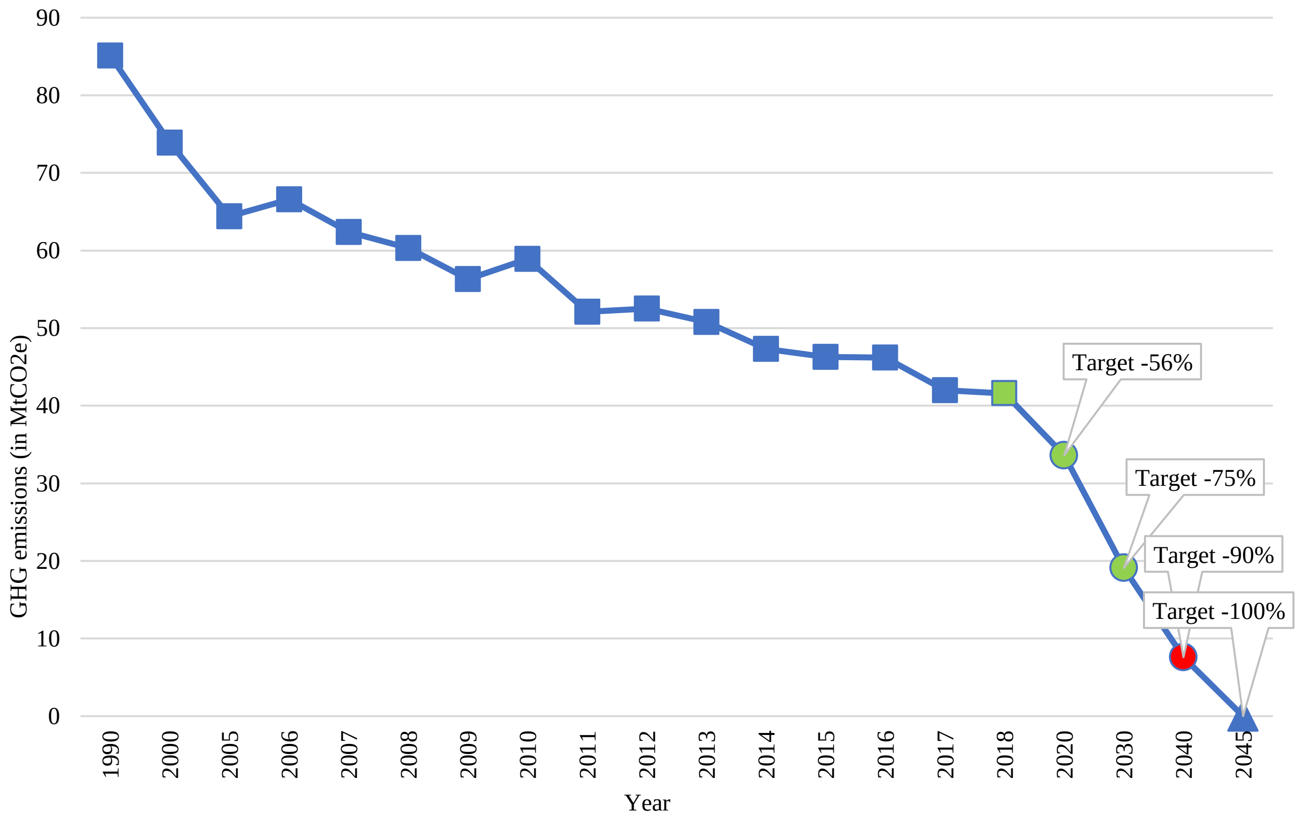

Figure 49: GHG emissions from 2000 to 2019 and targets set to 2045 [109]

As shown in below Figure 49 the Act also have stated intermediate objectives to reduce emissions by at least 56% by 2020, 75% by 2030, and 90% by 2040 from a 1990 baseline [109]. The graph also indicates that from 1990 to 2018, the estimated emissions decreased 45.4%.

The energy sector (electricity, heating, transport) is the largest contributing sector to slowing down the overall decrease in GHG emissions, which is 88.9 per cent of Scotland's total greenhouse gas emissions. An increasing amount of energy supply, driven almost exclusively by higher energy from power plants, was the principal driver to this growth between 2017 and 2018 [109]. As stated earlier in section 2.5.6.1, Scotland and the UK has a very well-established gas network, and the latest pipelines are laid which are future proof meaning hydrogen could replace natural gas for heating by using it either in gas or steam turbines or in a CHP. This also offers numerous possibilities, especially for exploiting O&G pipes in the North Sea (Figure 50), to export hydrogen either to the UK or to Europe or to the whole world [69].

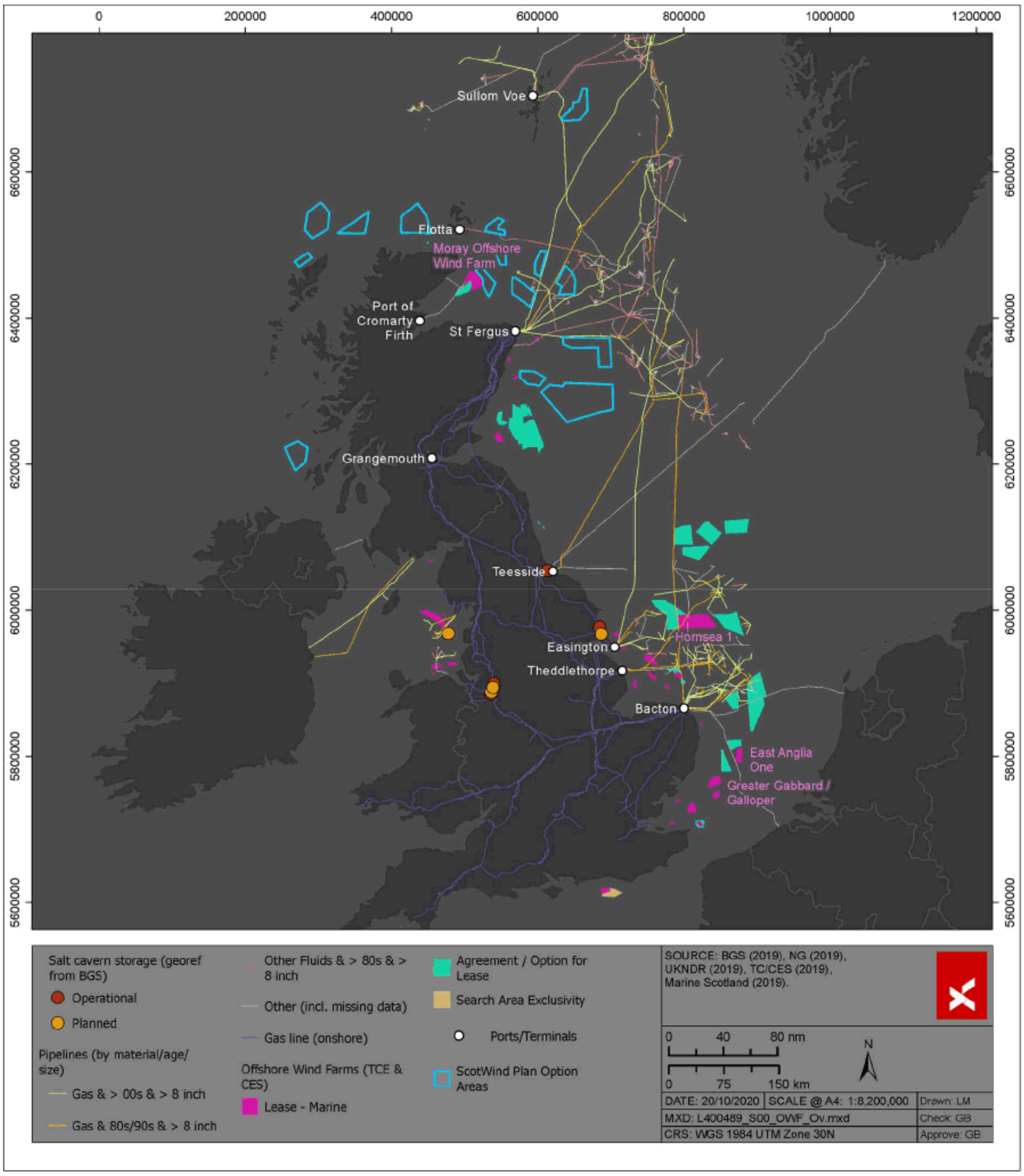

Figure 50: Scotland's existing pipeline and its connections to England and Europe [69]

In 2019, renewables provided only about 6.5% of the total heating, the remainder 93.5% of the demand is accomplished using natural gas. Policy documents on energy efficiency and heat supply are anticipated shortly from both the UK and Scottish governments. Heat supply is an essential element of energy consumption in all industries and accounts approximately 50.7% (79.65 TWh) (Table 10, Figure 48) of final Scottish energy consumption [115]. Considering a scenario if natural gas is replaced completely by hydrogen gas or if heating is electrified (assuming same efficiencies), it is estimated that in order to meet the current demand of heating, about 1.80 megatonnes (Mt) of hydrogen gas is required. It is also important to note that, Hydrogen gas has an energy density of 120 MJ/kg which is more than double of natural gas which suggests that hydrogen has three times more energy in 1 kg of hydrogen (1kg = 33.6 kWh) as compared to natural gas (1 kg =13.1 kWh) [103]. It also means that the volume of hydrogen gas needed to fulfil the demand will be half of natural gas. Contemplating a scenario of 2045 (Figure 51) assuming heating demand rose steadily by about 1% from current figures. In order to meet the demand projections for 2045, Scotland should produce 3.09 megatonnes of hydrogen which is equivalent to 103.17 TWh of electricity. This means an additional 25 GW plants needs to be planned. And as specified before at 700 bars, the density of hydrogen is 42 kg/m^3 and equals 33.6 kWh meaning the volume of hydrogen gas required in the year 2045 would be almost half of as much as natural gas (see Figure 51).

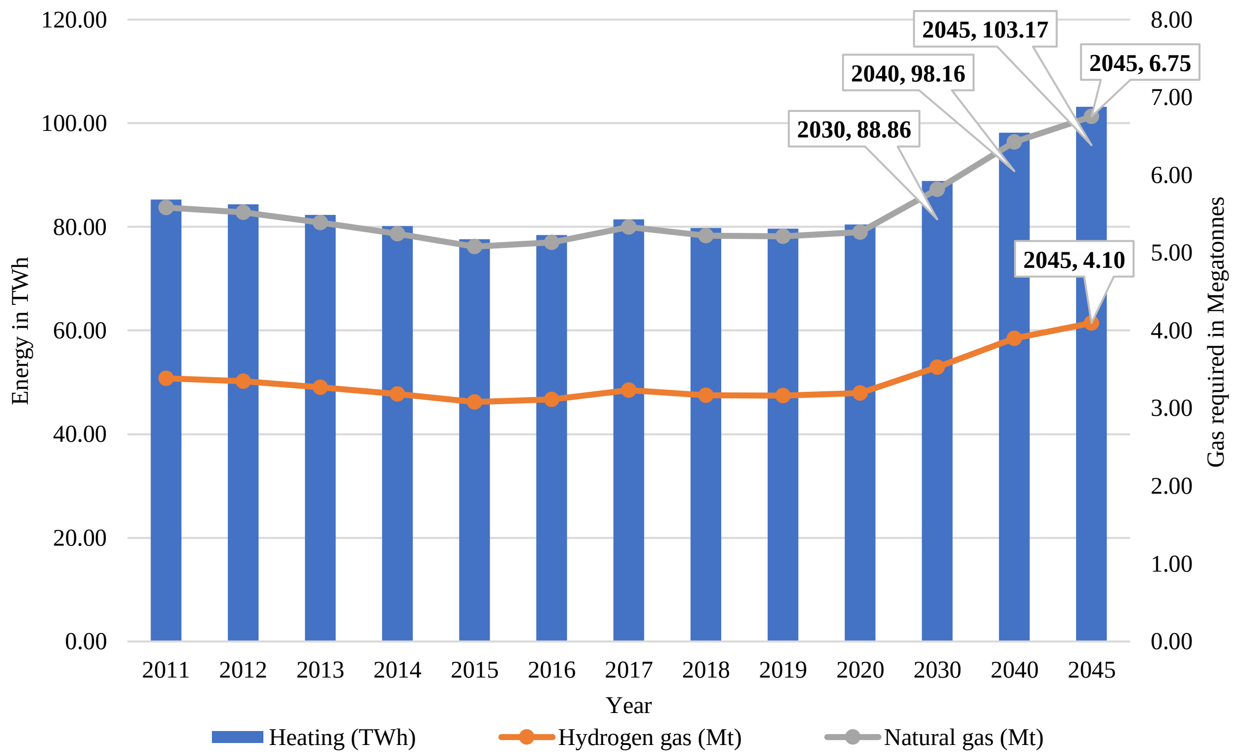

Figure 51:Energy consumption prediction of heating for the year 2045 with 1% increase

However, the basic finding from these estimates is that it would be very difficult to provide heating with just wind energy. Even with all the planned windfarms Scotland cannot just rely on windfarms for heating. Unless offshore windfarms are explored more for their potential. For instance, like the recent world's first floating OWF (Hywind) at Peterhead, northeast of Scotland. Currently offshore windfarms cover about just a percent of the UK's seabed. If there were enough tools to calculate the area of North Sea between 100m to 1.km, it could be estimated how many such wind turbines can be installed without causing any environmental impacts, hence more potential wind energy could be estimated to meet such high demands.

Among all the sectors the transport sector is the most difficult sector to mitigate towards renewable energy. It is also a major contributor slowing the overall reduction in GHGs. This sector contributed the highest amount in 2018 at 12.9 metric tonnes of carbon dioxide equivalent ($MtCO_2e$), and there has been a decline of just 4.9% since 1990 [102]. The most plausible option to decarbonise the transport sector would be either switching to hydrogen fuelled cars i.e., Fuel cell electric vehicles (FCEV) or to Electric vehicles (EV) or to biofuels. The traditional internal combustion engines might as well be converted to run on pure hydrogen, but combustion of hydrogen is less efficient compared to fuel cell and it emits NO_x. Hydrogen gas and fuel cell applicability vary between modes of transport and illustrates the various character of the transport industry that covers land, sea, and air, including cargo and passengers keep increasing day by day [116].

In case of hydrogen cars (FCEVs) there is no extensive usage of land it doesn't pollute unlike biofuels, and there is no restricted range and significant recharge time involved as in case of EVs. Despite this, EVs are way ahead of hydrogen cars, because of its lower costs and easily available infrastructure [116]. At 300 bar, hydrogen gas has about 33.6 to 40 kWh per kg in comparison to lithium batteries which has only about 165 to 280 watt-hours per kg and about 12.06 kWh per litre of petrol (1 kg petrol = 0.711kgs) [103]. Although it will provide higher energy density per kg, it would need incredibly large and heavy fuel tanks. Also, the theoretical and actual efficiency of hydrogen fuel cells is very poor. Hydrogen fuel cells require a significant number of support system which complicate them and make them far more likely to fail compared to traditional combustion engines or electric engines [116].

Figure 52: Efficiency comparison of hydrogen cars and EVs [117]

The battery powered EVs have higher efficiency in comparison to hydrogen cars. As shown in Figure 52 in the EVs energy lost during transport & distribution (before storing in batteries of EVs) is very less i.e., approximately 8%. When this electrical energy is converted and consumed to run the motor, additional 18% is lost. The final efficiency of EVs is about 70 to 80%, varying from model to model [117]. The hydrogen car powered by either fuel cells or electricity has very low efficiency due to significant energy losses (see Figure 52). About 45% of the energy is initially lost in the process of producing hydrogen via electrolysis, compression, storage and transportation. Out of the remaining 55% of the initial energy, additional 55% is lost in the fuel cell and power generation (while converting hydrogen into electricity) in the vehicle. This illustrates that hydrogen-powered car can attain a maximum efficiency of about 25 to 30%, varying from model to model.

An example of the above discussion is clearly discussed by Ulf bossel as shown in the Figure 53 below. It illustrates the many processes involved for the hydrogen processing and converting it back into electricity to power the motor that drives the wheels of a hydrogen powered car [118]. Ulf Bossel a fuel cell consultant quotes that "An electron economy can offer the shortest, most efficient and most economical way of transporting the sustainable 'green' energy to the consumer."

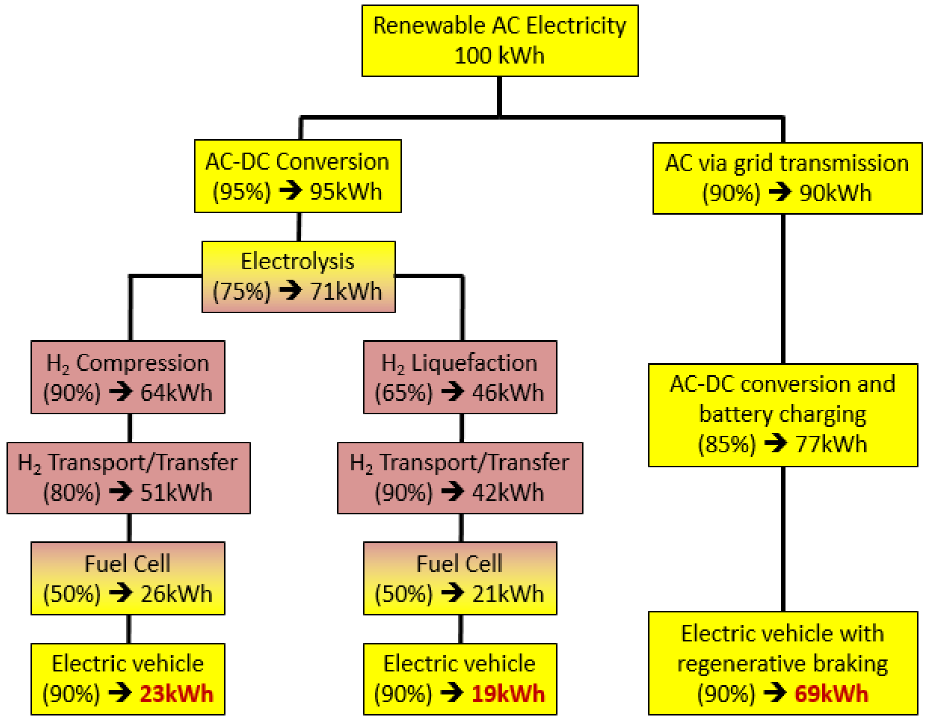

Figure 53: Comparison of energy requirement by a hydrogen powered car (left) vs EVs (right) [118]

From the above analysis, it is clearly understood that hydrogen usage in vehicles is currently not efficient. However, with the rate of technological progress, the battery powered EVs have a better future. While hydrogen as a gas could replace jet fuels in planes and could be used to power planes. ZeroAvia, a British-American hydrogen-electric manufacturer, is building the world's first practical zero-emission aircraft for commercial air travel [119].

Table 11: Advantages and disadvantages of hydrogen powered cars [117]

Advantages	**Disadvantages**
• It does not cause pollutions, as it emits only water. • Hydrogen is available in infinite quantities • It has a high range compared to EVs. • Fast refuelling (3 to 5 mins) • No engine sounds meaning less noise/traffic pollution	• It has very low efficiency due to high energy losses. • It is highly inflammable • There is no infrastructure currently • Higher costs i.e., very expensive to buy and maintain

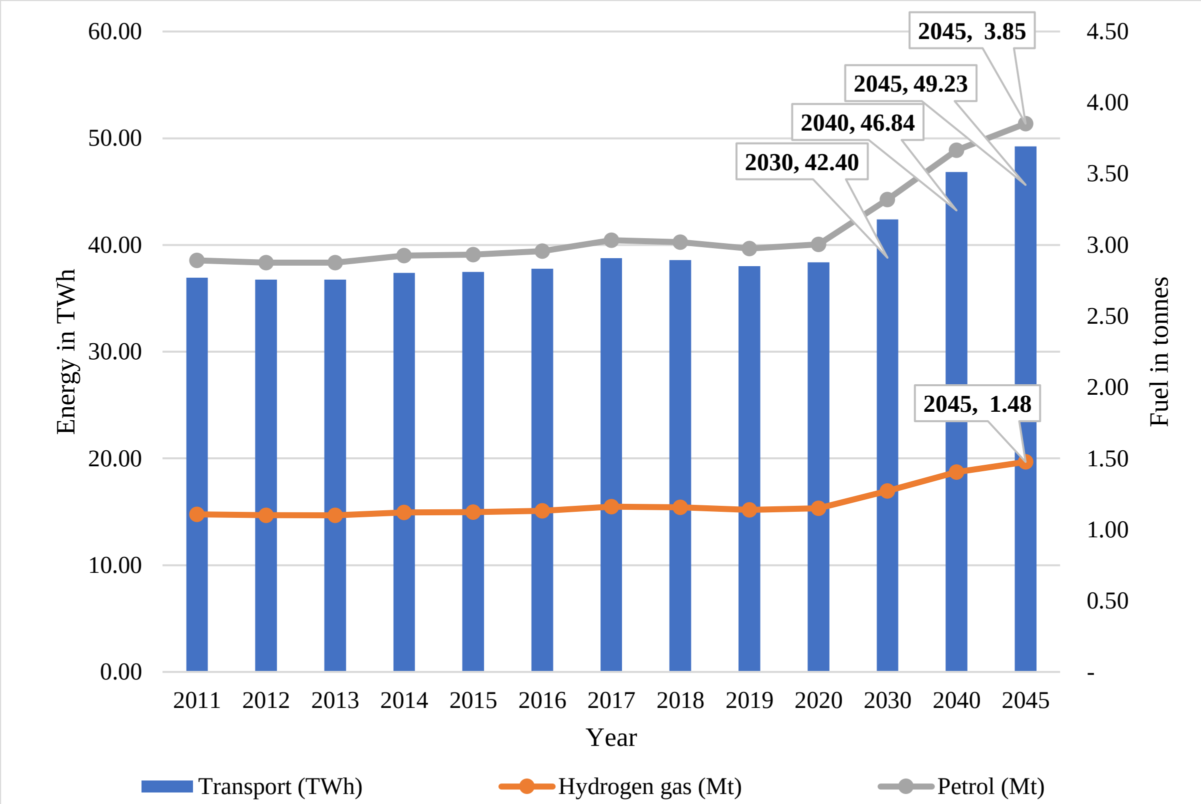

Figure 54: Energy consumption prediction of transport sector for the year 2045 with 1% increase

Considering a scenario in 2045 assuming the hydrogen technology is successful with higher efficiencies and better fuel cell designs and assuming that all the vehicles are hydrogen powered (Figure 54) and the energy demand in transport sector rose gradually by about 1% from current figures. To comply with the demand projections, Scotland should produce 1.48 Mt of hydrogen to meet the 50 TWh energy demand. However, in comparison with petrol, it can be seen in the graph that volume of hydrogen required is just about half of petrol.

It is estimated that around 44 to 46 GW wind power is necessary to fulfil the overall current energy consumption of 157 TWh (Table 10). But as per current plans, there would be a deficit and it is not possible to meet the total energy demand by just wind power. Although complete electricity and 50% transport sector could be decarbonised. Also, as per Scottish Energy Strategy forecasts energy demand will drop by 5 to 28% (110 TWh to 148 TWh) in the next few decades [120]. Currently about 23.9% of the total gross energy consumption is derived from renewable sources (see Figure 55). This was a rise from 20.9% in the year 2018 [109]. Wind energy is the major contributor with about 19.3% with a total capacity of 11.89 GW. Between 2018 and 2019, renewable energy produced have grown by more than 4,200 GWh. Most of this growth is attributable to increased electricity generation from wind; an increase in renewable energy from offshore wind of over 1,900 GWh and onshore wind of almost 1,000

GWh. The total energy generated by all forms of renewable energy accounted to about 37.34 TWh [109].

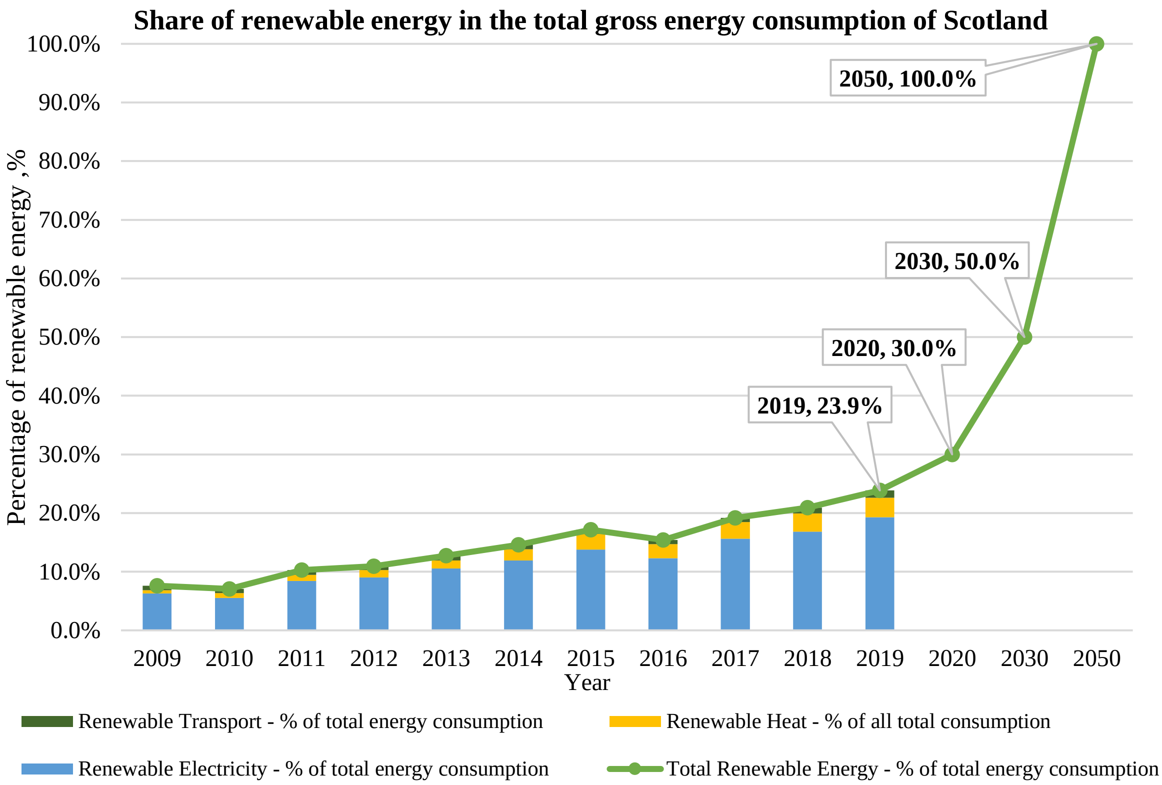

Figure 55: Percentage share of renewable energy in the total gross energy consumption of Scotland [109]

Worldwide, the hydrogen sector is expanding rapidly. It is very difficult to make estimations and projections in such a quick development because the underlying trend is continuously changing. This clearly shows that information from only a few years ago might perhaps be mistaken or provide a misinterpretation to the current condition. Hydrogen production costs mainly depends on the methods. Some methods are very old and hence have a very well-established pricing, some are new and still being investigated, hence there are chances they will reduce significantly over the years [121]. As the hydrogen usage increases, the value of hydrogen will decrease the cost of producing hydrogen currently differs greatly depending on the production process and production region. Several recent worldwide studies have tried to calculate the cost of producing green and blue hydrogen globally by 2050.Uncertainties as to how these expenses evolve can lead to significant variations in estimates [121]. This is very true in the case of green hydrogen production, since it is a latest and dependent on renewable electricity prices which itself has a wider range of prices. As shown in Figure 56 several studies have analysed that, over the next few years, blue hydrogen will be cheaper, with green hydrogen likely to compete with blue hydrogen from mid-2030 [121]. The current price of green hydrogen is around £5 to £8 per kg. In order to enhance usage of green hydrogen, attempts are being made to lower the price by introducing incentives on the capital costs. As per the forecasts by Scottish government, green hydrogen would cost around £1.5 to £3 by 2030.

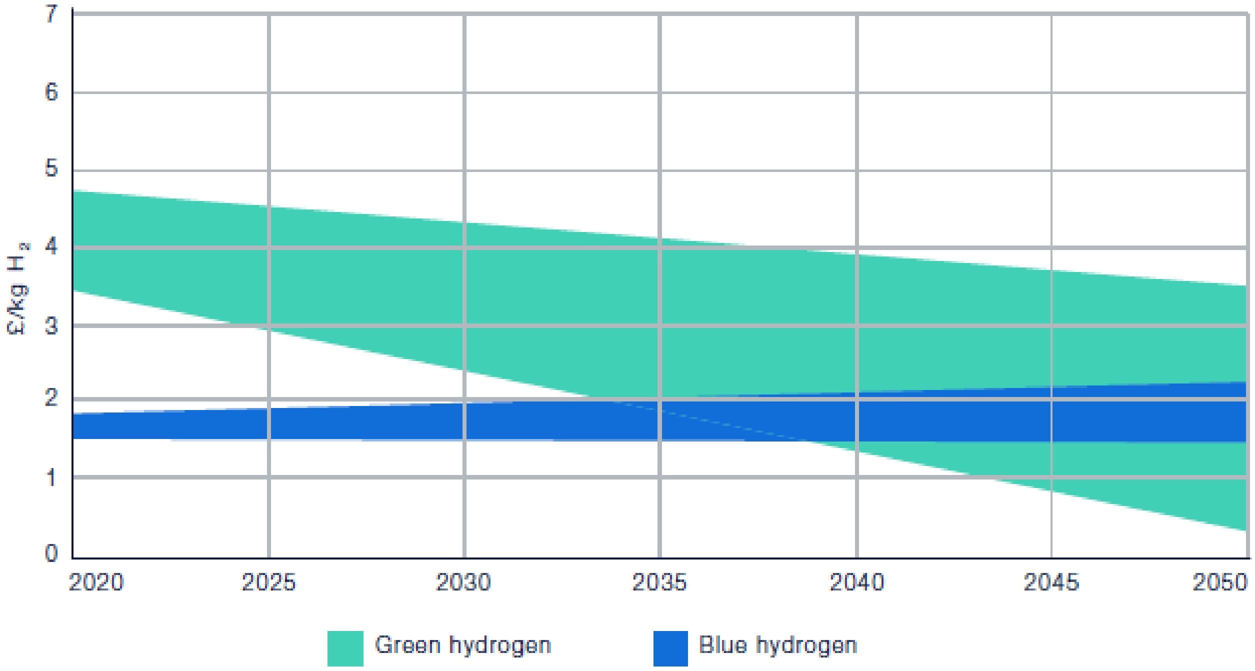

Figure 56: Cost estimation of blue and green hydrogen from 2020 to 2050 [121]

The production cost of green hydrogen is likely to be cut down significantly by 2050 due to the declining renewable energy price and expanded levels of electrolyser manufacturing combined with enhanced efficiencies. Reduction of offshore and onshore wind power generation costs will play a crucial role in Scotland's hydrogen economy [69]. Furthermore, it is necessary to consider initial set-up and operating expenses. Apart from production costs, there are other costs like transporting, storing and distribution which are very significant in calculating the overall costs. Most of the hydrogen production today is co-located with end usage which is not practical for all applications in the future. The cheapest and most economic method of transporting and distributing hydrogen will be using pipelines [121]. The construction costs of new pipeline networks will be a big investment and hence need to assess if there is considerable amount of hydrogen to be transported in order for it to be feasible. Most of these expenses could be prevented by converting the existing O&G pipeline network into a future proof gas line. As mentioned previously in the report, Scotland and whole of UK has a very well-established O&G network (within UK and also to various parts of Europe) in comparison with other nations of the world. This would be one of the main highlights of the Scottish government's hydrogen economy [69].

5.0 Conclusion

Using hydrogen as a mainstream fuel or as an energy storage system enables conservation of stochastic wind energy at high production times, with the confidence that a reliant storage is available to store and consume it during low generating points. With Scotland signing the hydrogen policy statement it is for sure hydrogen will play an integral role in decarbonising Scotland's energy system and economy by 2045 [15].

It is theoretically clear from the results and analysis that Scotland is capable of producing 100% of its total gross electricity consumption from wind energy with the current proposed plans by transforming the surplus electricity generated into hydrogen and storing it for the times when supply cannot meet the demand. It is also worth noting Scotland exports a lot of electricity which could instead be converted to hydrogen and utilised at downtimes. With already existing O&G pipelines which are believed to be future proof and safe to transport hydrogen Scotland has an inherent benefit in green hydrogen production in view of the vast offshore and onshore potential. This also offers Scotland with the possibility to becoming a net exporter of high-purity green hydrogen to the rest of the UK and most parts of the Europe. The calculated target of 45-50 GW wind energy capacity required to decarbonise Scotland by 2050 (assuming the gross energy consumption is around 150 TWh). However, as per current proposed plans, there would be a shortfall to meet this total energy demand and it is not possible to meet the total energy demand by just wind energy. While complete electricity and half of transport sector could be decarbonised, heating definitely cannot be covered with wind energy. Green hydrogen production from offshore winds can aid to reduce emissions in heating sector, transport and manufacturing industry that have been notoriously challenging since ages and can assist to overcome the power grid restrictions in Scotland to provide huge clean electricity.

Though the hydrogen energy technology may not have developed very well yet unlike traditional technologies and may have certain obstacles, such as significant hydrogen production costs, investments in the new infrastructure, heavy storage tanks, transport & distribution, and safety concerns. Nevertheless, they offer significant benefits related to zero emissions and fuel flexibility. With the emerging technologies like FES system, Concrete block energy storage system and discovery of storing hydrogen as Ammonia, the future seems to be bright for renewable energy technologies. This is a very essential and fascinating issue for future study and more additional research can be done on incorporating multiple alternative renewable resources for instance, solar PV, tidal/wave energy, biomass etc., to maximise energy generation. A considerable amount of oxygen and heat will be produced during electrolysis which can be recycled for other applications. In the long run offshore wind energy along with floating offshore wind farms is considered as a great opportunity to enhance hydrogen production in a large scale and to unleash more of Scotland's offshore wind potential.

6.0 References

[1] **E. Taibi, H. Blanco, R. Miranda,** and **M. Carmo,**, Green Hydrogen Cost Reduction; Scaling up Electrolysers to meet the 1.5C Climate Goal, [Online]. Available: http://www.irena.org/publications (Accessed Aug. 07, 2021).

[2] **C. Mitchell**, ‘Momentum is increasing towards a flexible electricity system based on renewables’, Nat. Energy, vol. 1, no. 2, pp. 1–6, Feb. 2016, doi: 10.1038/nenergy.2015.30.

[3] **Masson-Delmotte et al.,** Global warming of 1.5 C. An IPCC Special Report on the impacts of global warming of, 1, pp.1-9. vol. 32, p. pp, [Online]. Available: https://www.ipcc.ch/ (Accessed Jul. 12, 2021).

[4] ‘Global historical CO2 emissions 1758-2020’, Statista. https://www.statista.com/ (Accessed Aug. 01, 2021).

[5] **C. Oates**, ‘Companies are developing over 200 GW of Hydrogen electrolyser projects globally, 85% of which are in Europe’, Aurora Energy Research, May 11, 2021. https://auroraer.com/media/companies-are-developing-over-200-gw-of-hydrogen-electrolyser-projects-globally-85-of-which-are-in-europe/ (Accessed Aug. 01, 2021).

[6] ‘The Future of Hydrogen – Analysis’, IEA. https://www.iea.org/reports/the-future-of-hydrogen (Accessed Aug. 01, 2021).

[7] **Dincer, I.,** 2012. Green methods for hydrogen production. International journal of hydrogen energy, 37(2), pp.1954-1971. doi.org/10.1016/j.ijhydene.2011.03.173

[8] ‘Global hydrogen production outlook 2050’, Statista. https://www.statista.com/statistics/859104/hydrogen-production-outlook-worldwide-by-type/ (Accessed Aug. 01, 2021).

[9] Center on Global Energy Policy, Hydrogen Now to 2030: Opportunities and Limits in a Circular Carbon Economy. Accessed : Aug. 01, 2021. [Online Video]. Available: https://www.youtube.com/watch?v=9AGhoqSP1Tc

[10] ‘Renewable energy statistics’. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Renewable_energy_statistics (Accessed Aug. 01, 2021).

[11] Ecotec (2002). Renewable energy sector in the EU: Its employment and export potential. A Final Report to DG Environment, Birmingham. Available from http://ec.europa.eu/environment/enveco/eco_industry/pdf/ecotec_renewable_energy.pdf. (Accessed Aug. 02, 2021).

[12] R. Ltd, ‘Renewables outstrip fossil fuels in UK in 2020’, reNEWS - Renewable Energy News, Mar. 25, 2021. https://renews.biz/67478/renewables-outstrip-fossil-fuels-in-uk-in-2020/ (Accessed Aug. 02, 2021).

[13] ‘Renewable Energy Facts & Statistics, Scottish Renewables’. https://www.scottishrenewables.com/our-industry/statistics (Accessed Aug. 02, 2021).

[14] ‘Energy Statistics for Scotland Q4 2020 Figures’. (March 2021). [Online]. Available: https://www.gov.scot/ (Accessed Aug. 02, 2021).

[15] ‘Developing Scotland’s hydrogen economy: statement by the Energy Minister - gov.scot’.https://www.gov.scot/publications/ministerial-statement-developing-scotlands-hydrogen-economy/ (Accessed Aug. 02, 2021).

[16] ‘Wind Energy in the UK: Learn the basics’, The Switch. https://theswitch.co.uk/energy/guides/renewables/wind-energy (Accessed Aug. 02, 2021).

[17] ‘Average wind speed UK 2001-2020’, Statista. https://www.statista.com/statistics/322785/average-wind-speed-in-the-united-kingdom-uk/ (Accessed Jul. 31, 2021).

[18] ‘Scotland: installed wind power capacity 2020’, Statista. https://www.statista.com/statistics/497289/cumulative-installed-capacity-of-wind-energy-onshore-offshore-scotland/ (Accessed Jul. 31, 2021).

[19] ‘Bodinglee Wind Farm:: Banks Group’. https://www.banksgroup.co.uk/projects/renewables/bodinglee-wind-farm/ (Accessed Aug. 09, 2021).

[20] ‘Energy Storage, Battery Storage, Renewable Energy Enablement’, Clarke Energy. https://www.clarke-energy.com/energy-storage/ (Accessed Jul. 12, 2021).

[21] **S. Koohi-Fayegh** and **M. A. Rosen**, "A review of energy storage types, applications and recent developments," Journal of Energy Storage, vol. 27, p. 101047, Feb. 2020, doi: 10.1016/j.est.2019.101047.

[22] Student Energy, Energy Storage 101. Accessed : Jul. 19, 2021. [Online Video]. Available: https://www.youtube.com/watch?v=9eAFEU7pMwU

[23] **M. M. Rahman, A. O. Oni, E. Gemechu,** and **A. Kumar**, 'Assessment of energy storage technologies: A review', Energy Convers. Manag., vol. 223, p. 113295, Nov. 2020, doi: 10.1016/j.enconman.2020.113295.

[24] **D. N. Buckley**, **C. O'Dwyer**, **N. Quill**, and **R. P. Lynch**, 'Electrochemical Energy Storage', in Energy Storage Options and Their Environmental Impact, 2018, pp. 115–149. doi: 10.1039/9781788015530-00115.

[25] **Ioan Sarbu** and **Calin Sebarchievici**, 'A Comprehensive Review of Thermal Energy Storage', Sustainability, vol. 10, no. 2, p. 191, Jan. 2018, doi: 10.3390/su10010191.

[26] **P. Nikolaidis** and **A. Poullikkas**, 'A comparative review of electrical energy storage systems for better sustainability', p. 27, 2017. Journal of power technologies. http://papers.itc.pw.edu.pl/index.php/JPT/article/view/1096/776

[27] **H. Kerskes**, "Thermochemical Energy Storage," Storing Energy, no. 9780128034408, pp. 345–372, Jan. 2016, doi: 10.1016/B978-0-12-803440-8.00017-8. (Accessed Jul. 21, 2021).

[28] **A. H. Abedin**, 'A Critical Review of Thermochemical Energy Storage Systems', Open Renew. Energy J., vol. 4, no. 1, pp. 42–46, Aug. 2011, doi: 10.2174/1876387101004010042.

[29] **F. Díaz-González**, **A. Sumper**, **O. Gomis-Bellmunt**, and **R. Villafáfila-Robles**, 'A review of energy storage technologies for wind power applications', Renew. Sustain. Energy Rev., vol. 16, no. 4, pp. 2154–2171, May 2012, doi: 10.1016/j.rser.2012.01.029.

[30] **S. Hameer** and **J. L. van Niekerk**, 'A review of large-scale electrical energy storage: This paper gives a broad overview of the plethora of energy storage', Int. J. Energy Res., vol. 39, no. 9, pp. 1179–1195, Jul. 2015, doi: 10.1002/er.3294.

[31] **A. Evans**, **V. Strezov**, and **T. J. Evans**, 'Assessment of utility energy storage options for increased renewable energy penetration', Renew. Sustain. Energy Rev., vol. 16, no. 6, pp. 4141–4147, Aug. 2012, doi: 10.1016/j.rser.2012.03.048.

[32] **S. Faias**, **P. Santos**, J. Sousa, and R. Castro, 'An overview on short and long-term response energy storage devices for power systems applications', Renew. Energy Power Qual. J., vol. 1, no. 06, pp. 442–447, Mar. 2008, doi: 10.24084/repqj06.327.

[33] **P. Breeze**, 'Hydrogen Energy Storage', in Power System Energy Storage Technologies, Elsevier, 2018, pp. 69–77. doi: 10.1016/B978-0-12-812902-9.00008-0.

[34] "Renewable and low carbon energy - gov.scot," Gov.scot, 2019. https://www.gov.scot/policies/renewable-and-low-carbon-energy/. (Accessed Jul. 23, 2021).

[35] 'Liquid Hydrogen - an overview | ScienceDirect Topics'. https://www.sciencedirect.com/topics/engineering/liquid-hydrogen (Accessed Jul. 24, 2021).

[36] **P. Breeze**, 'Chapter 8 - Hydrogen Energy Storage', in Power System Energy Storage Technologies, P. Breeze, Ed. Academic Press, 2018, pp. 69–77. doi: 10.1016/B978-0-12-812902-9.00008-0.

[37] **M. S. Guney and Y. Tepe**, 'Classification and assessment of energy storage systems', Renew. Sustain. Energy Rev., vol. 75, pp. 1187–1197, Aug. 2017, doi: 10.1016/j.rser.2016.11.102.

[38] **A. Rathi**, 'Stacking concrete blocks is a surprisingly efficient way to store energy', Quartz. https://qz.com/1355672/stacking-concrete-blocks-is-a-surprisingly-efficient-way-to-store-energy/ (Accessed Aug. 08, 2021).

[39] 'Enabling a renewable world', Energy Vault. https://energyvault.com/ (Accessed Aug. 08, 2021).

[40] **M. Kayfeci, A. Keçebaş,** and **M. Bayat,** "Hydrogen production," Solar Hydrogen Production, vol. Chapter 3, no. 9780128148532, pp. 45–83, 2019, doi: 10.1016/b978-0-12-814853-2.00003-5.

[41] **E. Cetinkaya**, **I. Dincer**, and **G. F. Naterer**, ‘Life cycle assessment of various hydrogen production methods’, Int. J. Hydrogen. Energy, vol. 37, no. 3, pp. 2071–2080, Feb. 2012, doi: 10.1016/j.ijhydene.2011.10.064.

[42] **D. Gielen, E. Taibi,** and **R. Miranda**, “Hydrogen: A renewable energy perspective” 2019. [Online]. Available: http://www.irena.org/publications (Accessed Aug. 07, 2021).

[43] **R Ferroukhi**, **E. Bianco,** and **H. Blanco**, ‘Green hydrogen: A guide to policy making’, [Online]. Available: http://www.irena.org/publications (Accessed Aug. 07, 2021).

[44] ‘The hydrogen colour spectrum, National Grid Group’. https://www.nationalgrid.com/stories/energy-explained/hydrogen-colour-spectrum (Accessed Aug. 07, 2021).

[45] ‘UK: hydrogen production share by method 2019’, Statista. https://www.statista.com/statistics/457795/uk-hydrogen-production-share-by-method/ (Accessed Aug. 03, 2021).

[46] ‘Hydrogen Production: Natural Gas Reforming’, Energy.gov. https://www.energy.gov/eere/fuelcells/hydrogen-production-natural-gas-reforming (Accessed Aug. 03, 2021).

[47] **M. K. Lam, A. C. M. Loy, S. Yusup,** and **K. T. Lee,** “Biohydrogen Production From Algae,” Biohydrogen, no. 978–0444–642035, pp. 219–245, 2019, doi: 10.1016/b978-0-444-64203-5.00009-5.

[48] ‘Hydrogen Production: Biomass Gasification’, Energy.gov. https://www.energy.gov/eere/fuelcells/hydrogen-production-biomass-gasification (Accessed Aug. 03, 2021).

[49] **P. Nikolaidis and A. Poullikkas**, ‘A comparative overview of hydrogen production processes’, Renew. Sustain. Energy Rev., vol. 67, pp. 597–611, Jan. 2017, doi: 10.1016/j.rser.2016.09.044.

[50] **Scott, K.** (2020). Chapter 1 Introduction to Electrolysis, Electrolysers and Hydrogen Production. Electrochemical Methods for Hydrogen Production, The Royal Society of Chemistry: 1-27.

[51] 'Press release: Flow batteries to combine with tidal power to produce world's first continuous green hydrogen : EMEC: European Marine Energy Centre'. http://www.emec.org.uk/flow-batteries-combine-with-tidal-power-to-produce-green-hydrogen/ (Accessed Aug. 05, 2021).

[52] 'Methods of Producing Hydrogen at Scale | Royal Society'. https://royalsociety.org/topics-policy/projects/low-carbon-energy-programme/hydrogen-production/ (Accessed Aug. 03, 2021).

[53] 'Wind Turbine Facts, Wind Power UK', Business Electricity Prices. https://www.businesselectricityprices.org.uk/wind-turbine-facts/ (Accessed Aug. 02, 2021).

[54] 'How Do Wind Turbines Work?', Energy.gov. https://www.energy.gov/eere/wind/how-do-wind-turbines-work (Accessed Aug. 02, 2021).

[55] 'How Wind Turbines Work', Clean Energy Ideas, Sep. 21, 2016. https://www.clean-energy-ideas.com/wind/wind-turbines/how-wind-turbines-work/ (Accessed Aug. 02, 2021).

[56] 'Types of wind - U.S. Energy Information Administration (EIA)'. https://www.eia.gov/energyexplained/wind/types-of-wind-turbines.php (Accessed Aug. 02, 2021).

[57] **J. Twidell** and **T. Weir**, Renewable energy resources. London; New York: Routledge, Taylor & Francis Group, 2015.

[58] **Assoc. Prof. Dr. J. Waewsak**, **C. Chancham**, **M. Landry**, and **Y. Gagnon**, 'An Analysis of Wind Speed Distribution at Thasala, Nakhon Si Thammarat, Thailand', J. Sustain. Energy Environ., vol. 2, Jan. 2011.

[59] "Wind Turbine Power Calculations RWE npower renewables Mechanical and Electrical Engineering Power Industry,." [Online]. Available: https://www.raeng.org.uk/publications/other/23-wind-turbine.

[60] **A. Moore**, **J. Price**, and **M. Zeyringer**, 'The role of floating offshore wind in a renewable focused electricity system for Great Britain in 2050', Energy Strategy Rev., vol. 22, pp. 270–278, Nov. 2018, doi: 10.1016/j.esr.2018.10.002.

[61] ‘Offshore wind farms: the sea giants’, Iberdrola. https://www.iberdrola.com/environment/how-does-offshore-wind-energy-work (Accessed Aug. 03, 2021).

[62] ‘Floating offshore wind power: a milestone to boost renewables through innovation’, Iberdrola. https://www.iberdrola.com/innovation/floating-offshore-wind (Accessed Aug. 03, 2021).

[63] ‘Floating offshore wind in Equinor - equinor.com’. https://www.equinor.com/en/what-we-do/floating-wind.html (Accessed Aug. 03, 2021).

[64] ‘World’s first full-scale floating wind farm - World Wind Technology’. https://www.windpower-international.com/features/featureworlds-first-full-scale-floating-wind-farm-6124984/ (Accessed Aug. 03, 2021).

[65] **K. Koiwa, A. Umemura, R. Takahashi** and **J. Tamura**, "Stand-alone hydrogen production system composed of wind generators and electrolyser," Proceedings of Industrial Electronics Society, IECON, pp. 1873 - 1879, 2013.

[66] **M. A. Sakka**, **J. V. Mierlo**, and **H. Gualous**, DC/DC Converters for Electric Vehicles. IntechOpen, 2011. doi: 10.5772/17048.

[67] ‘3-Phase Rectifiers | Missouri Wind and Solar’. https://windandsolar.com/3-phase-rectifiers/ (Accessed Aug. 02, 2021).

[68] ‘Tame-Power | DC/DC energy converters’. https://www.tame-power.com/en (Accessed Aug. 02, 2021).

[69] ‘Offshore wind to green hydrogen: opportunity assessment’. http://www.gov.scot/publications/scottish-offshore-wind-green-hydrogen-opportunity-assessment/pages/3/ (Accessed Aug. 11, 2021).

[70] **Nicholasnhede**, ‘Scottish Power plans to deliver the UK’s largest electrolyser in Glasgow’, Power Engineering International, Apr. 16, 2021. https://www.powerengineeringint.com/hydrogen/scottishpower-plans-to-deliver-the-uks-largest-electrolyser-in-glasgow/ (Accessed Aug. 12, 2021).

[71] **D. C. Spiegel,** ‘Introduction to Electrolyzers’. https://www.fuelcellstore.com/blog-section/introduction-to-electrolyzers (Accessed Aug. 05, 2021).

[72] **S. Shiva Kumar** and **V. Himabindu**, 'Hydrogen production by PEM water electrolysis – A review', Mater. Sci. Energy Technol., vol. 2, no. 3, pp. 442–454, Dec. 2019, doi: 10.1016/j.mset.2019.03.002.

[73] 'Electrolyzers 101: What they are, how they work and where they fit in a green economy', Cummins Inc. https://www.cummins.com/news/2020/11/16/electrolyzers-101-what-they-are-how-they-work-and-where-they-fit-green-economy (Accessed Aug. 05, 2021).

[74] 'Hydrogen Production: Electrolysis', Energy.gov. https://www.energy.gov/eere/fuelcells/hydrogen-production-electrolysis (Accessed Aug. 05, 2021).

[75] **R. El Mrabet** and **A. Berrada**, 'Chapter 10 - Hydrogen production and derivatives from renewable energy systems for a best valorization of sustainable resources', in Hybrid Energy System Models, 2021, pp. 343–363. doi: 10.1016/B978-0-12-821403-9.00010-X.

[76] **S. Giddey, S. P. S. Badwal**, and **H. Ju**, "Chapter 10 - Polymer Electrolyte Membrane Technologies Integrated With Renewable Energy for Hydrogen Production," Current Trends and Future Developments on (Bio-) Membranes, no. 978–012–8135457, pp. 235–259, Jan. 2019, doi: 10.1016/B978-0-12-813545-7.00010-6..

[77] **K. Hall**, 'Putting the Pressure on Hydrogen: A Look at Compressors and Pumps', gasworld. https://www.gasworld.com/open-access/putting-the-pressure-on-hydrogen-a-look-at-compressors-and-pumps (Accessed Aug. 02, 2021).

[78] 'Compressors for Hydrogen Fuel Cells | Howden'. https://www.howden.com/en-gb/applications/compressors-for-hydrogen-fuel-cell (Accessed Aug. 02, 2021).

[79] J. Larminie and A. Dicks, "Fuel Cell Systems Explained Second Edition,." [Online]. Available:https://www.ucursos.cl/usuario/c1f33623c53cd7f58fd77ef459693d6c/miblog/r/Fuel_Cell_Systems_Explained.pdf.

[80] **M. K. Mahapatra** and **P. Singh**, 'Chapter 24 - Fuel Cells: Energy Conversion Technology', in Future Energy (Second Edition), T. M. Letcher, Ed. Boston: Elsevier, 2014, pp. 511–547. doi: 10.1016/B978-0-08-099424-6.00024-7.

[81] 'Fuel Cell Basics', Fuel Cell & Hydrogen Energy Association. https://www.fchea.org/fuelcells (Accessed Aug. 02, 2021).

[82] 'Physical Hydrogen Storage', Energy.gov. https://www.energy.gov/eere/fuelcells/physical-hydrogen-storage (Accessed Aug. 02, 2021).

[83] **C. Winnefeld, T. Kadyk, B. Bensmann, U. Krewer,** and **R. Hanke-Rauschenbach**, 'Modelling and Designing Cryogenic Hydrogen Tanks for Future Aircraft Applications', Energies, vol. 11, no. 1, p. 105, Jan. 2018, doi: 10.3390/en11010105.

[84] 'Hydrogen Storage', Energy.gov. https://www.energy.gov/eere/fuelcells/hydrogen-storage (Accessed Jul. 23, 2021).

[85] **J. Andersson** and **S. Grönkvist**, 'Large-scale storage of hydrogen', Int. J. Hydrog. Energy, vol. 44, no. 23, pp. 11901–11919, May 2019, doi: 10.1016/j.ijhydene.2019.03.063.

[86] 'Introducing the PHG830 – our latest PRISM® Hydrogen Generator offering the best natural gas efficiency on the market.' https://microsites.airproducts.com/uk/phgbenefits/index.htm (Accessed Aug. 02, 2021).

[87] 'Hydrogen Storage - an overview | ScienceDirect Topics'. https://www.sciencedirect.com/topics/engineering/hydrogen-storage (Accessed Jul. 24, 2021).

[88] **V. A. Yartys** and **M. V. Lototsky**, 'An Overview of Hydrogen Storage Methods', in Hydrogen Materials Science and Chemistry of Carbon Nanomaterials, Dordrecht, 2005, pp. 75–104. doi: 10.1007/1-4020-2669-2_7.

[89] 'Hydrogen Solutions', siemens-energy.com Global Website. https://www.siemens-energy.com/global/en/offerings/renewable-energy/hydrogen-solutions.html (Accessed Aug. 12, 2021).

[90] 'Hydrogen Production Technologies, The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs, The National Academies Press'. https://www.nap.edu/read/10922/chapter/10#95 (Accessed Aug. 04, 2021).

[91] 'Could Hydrogen Help Save Nuclear?', Energy.gov. https://www.energy.gov/ne/articles/could-hydrogen-help-save-nuclear (Accessed Aug. 05, 2021).

[92] **S. Timmerberg, M. Kaltschmitt,** and **M. Finkbeiner**, 'Hydrogen and hydrogen-derived fuels through methane decomposition of natural gas – GHG emissions and costs', Energy Convers. Manag. X, vol. 7, p. 100043, Sep. 2020, doi: 10.1016/j.ecmx.2020.100043.

[93] **M. El-Shafie, S. Kambara,** and **Y. Hayakawa**, 'Hydrogen Production Technologies Overview', J. Power Energy Eng., vol. 7, no. 1, Art. no. 1, Jan. 2019, doi: 10.4236/jpee.2019.71007.

[94] 'Hydrogen production from renewables - Renewable Energy Focus'. http://www.renewableenergyfocus.com/view/3157/hydrogen-production-from-renewables/ (Accessed Aug. 05, 2021).

[95] 'Hydrogen energy storage in ammonia – Just Have a Think'. https://www.justhaveathink.com/hydrogen-energy-storage-in-ammonia/ (Accessed Aug. 06, 2021).

[96] **D. R. MacFarlane et al.**, 'A Roadmap to the Ammonia Economy', Joule, vol. 4, no. 6, pp. 1186–1205, Jun. 2020, doi: 10.1016/j.joule.2020.04.004.

[97] IChemE, 'H2 and NH3 – the Perfect Marriage in a Carbon-free Society'. https://www.thechemicalengineer.com/features/h2-and-nh3-the-perfect-marriage-in-a-carbon-free-society/ (Accessed Aug. 06, 2021).

[98] **P. Breeze**, 'The Environmental Impact of Energy Storage Technologies', in Power System Energy Storage Technologies, Elsevier, 2018, pp. 79–84. doi: 10.1016/B978-0-12-812902-9.00009-2.

[99] 'Hydrogen - Fuels & Technologies', IEA. https://www.iea.org/fuels-and-technologies/hydrogen (Accessed Aug. 04, 2021).

[100] **R. Derwent**, **P. Simmonds**, **S. O'Doherty**, **A. Manning**, **W. Collins**, and **D. Stevenson**, 'Global environmental impacts of the hydrogen economy', Int. J. Nucl. Hydrog. Prod. Appl., vol. 1, no. 1, p. 57, 2006, doi: 10.1504/IJNHPA.2006.009869.

[101] **V. Niculescu, M. Anghel**, and **I. Stefanescu**, 'Environment impact of hydrogen - a renewable source of energy', in 2010 2nd International Conference on Chemical, Biological and Environmental Engineering, Nov. 2010, pp. 15–18. doi: 10.1109/ICBEE.2010.5649058.

[102] 'Online calculator: The Newton Polynomial Interpolation'. https://planetcalc.com/9023/ (Accessed Aug. 12, 2021).

[103] 'Fuels - Higher and Lower Calorific Values'. https://www.engineeringtoolbox.com/fuels-higher-calorific-values-d_169.html (Accessed Aug. 14, 2021).

[104] 'How is hydrogen stored ?', Air Liquide Energies, Jun. 16, 2017. https://energies.airliquide.com/resources-planet-hydrogen/how-hydrogen-stored (Accessed Aug. 11, 2021).

[105] 'The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs' at NAP.edu. doi: 10.17226/10922.

[106] '**System Advisor Model (SAM)**'. https://sam.nrel.gov/ (Accessed Aug. 14, 2021).

[107] **N. R. Canada, 'retscreen'**, Mar. 10, 2010. https://www.nrcan.gc.ca/maps-tools-and-publications/tools/modelling-tools/retscreen/7465 (Accessed Aug. 14, 2021).

[108] **'energyPRO**, EMD International'. https://www.emd.dk/energypro/ (Accessed Aug. 14, 2021).

[109] **'gov.scot, 2020'. 'Scottish Energy Statistics Hub'**. https://scotland.shinyapps.io/Energy/ (Accessed Jun. 13, 2021).

[110] 'Energy Statistics for Scotland Q1 2020 Figures'. (June 2020) Accessed : Aug. 13, 2021. [Online]. Available: https://www.gov.scot/

[111] **G. Goodman** and **V. Martin**, "Special feature -Wind powered electricity in the UK Wind powered electricity in the UK," 2019. [Online]. Available: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/875384/Wind_powered_electricity_in_the_UK.pdf.

[112] **A. Frangoul**, 'Scotland just produced enough wind energy to power all its homes twice over', CNBC, Jul. 15, 2019. https://www.cnbc.com/2019/07/15/scotland-has-

produced-enough-wind-energy-to-power-its-homes-twice-over.html (Accessed Aug. 13, 2021).

[113] 'Energy Trends: UK electricity', GOV.UK. https://www.gov.uk/government/statistics/electricity-section-5-energy-trends (Accessed Aug. 13, 2021).

[114] 'Climate change: Reducing greenhouse gas emissions - gov.scot'. https://www.gov.scot/policies/climate-change/reducing-emissions/ (Accessed Aug. 14, 2021).

[115] **SCCS and FoE, WWF, WDM, RSPB**, "The Power of Scotland Renewed," 2009. Accessed : Aug. 17, 2021. [Online]. Available: http://assets.wwf.org.uk/downloads/powerofscotland_renewed.pdf.

[116] **I. Staffell et al.,** 'The role of hydrogen and fuel cells in the global energy system', Energy Environ. Sci., vol. 12, no. 2, pp. 463–491, Feb. 2019, doi: 10.1039/C8EE01157E.

[117] 'What's more efficient? Hydrogen or battery powered?' https://www.volkswagenag.com/en/news/stories/2019/08/hydrogen-or-battery--that-is-the-question.html (Accessed Aug. 14, 2021).

[118] **U. Bossel**, 'Does a Hydrogen Economy Make Sense?', Proc. IEEE, vol. 94, no. 10, pp. 1826–1837, Oct. 2006, doi: 10.1109/JPROC.2006.883715.

[119] 'First Practical Zero Emission Aviation Powertrain | USA & UK', ZeroAvia. https://www.zeroavia.com (Accessed Aug. 14, 2021).

[120] Scottish Government, "Scottish Energy Strategy: The future of energy in Scotland," 2017. [Online]. https://www.gov.scot/publications/scottish-energy-strategy-future-energy-scotland-9781788515276/ (Accessed Aug. 14, 2021).

[121] 'Scottish hydrogen: assessment report'. http://www.gov.scot/publications/scottish-hydrogen-assessment-report/pages/7/ (Accessed Aug. 15, 2021).

[122] P. Alexander, 'Shaping Our Energy Future: Energy Demand', Energy Demand, p. 4. [Online]. Available: https://www.climatexchange.org.uk/media/1740/shaping_our-energyfuture-energydemand.pdf (Accessed Aug. 15, 2021).

7.0 Appendix

7.1 Calculations used for hydrogen conversion

Useful conversion units:

Density of hydrogen at 700 bars	= 42kg/m3
LHV of hydrogen	= 120.10 MJ/kg
1 kilowatt hour(kWh)	= 3.6 Megajoules (MJ)
1 gigawatt hour (GWh)	= 3.6×10^{6} Megajoules (MJ)
1 Terawatt hour (TWh)	= 3.60×10^{9} Megajoules (MJ)
1MJ	= $2.78*10^{-7}$ Gigawatt-hour
Overall Efficiency of Electrolyser	= 75.50%
Energy density of Unleaded petrol	= 46 MJ/kg
Energy density of Natural gas	= 55 MJ/kg
Energy density of hydrogen	= 120.1 MJ/kg
1 kg Hydrogen	= 33.6 kWh
1 kg unleaded petrol	= 12.06 kWh
1 kg natural gas	= 13.1 kWh
1L petrol	= 0.711 kgs
1kg petrol	= 1.41 litres

Amount of hydrogen generated is given by equation 17:

$$\text{Amount of } H_2 = \frac{\text{Energy in kWh} * \text{conversion factor(kWh to MJ)}}{LHV\ of\ H_2\ (\frac{MJ}{kg})}$$

- **Current scenario (2019):**

  Total average electricity generated from wind energy (TWh) = 22.37 TWh

  Total average electricity consumption (TWh) = 22.62 TWh

  Surplus energy = 0.74 TWh

  Energy shortage = -1.00 TWh

  Therefore, amount of hydrogen generated from excess electricity is given by:

  Energy = 0.74 × 75.5% = 0.56 TWh

  Amount of H_2= $\frac{\text{Energy in TWh}*\text{conversion factor(TWh to MJ)}}{LHV\ of\ H_2\ \left(\frac{MJ}{kg}\right)}$

  $=\frac{0.56\times3.6\times10^9}{120.10}$ = 16,747,044.13 kg /year =**16,747 Tonnes/year**

  Volume of H_2=$\frac{Mass\ of\ hydrogen}{Density\ of\ H_2\ at\ 700bar} = \frac{16{,}747{,}044.13}{42} = 398{,}739.15\ m^3/year$

- **Estimation of 2045 scenario:**

  Estimated total average electricity generated from wind energy (TWh) = 49.44 TWh

  Total average electricity consumption (TWh) = 43.89 TWh

  Surplus energy = 5.55 TWh

  Therefore, amount of hydrogen generated from excess electricity is given by:

  Energy = 5.55 × 75.5% = 4.19 TWh

  Amount of H_2= $\frac{\text{Energy in TWh}*\text{conversion factor(TWh to MJ)}}{LHV\ of\ H_2\ \left(\frac{MJ}{kg}\right)}$

  $=\frac{4.19\times3.6\times10^9}{120.10}$ = 125,602,830.97 kg /year = **125,602.83 Tonnes/year**

  Volume of H_2=$\frac{Mass\ of\ hydrogen}{Density\ of\ H_2\ at\ 700bar} = \frac{125{,}602{,}830.97}{42} = 2{,}990{,}543.59\ m^3/\text{year}$