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Green Hydrogen Market and Technology Insight: Utilizing Existing Data to Develop Strategic Approach for LV Product Manufacturers

ABB- Smart Power

School of Technology and Innovations
Master's thesis in Smart Energy Programme

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ABSTRACT :

Green hydrogen has appeared as a promising alternative to fossil fuels in the decarbonization process because of the pursuit of sustainable energy solutions. This master's thesis focuses on its application in carbon-neutral power generation using fuel cells. Where green hydrogen is positioned as an answer to the challenge of storing abundant renewable energy for extended periods. The primary objective is to investigate the green hydrogen market, focusing on electrolyser and fuel cell technologies. Further, investigate the factors influencing the efficiency of these components and explore academic case studies and real-world scenarios. The study aims to develop a strategic approach to understand market dynamics and technology requirements.

This thesis was conducted for ABB Oy, Smart Power's Solar, ESS, and H2 development application team. Comprehensive understanding arose with the exponential growth of the green hydrogen market intertwined with the advancement of renewable energy. This study extensively explores electrolyser and fuel cell technology and finds key challenges impacting the overall performance of the solution. Renewable energy cost is known as the significant factor driving the cost of the solution, study emphasizes the vital role of the efficiency of the system in controlling the cost. Furthermore, a market study is conducted in this work to identify the growth trends of the green hydrogen sector. The market study provides a brief navigator for LV product manufacture in this evolving landscape.

The technological maturity is explored of electrolyser and fuel cell technologies efficiency in P2G-G2P solution. An extensive review of academic case studies and real-world scenarios scrutinizes the impact of efficiency on P2G-G2P. This found the critical gap between academic studies and industrial implementations. Therefore, a strategic approach was developed based on limitations in knowledge and insights from stakeholders. As the tool to collect valuable information, the questionnaire is presented with a specific focus on technology, efficiency, market status, and LV product specifications. This tool will serve to support product manufacturers to adapt to technical and market changes.

To conclude, this master's thesis contributes to the understanding of green hydrogen energy technology and guides LV product manufacturers in transitioning to sustainable future.

KEYWORDS: Green Hydrogen, Electrolyser, Fuel Cell, Power to Gas, Gas to Power

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Abbreviations

PEM	Polymer Exchange Membrane
AEL	Alkaline Electrolyser
SO	Solid Oxide
AEM	Anion Exchange Membrane
FC	Fuel Cell
IRENA	International Renewable Energy Agency
IEA	International Energy Agency
AEME	Anion Exchange Membrane Electrolyser
G2P	Gas to Power
P2G	Power to Gas
PEMFC	Proton Exchange Membrane Fuel Cell
AFC	Alkaline Fuel Cell
SOFC	Solid Oxide Fuel Cell
PAFC	Phosphoric Acid Fuel Cell
MCFC	Molten Carbonate Fuel Cell
NASA	National Aeronautic and Space Administration
IEC	International Electrotechnical Commission
UL	Underwrites Laboratories
LV	Low Voltage
USD	United States Dollar
NEZ	Net Zero Emission
HOR	Hydrogen Oxidation Reaction
ORR	Oxygen Reduction Reaction

1 Introduction

1.1 Background and motivation

Booming economies are driving population growth and modernizing living standards, putting pressure on existing infrastructure and the global economy. The demand for electricity, thermal energy, and fuels to meet this demand is increasing day by day. Owing to global warming, the depletion of fossil fuels, and various energy crises, there is a worldwide movement toward carbon-free, efficient, and sustainable fuels to obtain cleaner energy resources. Therefore, many countries, regions, and world organizations have begun to formulate rules, policies, and standards to solve this problem and aim to achieve carbon neutrality by 2050.

The development of hydrogen as a fuel began in 1970, but the emergence of hydrogen as an alternative to fossil fuels has only begun in the last two decades (IEA, 2019). Of the various methods of producing hydrogen, electrolysis which involves splitting water molecules using electrical current to extract hydrogen. Even though artificial hydrogen production done first time back in 16^{th} century and in 19^{th} century the first electrolysis and fuel cell technology-initiated electrolysis has recently gained prominence with the introduction of numerous renewable energy generation plants around the world. The surplus energy generated from these renewable energy plants provides an opportunity to promote the production of green hydrogen, the cleanest form of hydrogen. Since then, several renewable energy plants have been built with the aim of producing hydrogen, as hydrogen offers numerous advantages as an energy carrier, storage solution and contributes to the achievement of carbon neutrality targets (Baraniuk, 2021).

In this case, many countries have considered initial investments in green hydrogen production; more than 25 countries have published their hydrogen roadmaps in the last 1.5 years' target of 12% global energy use in 2050 to be fulfilled by hydrogen (Wood, 2022). This improvement in energy production had an impact on the energy market and energy infrastructure. From building generation facilities, transportation methods, and pipelines to expanding infrastructure, rigorous improvements are required to meet the world's net-zero targets. Green hydrogen exhibits a multifaceted approach to providing energy requirements in different sectors including, industrial, transportation, backup power, and power generation (Rabiee et al., 2021). This capability to commit to the energy requirement in various sectors is one key element that green hydrogen underlined as the major solution to contribute to sustainable transition.

Specifically, the use of green hydrogen as backup power and power generation sources incorporating fuel cell technology emerges as a promising solution for storing excess renewable energy and balancing the grid. Fuel cell's fast response capability, efficiency, and environment-friendly performance make them ideal to serve for sensitive loads as well as typical loads (Cheng et al., 2022).

However widespread this solution is still under development with support from the governments and policy makers around the world. At this moment, green hydrogen highlights its potential to contribute to the world's sustainable development through electrolyser and fuel cell systems. Green hydrogen with a small carbon footprint is yet to be developed to become competitive compared to other main energy production methods.

1.2 Research Problem and Objectives

The research question can be viewed as simply understanding the green hydrogen market, electrolyser technology, and fuel cell technology and reviewing electricity-to-gas-to-electricity solutions based on existing knowledge. This master’s thesis is written to serve the ABB Oy, Smart Power unit. Specifically, sustainable energy solution unit, which is mainly responsible for low voltage products such as switch-disconnectors, switch fuses, change-over switches, and automatic transfer switches (“Smart Power,” n.d). Aims to understand the market and technology and develop an appropriate strategic approach to understand the green hydrogen industry requirements for low voltage product manufacturing.

As the green hydrogen industry very rigorously with various technologies and due to the underdevelopment fact. The questions expand and open into subsections of different sectors as the market is understood. Since the green hydrogen accommodate solutions for wide range of application with use of its different characteristics, here in this study the concentration narrows down to the production of green hydrogen to use in fuel cells to generate electricity which falls under the Power to Gas (P2G) and Gas to Power (G2P) solution. P2G solution utilizing electrolysis process is identified as one of the key solutions to address variation and abundant of renewable energy sources with highly environmentally friendly manner (Brown et al., 2018). While fuel cells perform the conversion of chemical energy to electrical energy with offering low emission and high efficiency (Elmer et al., 2015). Serving to the green hydrogen sector it is important to understand the specific requirements from low voltage products to plan improvements and adjust to the market needs.

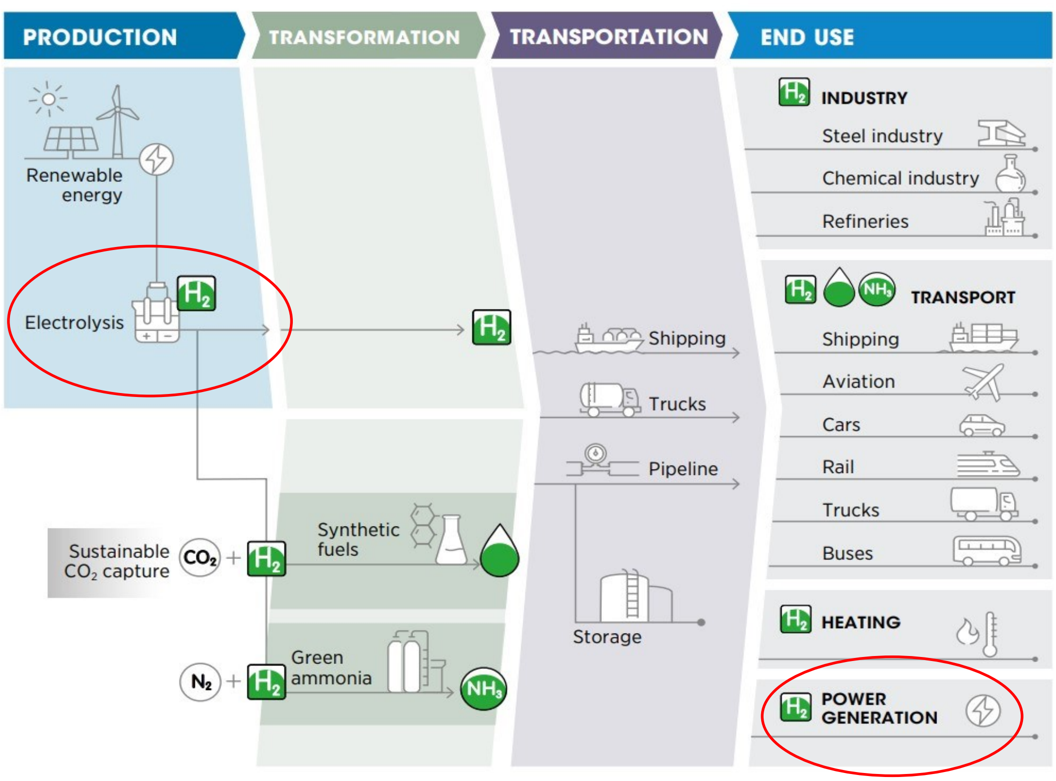


Figure 1 Technology leadership opportunities in green hydrogen value chains. Source: IRENA (2020b).

Note: CO2 = carbon dioxide; N2 = dinitrogen, ⬭ =Focus area

Weekes et al. (2018) emphasise the importance of understanding the operation and challenges associated with parameters and other factors in the electrolysis process in P2G solution and in the other hand Sasaki et al. (2002) underlines precise control of fuel cell to optimize the performance in G2P. Therefore, the requirement of fundamental understanding, operation parameters, and market behaviour in P2G with electrolysis and G2P with fuel cells to perform as to contribute to the development and implementation of P2G and G2P systems.

Therefore, in this study as shown in figure 1, focus on following sections,

- Green hydrogen production and electrolyser performance
- Use of green hydrogen and generate electricity with fuel cells and fuel cells technology.

Despite the growing interest on green hydrogen as a replacement to polluting fossil fuels the technology and market understanding as a supporting product manufacture is crucial. While studies have focused specifically on the need and challenges in electrolyser and fuel cell technical developments research have largely been empirical or theoretical modelling in nature, without less attention to analysis of existing data. Thus, the research questions that this thesis work commit to answer can be elaborate as follows,

1. What is green hydrogen? Where green hydrogen stands now and what is its role in energy transition?
2. What is the green hydrogen market behaviour, it’s evolution and the future?
3. What is the status of electrolyser and fuel cell technologies?
4. How being electrolyser and fuel cell technology utilized in P2G and G2P solutions?
5. How to approach the market to get better understanding?

1.3 Method, Scope and Execution

As the hydrogen industry is widely ramified, it is difficult to understand the market for green hydrogen and smoothly determine the demand from low-voltage manufacturers. Therefore, the research objective of this thesis is to understand the basics of green hydrogen, its performance in P2G and G2P solutions and related electrolyser and fuel cell technologies to support the newly integrated hydrogen sector in sustainable energy agile units. Hence, the main methods to answer to research questions can be identified as the literature review, market study, academic case study and existing application review as present in Figure 2.

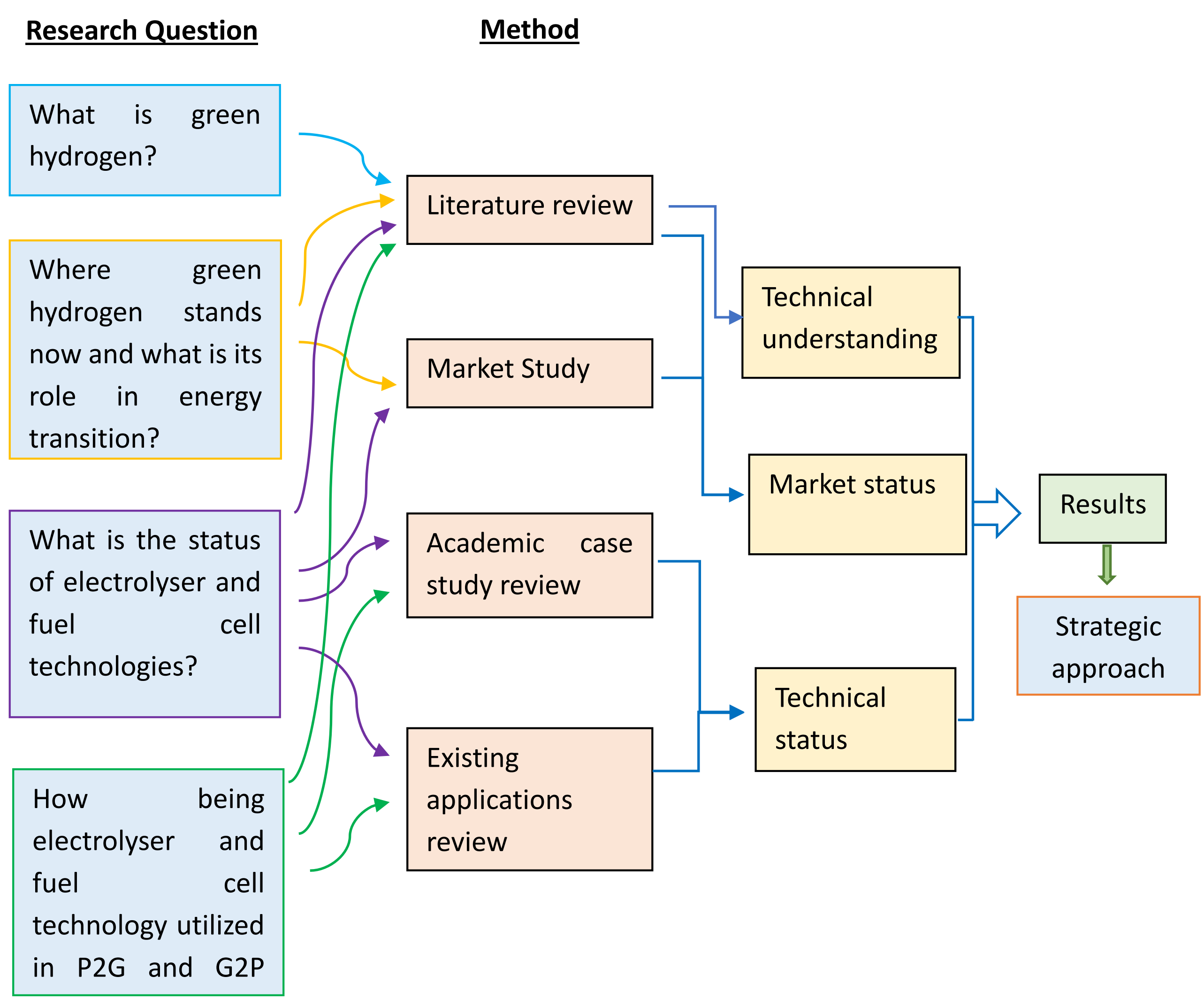


Figure 2: Method, Scope and Execution

To access existing scientific literature through university libraries, IEEE explored digital libraries, Wiley Online Library, Journal of Engineering Science and Technology (Elsevier), and Science Direct were used as initial resources to build the literature review. Additionally, documents and surveys done by intergovernmental organization, governmental organizations Such as International Energy Agency (IEA), International Renewable Energy Agency (IRENA), and National Renewable Energy Laboratory (NREL) and global research consultancy firm analysis reports and date, which supports the world energy transition were used to understanding technology and market, and support literature review. Also, case studies done in P2G and combined P2G and G2P involved to review the academic status of the solution. Finally, few real-world scenarios have been incorporated into the reviewed studies to illustrate the practical use of green hydrogen in P2G-G2P solutions.

When selecting articles and resources, I decided to refer to the most recent publications, as green hydrogen started to gain significant improvements and attention in the last two decades (IEA, 2019). Therefore, preference was given to reports and resource publications completed after 2015 in this work. Since the scope of the thesis work covers the broad range, it does not intend to delve into intricate details of all specified technologies. However, it is intended that the focus in understanding the green hydrogen market and technology will be on P2G-G2P applications.

1.4 Structure of the thesis

The thesis is mainly consisting of five chapters. In chapter 1 introduced to the thesis question and methodology of execution based on the interest and background of the work. However, methods and goals are constantly adjusted and improved as the work progresses. Chapter 2 combines several aspects of theoretical knowledge. First briefly introduce to the hydrogen, different types of hydrogen, different applications, regulations and policies, safety concerns including various applications of hydrogen. Then, the focus then narrows down to the green hydrogen manufacturing process, and the specific regulations and restrictions we see in discussions of green hydrogen development. Finally, the theoretical background covers P2G and G2P application technologies of green hydrogen as well as electrolyser and fuel cell technologies.

Chapter 3 jumps to market research to understand the drivers of the green hydrogen market, such as rising demand for renewable energy and government and policy support for development. In this chapter, readers will learn about the true growth of the green hydrogen industry and the benefits that green hydrogen brings. Fourth, develop strategic approaches for low-voltage product manufacturers to implement green hydrogen in P2G-G2P by reviewing academic case studies and existing operational plants. First, start by identifying the factors that affect the efficiency of electrolyser systems and fuel cell systems. Then, deep dive into these technical details on selected case studies and existing plants to see how well these factors reflect in the academic level case studies and real-world applications to understand the status of maturity of the green hydrogen solutions. Finally, in the last chapter, based on the findings, a strategic approach plan is developed to collect useful information to contribute to the future of green hydrogen as the low-voltage product manufacturer.

2 Theoretical Framework

2.1 Hydrogen

2.1.1 Overview of hydrogen

Hydrogen is a colorless, odorless gas at room temperature, the first element in the periodic table. As an element, it is a diatomic gas with a molecular weight which is close to 2.016g making it the least dense of all gasses ("Hydrogen," n.d). This low-density property of hydrogen made it a natural choice for one of its practical uses for filling airships. However, this idea ended when the Hindenburg airship caught fire on the 6th of May 1937 (DiLisi, 2017).

Hydrogen is easily the most abundant element in the universe; it is found in the sun, and most other stars and giant planets are composed mostly of hydrogen. On Earth, hydrogen is found in water, fossil fuels and living things but very little as the element on its own (National Academies of Sciences, 2023). In the chemical industry, Hydrogen is used to make ammonia for agricultural fertilizer, which is Haber process. Also, produce cyclohexane methanol, which is needed to make plastic and pharmaceuticals. Etc. (Abdin et al., 2020).

H in the pH scale denotes hydrogen, representing the concentration of Hydrogen ions in water. Metals above hydrogen in the reactivity series normally react with acids to form hydrogen. Also, most reactive metals will even react with water itself and release hydrogen. Basic hydrogen identification test is to exposing hydrogen gas to a flame which ignites with a squeaky pop and formed water condensate. Although hydrogen is an essential element for life it does not play a particularly active role, it remains bonded with carbon and oxygen atoms (Sidorenko et al., 2022).

In the energy side, when fossil fuel form more reactive elements removed during the decay process while leaving hydrocarbon skeletons behind as crude oil and natural gas. When comparing coal, oil and natural gas hydrogen as fuels when they combine with oxygen, coal and crude oil produce the most carbon dioxide while natural gas emits less carbon dioxide. Hydrogen which comes water when which is the burn is the 100% clean energy. However, production of hydrogen should also follow renewable processes. Hydrogen has tree isotopes as shown in figure 3. Normal hydrogen with one proton in the nucleus, the very rare deuterium or heavy hydrogen with one proton and one neutron which is with twice the atomic weight of normal hydrogen and the artificially made radioactive tritium with three neutrons. These isotopes being tested by scientists to copy the fusion reaction in starts to produce cleaner nuclear energy to overcome current nuclear power station use of large atoms to generate energy with fusion reaction cause to produce lots of radioactive wastes (Hosseini, 2022), (Sidorenko et al., 2022).

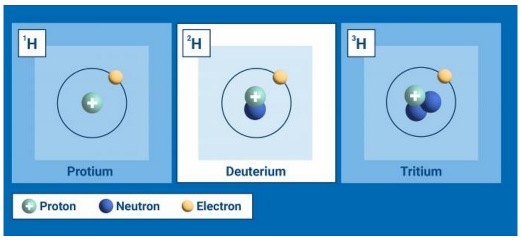


Figure 3-Hydrogen Isotopes

Source- "What is deuterium?" *2023*

Hydrogen's energy carrier capacity has identified as the possibility to serve clean and sustainable energy applications with the high energy density which is about 120MJ/Kg. The rise of hydrogen as an energy carrier gains the attention recently with this characteristic and capability to contribute to various applications (Akhtar et al., 2021). However, the production of hydrogen as energy carrier and chemical use in other industries always been in discussion since its impact on economic and environmental. Therefore, recent improvements in technology and infrastructure in energy industries cause to identify the possibility of hydrogen production in sustainable manner and promising to emerge of hydrogen applications as an energy carrier.

2.1.2 Different types of Hydrogen

Hydrogen itself, when we use it as a fuel emits only water while there is no direct CO2 emission at the point of use. Hence, the carbon intensity of hydrogen depends on the way it is produced. The existence of pure hydrogen is rare on earth and needs to extract hydrogen from elements containing hydrogen such as water (H2O) and methane (CH4). Today most hydrogen is extracted from fossil fuels making hydrogen a carbon intensive energy carrier. Infection in addition to fossil fuel being the feedstock for hydrogen production in most cases. In many applications, fossil fuels are also combusted to provide heat to drive the production process. Further increasing the carbon footprint. It is beneficial for LV product manufacturers to have a basic understanding of the several types and methods of hydrogen production, as well as the color code of hydrogen to support sustainable development. Low carbon hydrogen colors are green, blue, and white while gray, brown or black, yellow, turquoise, purple, or pink and red have higher carbon concentration (Arcos & Santos, 2023).

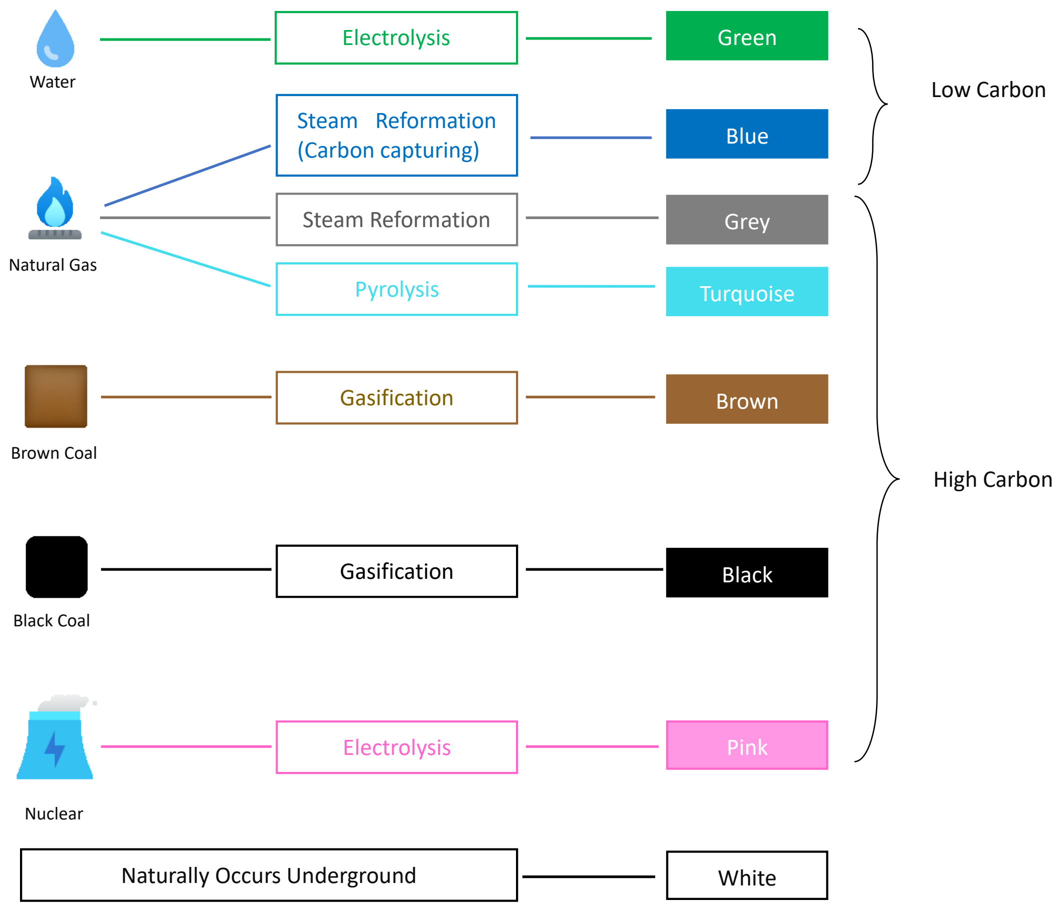


Figure 4: Hydrogen Colour Code

The hydrogen production mechanism can be categorized as figure 4, based on the course of fuel used to hydrogen production and the process to identify the hydrogen color code. As the fueling process using natural gas there are three types of hydrogen can be produced as blue, gray, and turquoise. Gray is the most common type of hydrogen. The process is called steam reforming and natural gas, mainly methane, will react with heated water in the form of steam to produce hydrogen and carbon monoxide. This event is a catalytic chemical reaction that takes place at remarkably high temperature (700-1,100°C) and pressure, Nickel is the most common metal catalyst in the process ("Hydrogen Production: Natural Gas Reforming," n.d). Produced hydrogen purity is around 95% with consisting 5% of carbon dioxide, carbon monoxide, and other impurities.

In the other hand blue hydrogen to overcome the disadvantage of emission of a great deal of carbon dioxide due to the energy intensive process, use of carbon capturing and storing mechanism. In this way, blue hydrogen successfully reduces carbon emissions from the steam reforming process without releasing it into the environment. Intensity of carbon in blue hydrogen can be regulated from 1.5kg to 5kg per kilogram of hydrogen based on the carbon capturing process. However, the process of carbon capturing and storing technology comes at 60-90€ overall cost per captured one ton of carbon dioxide (Stephenson, 2018). Even though blue hydrogen is not 100% environmentally, however with carbon capturing mechanism efficiency of blue hydrogen process can range from 60%-90% and the efficiency is depending on the technology and the energy source (Qadir, 2021). Then, blue hydrogen is identified as low carbon fuel and the purity of the hydrogen depends on the factors like production methods, mechanism of carbon capturing and purity of the natural gas source.

The method of hydrogen production using natural gas is known as methane pyrolysis. The hydrogen produced using this method is named turquoise hydrogen. This process breaks down methane into hydrogen and solid carbon, which poses a challenge for steam methane reforming (SMR), which produces gray and blue hydrogen (Sorcar & Rosen, 2023). In addition, the methane pyrolysis process has shown great appeal due to its environmental friendliness and techno-economic capabilities, emphasizing its economic possibilities and gaining recognition in the hydrogen production industry. However, processes still produce carbon as a solid material known as carbon black, which has various applications and there is a possibility to produce stoichiometric CO_2, which is harmful to the environment and may cause to add extra cost to control the effect (Palmer et al., 2019).

Brown and Black hydrogen produced by carbonous materials are heated into gas which is known as gasification. This process of turning coal into gas emits a large amount of carbon into the environment. The output hydrogen named after based on the fuel type brown coal and black coal. Gasification method is well established in many industries where the requirement of carbon rich materials' conversion to carbon dioxide and hydrogen. Solid coal is converted into gas form by expose to steam and oxygen under high pressure and temperature. Even though brown and black hydrogen leads to heavy environmental impact, due to the low material cost and less production cost, it is highly available (Ajanovic et al., 2022).

Type of Hydrogen	Production process	Advantages	Disadvantages	Cost
Gray	Steam Reformation	Relatively inexpensive. Highly matured technology.	Not environmentally friendly 9-12Kg CO_2/Kg H_2	Low 0.7-1.6 USD/kg
Blue	Steam Reformation with Carbon capturing	Less carbon emission 3-5Kg CO_2/Kg H_2	Compared to gray hydrogen expensive.	Medium 1.2-2.1 USD/kg
Turquoise	Methane pyrolysis	No CO_2 gas emission CO_2 collects as solid carbon black. Captured solid carbon has various applications.	Process requires a significant amount of energy. Storing of solid carbon is challenging.	Medium
Brown/Black	Gasification		Highly environmentally damaging 20-25Kg CO_2/Kg H_2	Medium 1.9-2.5 USD/kg
Pink	Electrolysis	Zero carbon emission. Scalability	Not 100% environmentally	High

			friendly due to radioactive waste Costly mechanism	
Green	Electrolysis	Totally environment friendly	Production method is expensive due to high energy requirement	High 4.5-6.5 USD/Kg
White	Naturally occurs	Nonpolluting	Still not clear how white hydrogen deposits and whether commercially available	-

Table 1:Comparison of different color hydrogen (IEA, 2023)

Water electrolysis process generated hydrogen can be categorized as pink hydrogen and green hydrogen. Electrolysis uses water as input material and splits into hydrogen and oxygen using electricity. Green hydrogen is produced by electrolysis mechanism using renewable energy sources. On the other hand, pink hydrogen is produced through the same electrolysis process using electricity generated from nuclear energy (Ajanovic et al., 2022). Since nuclear energy is nonrenewable even though this process is totally carbon free technically the hydrogen technically cannot be called green hydrogen. Nevertheless, pink hydrogen is known as a one of the solutions to overcome carbon emission issue in hydrogen production which is a very low efficient process, and the market is not well established. However, in the process of improvements to achieve higher efficiency World Nuclear Association introduced 4 different methods of hydrogen production in nuclear plants which are, cold electrolysis (use only electricity), low temperature stem electrolysis (electricity and low heat), high temperature steam electrolysis (electricity and high heat), high temperature thermochemical production (use only heat) (“Hydrogen Production and Uses,” n.d).

Green hydrogen is the most environmentally friendly option and will be further discussed in the next chapter. Hydrogen is a colorless gas and diverse types of hydrogen from hydrogen color code have their own advantages and disadvantages. The colors indicate its environmental impact and its production process. However, this color code is not international standard this may vary between countries as well as over the time (“The hydrogen color spectrum,” n.d).

2.1.3 Regulations and policies and safety concerns for hydrogen

Similarly, to other industries hydrogen economy is also effects and shapes up and landscapes with global, regional, and local regulation and policies respectively to different color of hydrogen. As we observe in the last chapter hydrogen market is growing continuously over the years. Therefore, rules and regulations are trying to mitigate the carbon dioxide emissions by making more favorable decisions towards greener hydrogen solutions while allowing blended solution of different hydrogen colors to accommodate market requirement during this transition period. Because there are several limitations in the implementation process of rules and regulations due to the requirement of major changes in the infrastructure and economy.

A significant amount of CO_2 emission happens due to production of gray, brown and black hydrogen generation due to the high concentration of fossil fuels in the production process. However, Green hydrogen which is produced through electrolysis procedure using renewable electricity has taken global, regional, and local authorities and policy makers’ attention with the intention to reduce emissions (Qiu et al., 2023). Even though hydrogen was well established among a wide range of industries, as an energy carrier the requirement of global, regional, and local policy and regulatory framework arose in past few years. This requirement is driven by environmental and economic considerations.

In early 2019 only few countries like China, France, South Korea, and Japan announced their local hydrogen regulatory framework initially (“National hydrogen strategies,” n.d)). Eventually according to ‘A green hydrogen Era: Hope or Hype?’ over 30 countries and regions have issued their own regulatory and policy guidelines to smoothen the hydrogen economy (Zhu & Wei, 2022). These policies have their own characteristics, scope and scale reflect the mixed hydrogen solutions in this transition era to support the scaling up process of hydrogen market.

While hydrogen is becoming versatile energy carrier with the potential to provide clean energy. Yet, like any other energy carrier, hydrogen has its unique storage and use safety concerns that need to be addressed to make sure safe production, transportation, and utilization. Hydrogen gas is lighter than air which is odorless and non-toxic. Therefore, in case of leak hydrogen gas would not concentrate and build up gas which could lead safety hazards ("Safe use of hydrogen," n.d). Main concern is hydrogen has a wide range of flammability and lower ignition energy requirement compared to gasoline and natural gas and has nearly invisible flame. Therefore, to prevent fire hazards when utilizing hydrogen, it is necessary to equip hydrogen detectors as well as flame detectors.

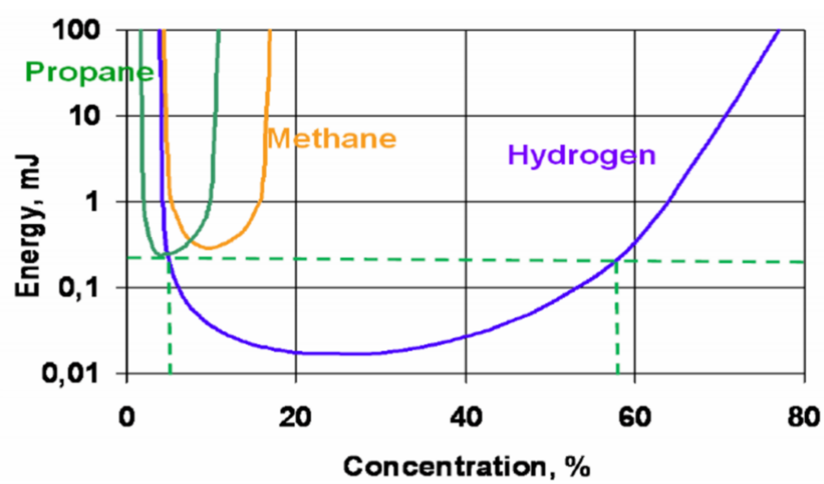


Figure 5: Comparison of Hydrogen wide range of combustible concentration and low ignition energy requirement (Source: HyResponse)

Hydrogen exhibits embrittlement characteristics with some metals therefore selection of material is crucial to avoid these metals becoming brittle and susceptible to cracking. Also, when transporting hydrogen leak could happen due to its low density and high diffusivity. Therefore, selection of material and arrangement of hydrogen system is crucial with concern to safety.

As per the records hydrogen safety has been taken into measures in industry use, storage, and handling since first edition of NFPA 567 (National Fire Protection Association 1963) (Rivkin et al., 2015). Since hydrogen is becoming used as commercial fuel and wide spread of use indicates the importance and grow rigorous standards and regulations to build safer utilization of hydrogen ("Safe use of hydrogen," n.d). Worldwide hydrogen use, storage and transportation regulated by international standards from international institutions as well as regionally and now locally by country its own hydrogen strategy. Despite the hazardousness of hydrogen, properties of hydrogen with proper safety standards make it safer to handle compared to conventional fuels.

2.1.4 Various applications of hydrogen

Hydrogen has a wide range of applications in different sectors such as energy sector, industrial applications, transportation industries, chemical processing, metallurgy, etc. Hydrogen is used in different applications with the use of its distinctive characteristics. Hydrogen's physical properties are colorless, lightweight, tasteless, odorless, and non-toxic. Its ability to store energy by chemically is the useful property to function as energy carrier. Hydrogen is highly reactive even when cold. It is a little bit reactive but when it is warm or in the presence of catalysts hydrogen shows its high reactive properties. Reactivity property of hydrogen combined with other properties open doors to many other applications for hydrogen. Hydrogen contributes to transportation industry as a fuel by use in combustion engines as well as fuel cells, heavy industry uses as a heat source and for chemicals production as a feedstock (Zhang & Sun, 2022).

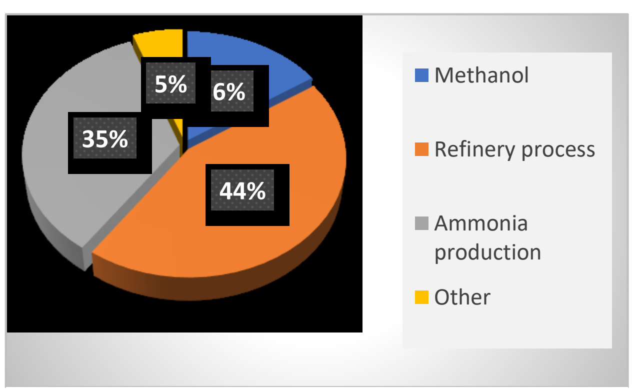


Figure 6: Global Hydrogen Market (Complied based on IEA 2023 data)

Industrial process uses hydrogen in oil refining, metal treatment, chemical production, fertilizer production, glass purification and food processing. The process in petroleum refining is called hydrodesulfurization, using hydrogen to remove sulfur in oil and hydrotreating makes the product more stable (“Use of Hydrogen,”2023). Ammonia is mainly used as a fertilizer and hydrogen is the critical component to produce ammonia. Also, in chemical industries hydrogen being used as chemical feedstock and catalyst of the process. According to Deloitte, currently in Europe over ten million tons of hydrogen use mainly as a feedstock for the ammonia production and refining

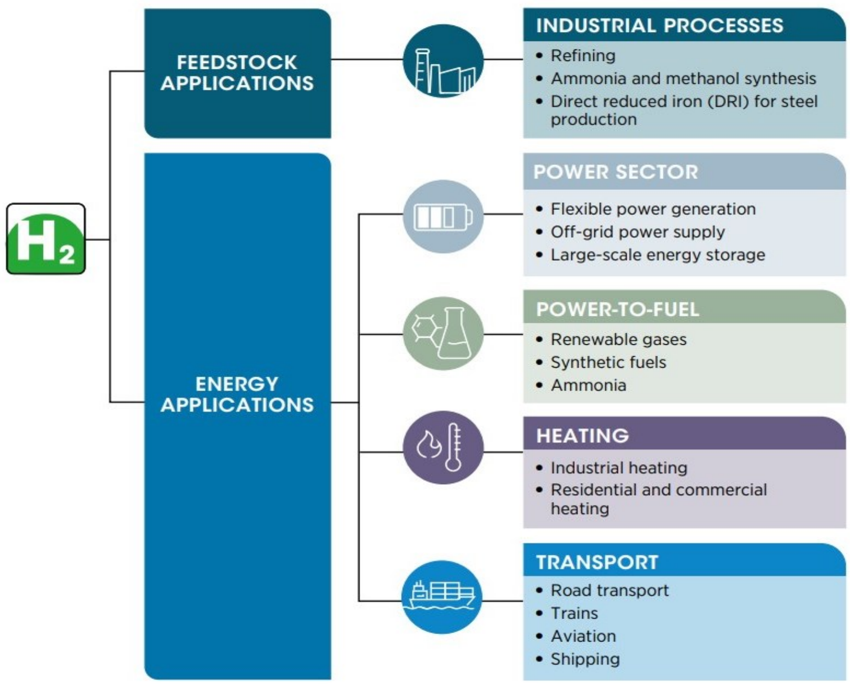


Figure 7: Various applications (source: IEA, 2020)

industry (“Potential of hydrogen for chemical industry,”2022). In food industries hydrogen is used to turn unsaturated fats into saturated fats and oils. Also perform as hydrogenating agent for food and drug production industries (“Uses of hydrogen in industry,”2019).

Hydrogen use in heavy industries such as cement manufacturing, steel industries and other high temperature processing industries as an alternative source. Traditionally fossil fuels mainly large amount of coal burns in these industries to gain the required high temperature. The steel sector is currently the largest industry consumes coal and in annual around 2.6 gigatons which is responsible for 7% of global carbon dioxide emission (IEA, 2020). In this scenario hydrogen has a great opportunity to replace fossil fuel in heavy industry by working as a fuel to generate heat by combustion process. Which is more environmentally friendly and excess heat could be used in other industries or municipal heating requirements.

Hydrogen characteristics of storing and clean energy carriers create the opportunity for hydrogen to play a significant role in transportation sector. Passenger and small vehicles are equipped with fuel cells fed stored hydrogen and oxygen to create electricity and feed this electricity to power an electric motor which is zero greenhouse gas emission process ("Hydrogen's role in Transportation," 2022). However, due to the energy content of hydrogen by volume is low it makes it challenging to store and transport hydrogen as fuel for compact vehicles. In the other hand hydrogen has the highest energy content compared to any other fuel by weight three times more than gasoline. Also, in the shipping industry hydrogen is used in liquid form and still due to its low energy density causes losses in space for cargo. However, long distance trucks are feasible with hydrogen compared to battery powered trucks when compared to the long-distance ranges, shorter refueling time, and better load capacities. Also, in the shipping industry hydrogen is used in liquid form and still due to its low energy density cause to make losses in space for cargo ("Groundbreaking Edmonton-Calgary heavy-duty hydrogen truck pilot ready to roll,"2023). Regardless of advantages of hydrogen in transportation industry such as clean energy, high efficiency, zero emission and capability of long travel there are several factors hindering the implementation process such as high cost, requirement of specific technology advancement and the lack of infrastructure capability. However, all these disadvantages holding back the implementations are dependent on pace of the technological advancement.

Hydrogen's significant characteristics like clean energy carrier and energy storing capability are advantageous for hydrogen to be considered as the solution to replace fossil fuels in the energy industry. The use of renewable energy to generate power and store it as hydrogen is one solution that is attracted globally. Another significant application involves enhancing the performance of gas turbines by incorporating hydrogen. Additionally, the power energy sector uses hydrogen to generate electricity through electrolysis process. However, similar to other industries enablement of hydrogen in energy sector also face lack of infrastructure, limitations in regulatory frameworks with safety concern, higher production cost and proper market to match supply to demand (Balat, 2008). However, these challenges need to be addressed to unlock the full potential of hydrogen technology in the energy sector.

2.2 Green Hydrogen

2.2.1 What is Green Hydrogen

As per the name states, green hydrogen is produced through an environmentally friendly method known as electrolysis. Electrolysers are powered using renewable energy as wind, solar, geothermal, biomass and hydro as the source energy for the procedure (Ram et al., 2022). Many researchers and articles consider green hydrogen is one of the best environmentally friendly and sustainable solution to answer question of how to achieve carbon neutrality targets sets by various global and regional agreements as a potential substitute to fossil fuels. Whatsoever there are many challenges in the implementation process such as high cost and low conversion efficiency with existing technology (Bezrukovs et al., 2022).

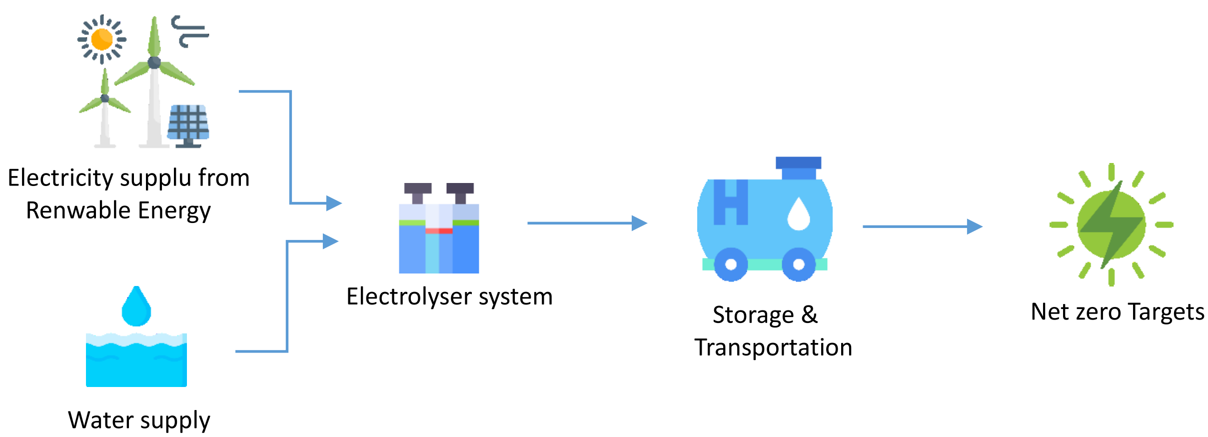


Figure 8: Green hydrogen process

Despite the economic factors hindering green hydrogen, regions with high improvements in technology and abundant renewable energy can be seen rapid improvements (Huang & Liu, 2020).

Transition to green hydrogen needs the capability to produce required renewable energy and better large-scale storing facilities. Since the transformation of renewable energy to green hydrogen and use of hydrogen to reproduce useful energy process undergoes several steps that cause to reduce overall efficiency of the solution (Yi et al., 2021). Challenges in the adoption of green hydrogen include almost all the steps in the process which are production cost, storage limitation, and transportation. Green hydrogen must compete in the market with other colors of hydrogen produced in various other ways. Therefore, to establish a stable market for green hydrogen, it is crucial to implement favorable policies and blend it with natural gases in limited percentages during the transition period. This strategy is important for smoothing the implementation and widespread adoption of green hydrogen (Tholen et al., 2021).

2.2.2 Green hydrogen manufacturing process and its development

Evolution of green hydrogen manufacturing process driven by the intention with achieve sustainability and improving the efficiency in production procedure. In 2017, Imperiyka et al., mentioned that the first-time pure hydrogen production using electrolysis of water process was invented in 1920s. Furthermore, according to Wang et al. (2017) the first-time produced gases using electrolysis process was confirmed as hydrogen and oxygen. As the end product high purity hydrogen is easily achieved with simple water electrolysis process.

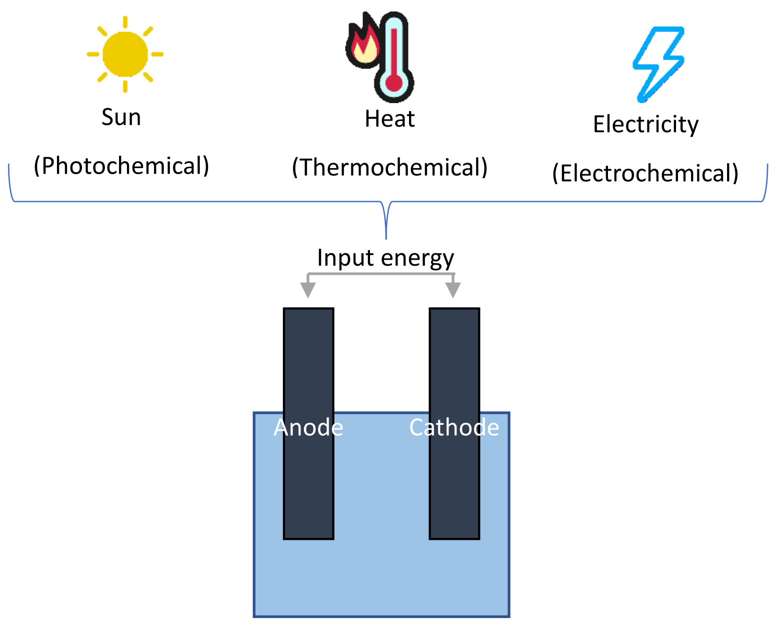


Figure 9:Water splitting technique

The electrolysis process, which is possible to perform in various methods such as, water electrolysis, high-temperature electrolysis or photochemical. Photochemical method equipped with photo anode; cathode immersed in electrolyte with external biasing system which is identified as use of solar energy directly to chemical energy (Hu, 2013). High temperature electrolysis (HTE) is known as large-scale low-cost method of hydrogen production which utilize high temperature range from 500 °C to 1000 °C. Solid oxide electrolyzes are used in the process and this method demonstrates overall higher efficiency while operating in low voltages however high temperature requirement fulfil by nuclear reactors, solar thermal collectors, or geothermal sources (Jin et al., 2012). Furthermore, HTE has the capability to contribute to other applications such as synthesis gas, methane and other by products which allows HTE to play vital role in transition process to carbon neutrality.

Water electrolysis, which is low temperature electrolysis of water, is currently known as the most matured method and for carbon free hydrogen production. Due to advancement in technology and excess generation of renewable energy shape up the market for green hydrogen ramps up the scale of production (Ayers et al., 2019). Most famous water electrolysis methods are Alkaline water electrolysis and polymer electrolyte membrane (PEM) electrolysis. Both are low temperature electrolysis methods, comes with their own pros and cons in the process of splitting

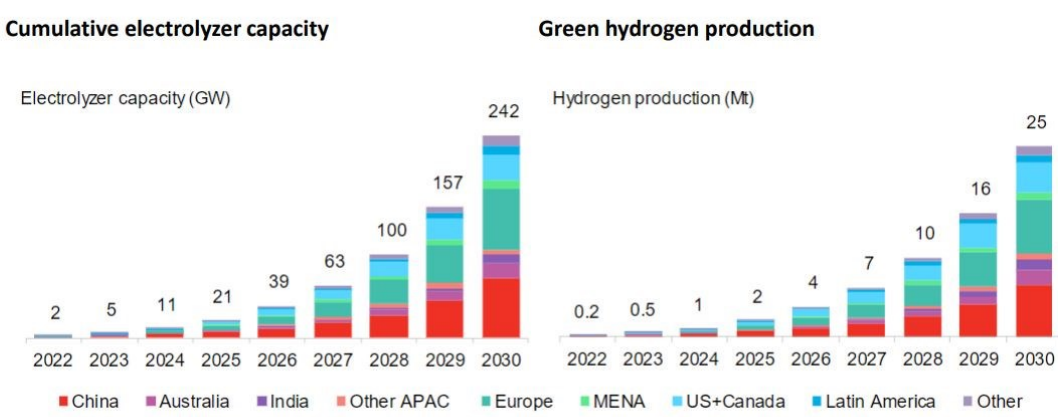


Figure 10: Adoption of electrolyser with predicted hydrogen demand increment (BloombergNEF)

water to produce hydrogen. Green hydrogen production evolved ever since the first-time recorded hydrogen production using electrolysis which has been known for about two centuries.

Over time different solutions come into play with their own characteristics. However, research and development work on some specific selected methods due to their own competitive advantages. Based on IRENA analysis electrolysers evolution is categorized into 5 generations based on the technology of each electrolyser introduced to the hydrogen generation.

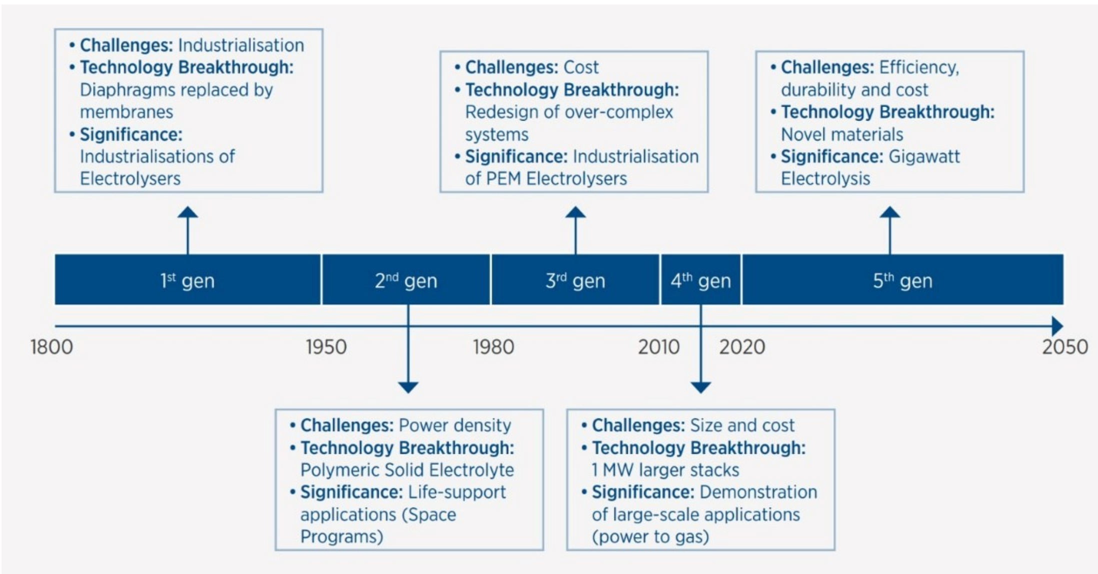


Figure 11: Electrolyser Generations (IRENA, 2020)

1st generation (1800-1950) was mainly targeting production of ammonia using alkaline electrolysis, from 1950-1980 2nd generation was the introduction to the PEM electrolysers with higher efficiency and more simple mechanisms, 3rd generation (1980-2010) identified as the period of making improvement to PEM and scaling up the system, 4th generation (2010-2020) aligned the electrolyser technology to support government policies arise to achieve carbon neutrality while addressing the useful way of utilizing abundant renewable energy. From 2020 onwards 5th generation expected to grow economic scale up with high efficiency, durability and cost-effective solution to become mainstream to uphold the carbon zero targets.

2.2.3 Regulations and policies

Green hydrogen is produced with renewable energy sources and known as alternative to the fossil fuels therefore, the regulations and policies undergo various research and developments to ensure the sustainably shape up the green hydrogen ecosystem landscape (Tholen et al., 2021). The production of green hydrogen heavily relies on the renewable energy source, considering factors such as production cost, scalability, availability, technical advancement, and regulatory framework.

Figure 12: Hydrogen energy policy framework (IRENA, 2020)

At the moment there is no global regulation and policy framework to drive green hydrogen solution. Nevertheless, various international institutions and organizations, including IRENA, the Hydrogen Council, and Mission Innovation, actively contribute to research aimed at formulating international agreements, initiatives, and collaborative endeavors. These efforts to help regional and local governments to develop their own green hydrogen policy framework (Cheng & Lee, 2022).

There are several types of hydrogen in the market and green hydrogen is not in the best price point to complete with other alternatives. The main support is the global interest to neutralization regulation and policy framework focused on blended solution and prioritizing blue hydrogen in the scaling up process (Bauer et al., 2022).

Regulation and policy framework should extend furthermore form broadening green hydrogen market including safety concerns, cost optimization, technical barriers, system adoption feasibility based on requirement and location and efficiency of the process as demonstrate in the figure 12. Therefore, to overcome limitations and open up green hydrogen with its full potential to contribute to a greener future, it is important to have proper regulation and policy structure.

2.2.4 Limitations for green hydrogen

Green hydrogen faces multiple challenges in the process of implementation since green hydrogen is not a commercially matured solution. It has to start from scratch to establish in the energy market. Additionally, green hydrogen needs to address the challenges arising from other industries due to its effect on other markets (Koo & Jung, 2022). Even though the global hydrogen market is growing with an expected annual compound rate of 5.48% from 2019 to 2025 (Elberry et al., 2021), Green hydrogen has the lowest contribution to the overall hydrogen production. As shown in Figure 13, the current contribution of green hydrogen to total hydrogen production is notably low, standing at 4%.

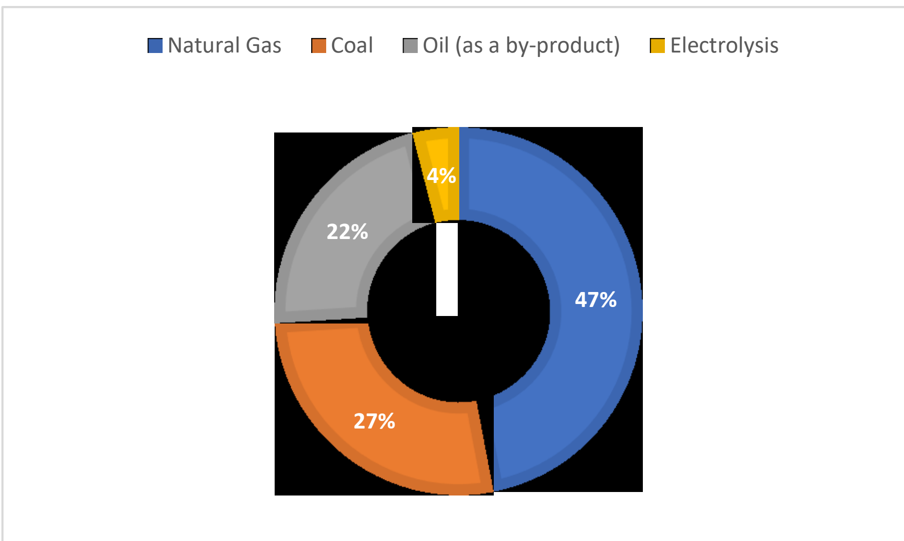


Figure 13: Word hydrogen production share based on the technology

There are several factors that need to be addressed accordingly to succeed in the green hydrogen adoption procedure.

1. High cost and economics: Green hydrogen is considered to be two or three times more expensive than blue hydrogen (IRENA). The price varies based on the location due to

other factors. According to the U.S. Department of Energy 5$/Kg would be the price for green hydrogen (“Hydrogen shot,” 2021). However Norwegian maritime standards analysis report indicate that the price of the green hydrogen will fall to 2$/Kg by 2030 (Parkes, 2023).

2. Infrastructure limitations (Storage and transportation): Existing infrastructure is primarily allocating provision required for conventional hydrogen which is mainly produced using fossil fuels. The infrastructure is relatively modest and aims to facilitate specific industrial requirements. However, the expectations in the wide spread of green hydrogen are to grow and cover several industries as well as commercialize of hydrogen. IEA predicts that the global hydrogen infrastructure investment would be around $20 billion -$70 billion by 2030 (IEA, 2019).
3. Manufacturing and developments in technology: Efficiency is measured in electrolyser as the proportion of electricity converted to useful chemical energy which is hydrogen. Efficiency of the system relies on the type of electrolyser, quality of the water, electricity, and system architecture. Now average efficiency of the electrolyser is identified as 64% (“Efficiency – electrolysis,” 2019). In other hand, the cost varies upon the course of energy, whichever renewable energy quipped in the process also control the green hydrogen price point. Since the development of the technology depends on improvements in the materials, optimizing the system design, improvements in manufacturing process, encourage with favorable policies and regulations would lead to enhance lifetime and performance of electrolysers.
4. Uncertainty in balancing supply and demand: Demand for green hydrogen depends on factors like availability, price, policies, regulations, consumer preference, and competition against other solutions. At the current status of the market, competing with alternative solutions poses a challenge for green hydrogen. Despite the green hydrogen anticipated growth there is no specific level of expansion and time frame for demand. This is uncertainty impact the planning and investment in green hydrogen sector (Ochoa Bique et al., 2021).

5. Safety measures: Chemical characteristics of hydrogen inherent risks like highly flammable and explosive gas, which has potential risk to human beings and the environment. Therefore, green hydrogen also needs strict rules and regulations in production, transportation and storing similar to regular hydrogen use process. Furthermore, well trained workers in the sector as well as public awareness programs and safety measures help to minimize safety hazards (Eljack & Kazi, 2021).
6. Geopolitical factors: There are several geopolitical factors that affect the green hydrogen establishment. Green hydrogen depends on renewable energy source availability and the cost of these sources. This is the major factor that affects green hydrogen development. Specific country trade and investment plans create the way how green hydrogen market shape up the country economy (Blasio et al., 2021). To meet global targets and contribute to the world green hydrogen market, it is essential to tailor strategies based on locally available resources. This involves adopting energy mix solutions, high commitment to technological advancement and investments, implementation of policies and regulations that enhance local opportunities, and prioritize environmental conservation and social well-being. (IRENA, 2022).

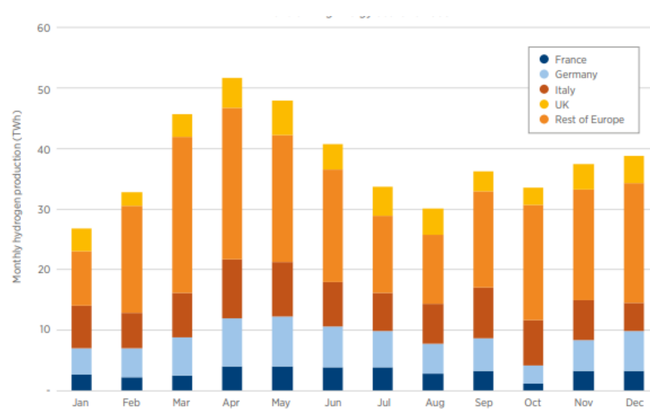


Figure 14: Seasonality of hydrogen production in Europe

2.2.5 Green Hydrogen Cost

To understand the factors affecting the green hydrogen cost it is important. Khan et al. (2021) underline that facts affect the production of hydrogen from alkaline electrolyser system with 28% solar to hydrogen efficiency. Such as solar PV panel cost, electrolyser stack cost, balance of system cost, balance of plant cost, operation and maintenance cost and efficiency of the system. Similarly, the cost of electricity generation using fuel cell technology has the effect from same factors and additionally fuel cell efficiency of fuel cell units' cost.

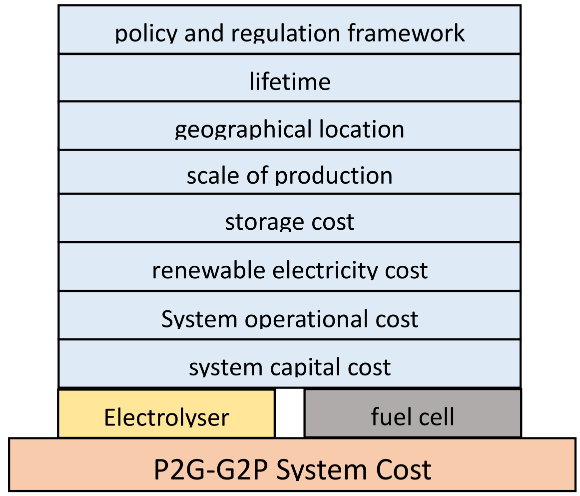


Figure 15: Factors effecting the total system cost

IRENA, green hydrogen cost reduction (2020) report states that the increase the plant size with innovative technology reduces the cost. Such as increasing plant size from 1MW to 20MW could reduce the cost by over one third. The cost of renewable energy is identified as the largest single component affecting the cost of green hydrogen. However, the efficiency and the lifetime of the system plays a crucial role in the cost of green hydrogen production (IRENA, 2020).

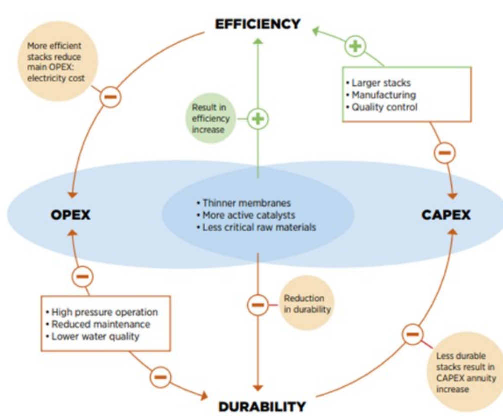


Figure 16: Trade-off between efficiency, durability and cost of electrolyser (IRENA, 2020).

The Hydrogen council announced according to McKinsey, cost of producing green hydrogen due to several factors rose by 30% to 65% in last year (up to June 2023). Therefore, the unsubsidized green hydrogen cost reached 4.5-6.5 USD/Kg. The reason behind the increment of the price was identified in the report. They are increment of labor cost, material cost, construction cost, capital cost and renewable power cost (Collins, 2023). However, the report states that the cost of green hydrogen is expected to decline to 2.5-4.5 USD/kg by 2030.

3.3 Power to gas to power (P2G –G2P)

3.3.1 Introduction

Many nations embrace their capacity to achieve renewable power sources such as wind and solar. However, when there is no sun and wind does not blow, it is not possible to achieve the total benefit of solar and wind power which leads to use of carbon dense fuel sources. Therefore, use of different types of energy storage solutions are being considered (Glenk & Reichelstein, 2022). Due to the higher rate of integration of renewable energy plants leads to considerations towards P2G-G2P concept. However, development of the most dependable, sustainable, and convenient in cost wise and operational perspective takes time and needs huge sum of investments. Conversion of energy to gas has been identified as one solution to overcome the issue of intermittent and variability of renewable sources. Several technologies can be identified in power to gas process such as hydrogen production using water electrolysis, methanation; conversion of carbon dioxide to methane through hydrogenation to produce methane under specific temperature and pressure which varies upon the catalyst $4H_2+CO_2 \rightarrow CH_4+2H_2O$. Furthermore, treatment of the methane synthetic natural gas produced which is similar to natural gases with the intention to produce methane in an environmentally friendly sustainable procedure (Burkhardt & Busch, 2013).

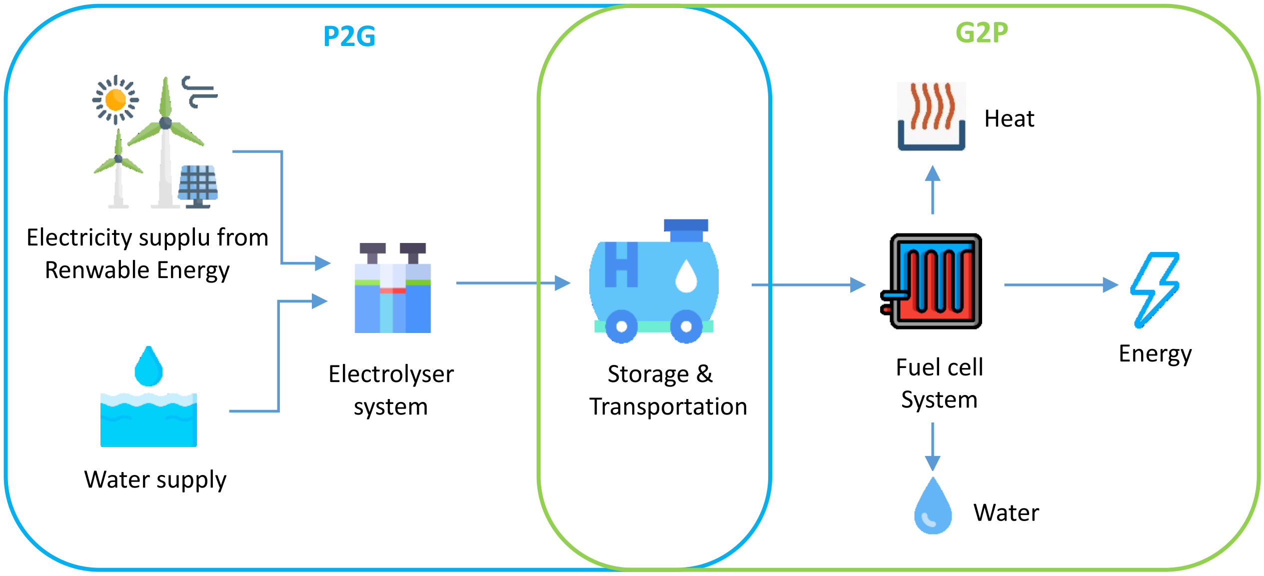


Figure 17: Power to gas & Gas to power system

The pivotal energy sources in the process of storing energy as gas, for later conversion back into power when needed, are abundant solar and wind energy. Method is regarded as environmentally friendly because the initial power produce relies on renewable resources, and the intermediate steps for producing green hydrogen do not involve carbon emission. Production of hydrogen procedure we discussed in chapter 3.2 in deep. Gas to power, which has several applications, is the next step of bringing back the useful energy from stored clean, flexible, and dependable green hydrogen such as power heavy industries, utilities, and power transportation. Here we focused on the use of green hydrogen to produce electricity (Raab et al., 2022).

There are several methods of producing electricity using green hydrogen; electrochemical conversion of green hydrogen to electricity done by using fuel cells, combustion of hydrogen similar to natural gas to produce electricity in combustion engines, burning green hydrogen in gas turbines is an efficient method to produce electricity, and simultaneous generation of heat and electricity by green hydrogen utilize in combined heat and power (CHP) (Armaroli & Balzani, 2007). Here we focus on the use of fuel cell technology in electricity generation.

3.3.2 Electrolyser technology and use in P2G

As we discussed earlier electrolysis is the process that splits the water into hydrogen and oxygen using electricity which is an electrochemical process. The process is powered using diverse types of electrolysers, from various other methods as per our focus on green hydrogen production is it evident that alkaline and PEM electrolysers are well-established mechanism which is known as suitable for large scale production. Alkaline exhibits lower cost compared to PEM initial cost and operation cost and longer lifespan ("Electrolysis for green hydrogen production," n.d). In other hand PEM electrolysis are famous for their unique high-performance capabilities including high current density, high gas purity and capability to operate in high pressure (Abdul Hannan et al., 2022).

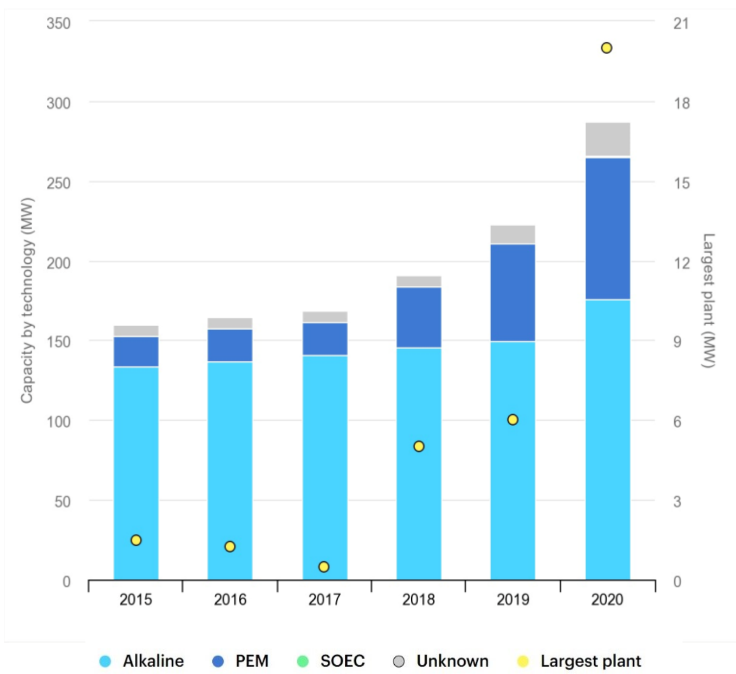


Figure 18: Maturity comparison of different types of electrolysers (IEA, 2021)

The most matured, highly commercialized, and widely implemented electrolyser types among five main categories are the alkaline and proton exchange membrane electrolysers. However, alkaline technology is old and has been in the industry for a very longer time compared to PEM electrolysers even though PEM electrolysers show significant increase in the adoption rate (IEA, 2021).

In P2G technology that converts excess renewable energy, commit in grid balancing by mitigate the load curtailment. Operating conditions are vital factor affecting the electrolyser performance and efficiency, typically for low temperature electrolyser operating temperatures is around 60°C -80°C, voltage of 1.8-2.2V and 200-500 mA/cm^3 (Miller et al., 2020). Furthermore, electrolysers produce hydrogen with high purity levels (above 90%) and high efficiency range from 50% to 80% in the process (Smith et al., 2020). However, the process is high cost and low level of overall efficiency compared to the other matured technologies existing.

Generally, electrolysers include anode, cathode, electrolyte, bipolar plates, gas diffusion later and compression plate (Gallandat et al., 2017). Anode and cathodes are the electrodes where oxidation reaction and reduction reactions take, respectively. Electrolyte is the medium which facilitates the movement of positively charged hydrogen ions from anode to cathode. Distribution of supply gases equally is the responsibility of the gas diffusion layer. Bipolar plates provide separation to the individual cells and maintain electrical contact between adjacent cells. Both Alkaline and PEM electrolysers have these components included in their structure. However, the materials used in the structure varies based on the type of the electrolyser and the improvements incorporated (Tuinema et al., 2020).

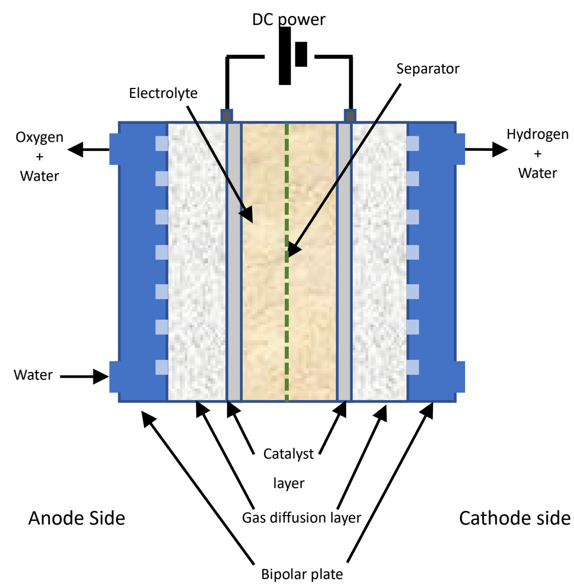


Figure 19: Components of electrolyser (Compiled by author)

$$2\ H_2O_{(l)} \longrightarrow 2\ H_2O_{(g)} + O_{2(g)}$$

Equation 1: Electrolyser general overall

In this reaction for two moles of water two moles of Hydrogen and one mole of Oxygen generates. Anode oxidation reaction leads to release positively charge hydrogen ions and oxygen while released electrons start flow though external circuit toward cathode,
$2\ H_2O_{(l)} \rightarrow O_{2(g)} + 4H^+_{(aq)} + 4e^-$. Electrons from the external circuit combined with hydrogen ions at the cathode to produce hydrogen gas. $4H^+_{(aq)} + 4e^- \rightarrow 2H_{2(g)}$ (Oener et al., 2020).

Alkaline electrolyser (AEL)

Alkaline electrolyser is one of the commercially established electrolyser types with two electrodes operating in liquid alkaline electrolyte. In general electrolyte is a solution of Potassium Hydroxide (KOH) or Sodium Hydroxide (NaOH) with 20-40 weight % (Chatenet et al., 2022). Diaphragm acts as the separator for this type of electrolysers and support the transportation of hydroxide ions from cathode to anode made of material that is not conductive to electrons. For commercially available systems typical operation temperature ranges from 60°C -100°C, current density of 0.2-0.7 A/cm^3, and pressure of 1atm-3atm while maintaining efficiency about 50-80% (Chatzichristodoulou et al., 2016).

Anode: $2\ OH^- \rightarrow H_2O + ½\ O_2 + 2e^-$

Cathode: $2\ H_2O + 2e^- \rightarrow H_2 + 2OH^-$

Overall: $H_2O \rightarrow H_2 + O_2$

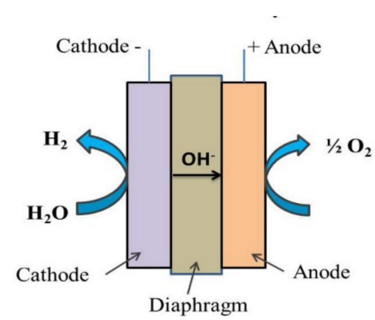


Figure 20: Alkaline Electrolyser (Shiva Kumar & Himabindu, 2019)

Alkaline electrolysers' hydrogen evolution and oxidation reactions are slow kinetic reactions in nature; hence the improvements are considered to be challenging (Sheng et al., 2013). While many factors like voltage and pH affect the performance of alkaline electrolyser Najafi et al. (2020) emphasis the importance of power supply stability to improve the efficiency of the alkaline electrolysers. Despite the challenging situation with catalyst material development of alkaline electrolysers are known as economic viable solution.

Proton Exchange Membrane electrolyser (PEM)

PEM electrolysers are equipped with solid polymer electrolyte and come with advantages over the conventional alkaline electrolysers with their high current density and high operating pressure. Due to the operating conditions such as high pressure there are several additional requirements in the design to fulfil the safety concerns and stability of the system. PEM electrolysers operate up to 30 bar pressure while some resources mentioned their capability to operate in even higher-pressure values (Gantenbein et al., 2022). PEM electrolysers hold operating temperature lower than 90°C common and operating temperature ranges from 70-90°C Wanjiku et al. (2010) express the importance of stability of the temperature to the stable operation. The current density ranges from 0.6-2.0 A/cm^2 and cell voltage is 1.8 V-2.2 V. Efficiency of the electrolyser ranges from 50% to 80% (Carmo et al., 2013).

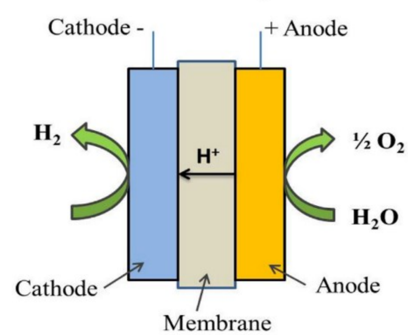


Figure 21: Alkaline Electrolyser (Shiva Kumar & Himabindu, 2019)

Anode: $H_2O \rightarrow H^+ + ½\, O_2 + 2\, e^-$

Cathode: $2H^+ + 2e^- \rightarrow H_2$

Overall: $2H_2O \rightarrow H_2 + ½\, O_2$

Additionally, Peng et al. (2022) discuss how PEM electrolysers exhibit higher load flexibility range from 5% - 120%. The ability to operate at wide range of power input while controlling the efficiency of the electrolyser vice versa with the power input which enables to perform better help the balance of electricity grid. However, PEM electrolysers are highly expensive due to the high-cost noble metal catalyst and their limited lifetime can be considered as some drawbacks.

Solid Oxide Electrolyser (SOE)

Solid oxide electrolysers are one of the widely available high temperature electrolysers which operate at the temperature of about 500 °C- 1000 °C and the operating temperature directly affects the performance of the electrolyser. This high temperature helps to convert power to gas in an efficient manner which is about 90%-100% (Laguna-Bercero, 2012). Hence SO electrolysers have lower power consumption which vary from 0.9-1.13V cell voltage and high current density compared to low temperature electrolysers. Solid oxide electrolyser consists of dense ionic conducting ceramic membrane, electrolyte with two porous electrodes. Another advantage of SO electrolyser is the capability to handle less water with less purity (Motylinski et al., 2019).

Anode: $O^{2-} \rightarrow \frac{1}{2} O_2 + 2e^-$

Cathode: $H_2O + 2e^- \rightarrow H_2 + O^{2-}$

Overall: $H_2O \rightarrow H_2 + \frac{1}{2} O_2$

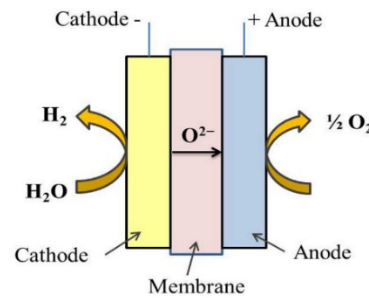


Figure 22: Solid Oxide electrolyser (Shiva Kumar & Himabindu, 2019)

Despite the production of high purity hydrogen, capable of fast response SO electrolysers have high material deration, system complexity and high capital cost due to its high operating temperature. Most importantly SO electrolysers are considered as next generation electrolysers which are still under development (Motylinski et al., 2019).

Anion Exchange Membrane Electrolyser (AEME)

Anion exchange membrane electrolysers equipped with semipermeable membrane and operated in alkaline environment without noble metals as catalyst. This is considered as the major advantage of AEME compared to PEM. (Li et al., 2021). Research has shown how AEME overcomes the current challenges in the limitation of current densities and different operating pressures in commercialization of electrolyser systems.

Anode: $2 H_2 \rightarrow 4 H^+ + 4 e^-$

Cathode: $O_2 + 4 H^+ + 4 e^- \rightarrow 2 H_2O$

Overall: $2H_2 + O_2 \rightarrow 2 H_2O + 4 e^-$

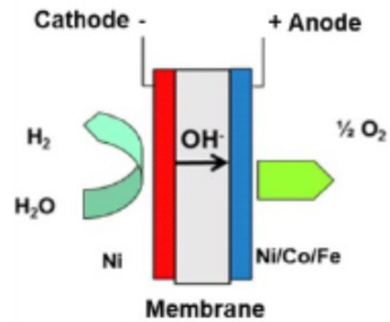


Figure 23: AEME (Trattner et al., 2021)

When considering operating parameters of AEME operates at 40-80°C, current density of 0.5-2 A/cm^2, at 40-80 bar operation pressure with up to 65% efficiency (Trattner et al., 2021). Due to AEME advantages it is considered as one of the promising technologies that requires further research and developments.

	AEL	PEM	SOE	AEME
Temperature (°C)	<100	70-90	500-1000	40-80
Pressure (bar)	atm - 30	atm - 40	1-3	30 - 35
Current density	0.2-0.7 A/cm^2	0.6-2.0 A/cm^2	0.3-1 A/cm^2	
Electrolyte	KOH or NaOH with 20-40 wt %	Solid specialty plastic material	Solid ceramic material	Solid material
Cell separator	Diaphragm	Electrolyte membrane	Solid oxide membrane	semipermeable membrane
System Capacity	Large scale central production facilities	Small scale distributed hydrogen production	Large scale central production facilities	Small scale distributed hydrogen production
Durability	Long lifetime	Good durability	Fast degradation	-
Cost	Low CAPEX	High CAPEX	High CAPEX due to	Low CAPEX
H_2 Purity	99.9-99.9998%	99.9-99.9999%	99.9%	99.99%

Voltage efficiency	50-68%	50-60%	75-85%	65%
Status	Commercially available	Commercially available	Research and development	Commercially available and under Research and development

Table 2: Comparison of electrolyser performance (Trattner et al., 2021), (IRENA 2020), (Shiva Kumar & Himabindu, 2019)

3.3.3 Fuel cell technology and use in G2P

In simple terms fuel cell operation consider as the opposite of the electorlyser operation with similar construction and structure of the electrolyser. In the fuel cell to proceed the function of electrochemical process or reverse electrolysis structure designed consist of three parts anode, cathode, and electrolyte. Similarly, anode performs as positively charged terminal, cathode as the negatively charged terminal while electrolyte works as the separation membrane. The electrolyte is placed in between the anode and the cathode ("Hydrogen production Electrolysis," n.d).

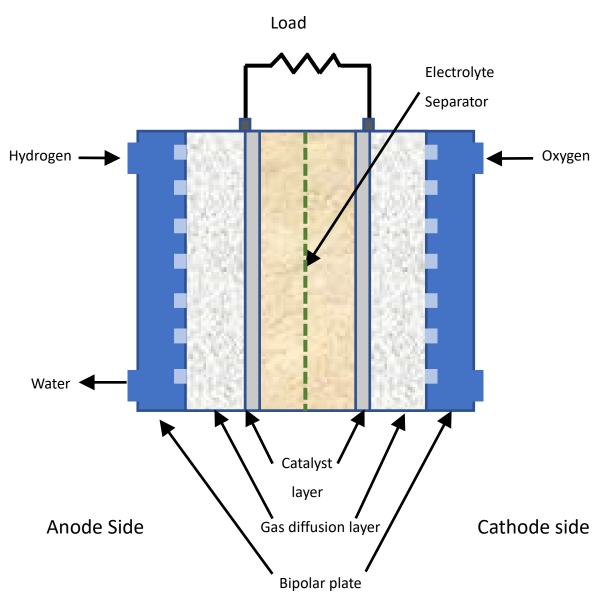


Figure 24: Components of fuel cell (Compiled by author)

Therefore, when generated electricity flows through external circuit water as vapor or steam, oxygen and heat produce as byproducts (Lai & Ellis, 2017). However, depending on the application requirement the number of fuel cells stack in series and combined stacks in parallel since the single fuel cell output is typically from 0.2-1.1 V in high performance fuel cells. Output voltage of a fuel cell varies depending on the type, construction, and the performance of the fuel cell (Mitra et al., 2021).

Hydrogen fuel cells systems offer a wide range of advantages compared to traditional combustion engines. Energy efficiency, energy density, expandability, modularity and adaptability in various applications and carbon free operation with high reliability are mostly known advantages. In terms of efficiency, fuel cells can convert 35%-65% of input power into useful electrical energy, which is higher compared to efficiency range of internal combustion engines, which is 25% -30% (Staffell et al., 2019). Combining fuel cells in series to increase the voltage to usable level, while stacking and combining stacks are employed to meet necessary power levels. The decision of parallel combination for higher current or series attachment for higher voltage depends on the application, system cost, and complexity ("Fuel Cell Systems," n.d). Furthermore, fuel cell operation temperature varies based on the type of fuel cell and the lifetime of the fuel cell affected by the operating temperature. Similarly, when considering other characteristics and operating conditions are also depending on the type of the fuel cell ("Fuel Cell Basics," n.d).

Fuel cell type variation mainly depends on the equipped electrolyte material. Some fuel cells can operate with different fuels other than hydrogen such as natural gas, ammonia, and hydrocarbons. Even though all different types of fuel cells follow the same electrochemical principle to convert hydrogen to produce clean electricity directly, they vary widely with distinct characteristics, operation conditions and applications. Well known types of fuel cell types are polymer electrolyte membrane fuel cell, alkaline fuel cells, solid oxide fuel cells ("Fuel Cell Basics," n.d).

3.3.4 Types of Fuel cells

Proton Exchange Membrane Fuel Cell (PEMFC)

Also known as polymer exchange electrolyte membrane fuel cells. PEM fuel cells have the capability to serve in different applications from stationary applications to nonstationary applications due to its unique characteristics such as low corrosion, lightweight, and compact design. PEM fuel cells electrolyte is a polymer which is a thin form of a permeable sheath. Operating temperature varies from 30°C to 100 (SALEH et al., 2016). Most commonly the catalyst use in PEM is platinum based which has good oxygen binding energy high reactance rate. Anode cathode materials are similar and typically carbon-based material is being used.

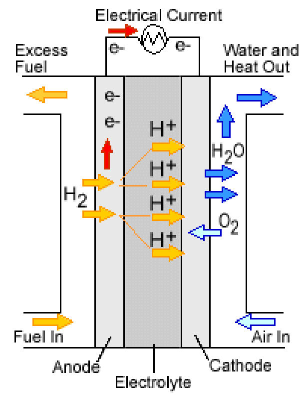


Figure 25: PEMFC ("Fuel cell Types,"n.d)

Oxidation at Anode: $H_2 \rightarrow 2H^+ + 2e^-$

Reduction at Cathode: $2H^+ + 2e^- + ½ O_2 \rightarrow H_2O$

Total reaction: $H_2 + ½ O_2 \rightarrow H_2O$ + electricity (external circuit)

However, due to high cost and scarcity of platinum and the requirement of catalyst in both sides of the membrane research programs are being taken place to see the performance of other platinum group materials ("Fuel Cell Basics," n.d). Such as oxides, nitrides, carbides, phosphides, and sulfides with the advantage of is low cost, durable and higher availability. In other hand there are challenges arise like integration procedure with membrane electrode, optimizing and performance and design of the catalyst layer structure (Mustain & Pivovar, 2020). PEM fuel cells exhibit higher transient response and better dynamic behaviors. However, like other fuel cells the output power of the fuel cell depends on its own polarization curve parameters which change with the reactance pressure, temperature, and flow rate of the reactants (Mo et al., 2023).

Alkaline Fuel Cell (AFC)

Alkaline fuel cells are considered as a promising fuel cell technology type since they have many advantages due to their characteristics. Due to several improvements and developments done with the help of several research they can perform stable operation at around 80 °C with high power density (Peng et al., 2018). However, operating temperature can vary between 60 °C – 250 °C. This low operating temperature accommodates these fuel cells to perform quick start up. Alkaline fuel cells have been equipped in varies applications even for space projects since mid-1960s (Duerr et al., 2007).

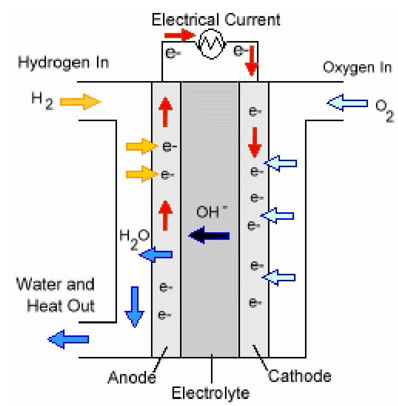


Figure 26: Alkaline FC ("Fuel cell Types, "n.d)

Anode: $H_2 + OH^- \rightarrow 2\ H_2O + 2\ e^-$

Cathode: $O_2 + 2\ H_2O + 4\ e^- \rightarrow 4\ OH^-$

Overall: $2H_2 + O_2 \rightarrow$ H2O + electricity (external circuit)

Moreover, with their high oxygen reduction reaction kinetics enable them to exhibit high voltage and competitive current densities in comparison to other fuel cell types. One of the biggest advantages of alkaline fuel cells is using non noble metals as catalysts such as Nickel (Ni) and silver (Ag) a mixture of potassium hydroxide, which makes alkaline fuel cells cost effective than other fuel cells. Anode and cathodes are made from porous nickel electrodes (Vidakovic-Koch, 2016). At the anode hydrogen oxidizer and hydrogen gas combined with hydroxide ions from the electrolyte to produce water this reaction results in release of electrons. These electrons are forced out of the anode and produce electricity in the external circuit and reach cathode. At cathode oxygen combines with water and produces hydroxide ions with the help of electrons to keep the process continuing while excess water, oxygen and heat are taken out from the fuel cell as the byproducts (Zeng & Zhang, 2010). However alkaline fuel cells come with great draw back which is its susceptibility to carbon dioxide contamination, hydroxide ions lead to form carbonates and bicarbonates which affect overall efficiency of the fuel cell and green power concept. Therefore, use of highly pure hydrogen with reformer, gas purification system and other advancement in operation and control system significantly affect the alkaline fuel cell cost and complexity of the system.

Solid Oxide Fuel Cell (SOFC)

Solid oxide fuel cells are considered as one of the most stable fuel cells that operate at high temperatures in general from 600 °C to 1000 °C. However, this elevated temperature operation allows solid oxide fuel cells to perform without requiring expensive metals as catalysts. In other hand this high temperature operation causes to slow start up, mechanical and chemical sustainability issues such as high degradation of materials, thermal stress, material compatibility, etc. (Singh et al., 2021). However, there are several research ongoing to see the potential to reduce operating temperature to intermediate level of 500-700°C and some even more down to 450-600°C, to reduce high requirements from materials and durability of the SOFC (Tarancón, 2009) ("Investigating new materials to reduce the operation temperature of solid oxide fuel cells,"2021). SOFC consists of solid ceramic electrolyte typically zirconia doped with yttrium which is known as Yttria-stabilizeed zirconia (YSZ). Nickel-zirconia cement is often used as anode and cathode is commonly made of lanthanum strontium manganite (LMS). There are few other materials used to build SOFC and some materials are under development to equip in SOFC (Hussain & Yangping, 2020). Apart from cons related to high operating temperature SOFC has relatively low construction cost, scalability and better efficiency performance which is around 60% ("Solid oxide fuel cells," n.d).

Anode: $H_2 + o^{2-} \rightarrow H_2O + 2\ e^-$

Cathode: $½\ O_2 + 2\ e^- \rightarrow O^{2-}$

Overall: $H_2 + ½\ O_2 \rightarrow H_2O$ + electricity (external circuit)

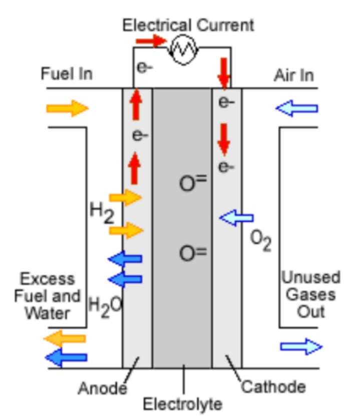


Figure 27: SOFC ("Fuel cell Types, "n.d)

The hydrogen fuel is oxidizing at the anode and the reduction of oxygen takes place at the cathode while electrons are moving from anode to cathode through the outer circuit.

Phosphoric Acid Fuel Cell (PAFC)

Phosphoric acid fuel cell uses liquid phosphoric acid as an electrolyte. Operates at 150°C to 200°C temperature. Consist of pair of porous electrodes mainly formed by carbon material coated with a finely dispersed platinum catalyst. Electrolyte is either highly concentrated or pure liquid phosphoric acid saturated in silicon carbide matrix (Vaghari et al., 2013).

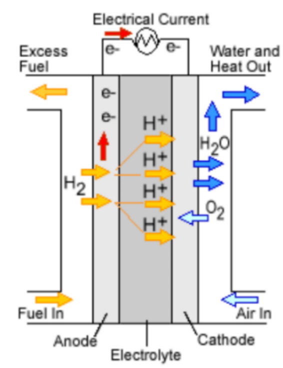


Figure 28: PAFC ("Fuel cell Types, "n.d)

At the anode pure hydrogen is supplied and at the cathode air (oxygen) is supplied. Hydrogen splits and generates hydrogen ions at the anode and migrates towards cathode through electrolyte while electrons flow through external circuit to generate electricity which is similar to PEM fuel cell operation. In general, PAFC reaches higher efficiency only in combined heat and power systems and capable of handling some with tolerance of fuel impurities. Furthermore, PAFC are relatively less sensitive to carbon monoxide poisoning (Jiang & Li, 2021). However, PAFC takes longer time to start up in comparison to some other fuel cells and use of platinum catalyst causes to increase the cost of the fuel cell.

Molten Carbonate Fuel Cell (MCFC)

MCFC is also another example for high operating temperature fuel cells which operate typically from 650 °C - 850°C. It is equipped with molten carbonate electrolyte usually combined with lithium and potassium carbonate (Nabae et al., 2008). Because of high operation temperature it is possible to use carbon-based fuels other than hydrogen. Efficiency of the MC fuel cell can be around 50% and even higher in heat and power combined systems (Gürbüz et al., 2021). Both anode and cathodes are porous nickel-based material saturated with molten carbonate electrolyte. Similar pros and cons to SOFC exhibits from MCFC however, MCFC has the potential to facilitate carbon capturing due to the presence of carbonate ions (Dou et al., 2021).

Anode: $H_2 + CO_3^{2-} \rightarrow H_2O + CO_2 + 2^{e-}$

Cathode: $CO_2 + ½ O_2 + 2^{e-} \rightarrow CO_3^{2-}$

Overall: $H_2 + ½ O_2 \rightarrow H_2O$ + electricity (external circuit)

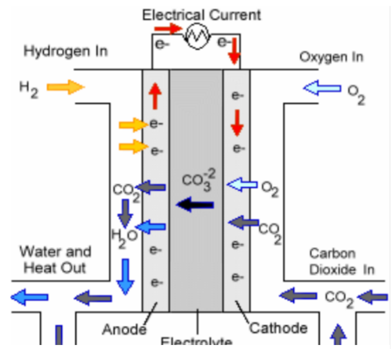


Figure 29: MCFC ("Fuel cell Types, "n.d)

Therefore, the selection between SOFC and MCFC depends on the application and the available fuel and type and the application requirement.

	PEMFC	AFC	SOFC	MCFC	PAFC
Operating temperature	30°C -100°C	60°C-250°C	500°C-1000°C	650°C-850°C	160 °C -220 °C
Operating pressure (bar)	3 - 4	Atmospheric pressure	Atmospheric pressure - 8	Atmospheric pressure- 7	Atmospheric pressure- 8
Voltage	0.6-0.9 V	1.0-1.4 V	0.7-1.2 V	0.6-0.8 V	0.6-0.7V
Current Density	600 mA/cm^2	300-600 mA/cm^2	100-300 mA/cm^2	100-250 mA/cm^2	150-350 mA/cm^2
Electrical efficiency	30% - 40%	60%	50% - 60%	43% - 47%	40% - 42%
Transient time	Fast	Moderate	Moderate	Moderate	Moderate
Dynamic behavior	Fast start	Moderate start	Relatively slow start	Moderate, slower than PEM	Limited behavior
Power	0.01-250kW	0.1-50kW	0.5-3000kW	1-100000kW	50-1000kW
Status	Commercial/ Research	Commercial/ Research	Commercial/ Research	Commercial/ Research	Commercial/ Research

Figure 30: Comparison of Fuel cell operation parameters (Irshad et al., 2016), (Ramadhani et al., 2019)

3.3.5. Limitations and evolution of fuel cells

Fuel cell development can be identified under a few development generations. The first generation of fuel cells are alkaline fuel cells which were developed in the year 1930s- 1940s and used by NASA for Apollo space mission (Harold & Wallace, 2019). Since then, for several decades' fuel cell developments have taken place, and at the current stage there are several commercially available fuel cells which still need developments in performance, durability, and cost to enhance the dependency on fuel cell technology.

Fuel cells gain significant attention due to their promising capability to uphold the green energy concept and higher efficiency. However, due to several drawbacks in commercialization and improvements in the perforce fuel cells face challenges in the wide spared of the technology (Barbir & Yazici, 2008). Enhancing reliability and reducing manufacturing cost are key problems faced by many fuel cell types. Challenges related to better control of transient time and start/stop time control which cause durability of the fuel cell due to degradation of catalyst and designing fuel cell to cater in various applications under different conditions (Kazula et al., 2023).

	Fuel cell	Battery
Technology	Electrochemical power generation	Electrochemical power generation
Duration	Long period of time	Comparatively short period of time
Process	Required continuous oxygen and hydrogen supply	Contain limited amount of energy
Device type	Conversion device	Storage device
Electrode decay	Electrodes will decay	Electrodes will decay
Size/weight (For particular power output)	Relatively small and light package	Larger and heavier
Efficiency	Less efficiency	High efficiency
Cost	Comparatively less expensive	Expensive

Table 3: Comparison of Fuel cell with Battery

3.4 Low Voltage Products

3.4.1 Introduction to LV products

Definition for low voltage range could vary based on the region or country. However, according to the International Electrotechnical Commission (IES) defines the low voltage under IEC 61140:2016 as up to 1000V ac or up to 1500V dc. Also, based on IEC 60038 considering supply system low voltage range defines as 50-1000V AC or in DC as 120-1500V. As per the regional changes British standards which is BS standards, low voltage is defined by BS 7671 voltage exceeding 50V AC up to 1000V AC or ripple free 120V DC- 1500V DC. ANSI is the America National Standards specify low voltage as 240 to 600V, ANSI C84.1-20201 ("Classification of voltage levels - extra-high, high, medium, low." 2022).

Existing low voltage products have several standards. IEC 60947 standard series refers to the international standardization guidelines for low voltage switchgears and controlgear. IEC 60947 covers equipment up to 1kV AC or 1.5kV DC, consisting of several parts, each focusing on specific aspects of low voltage electrical equipment. This standard provides general rules for construction, testing, and performance for switches, disconnectors, etc (IEC,2020). While UL98 is developed by Underwriters Laboratories (UL) mostly for North American region. UL 98 deals with enclosed and dead-front switches with detail design and testing requirements (UL standards 2021). Both standards have their own versions for AC and DC applications. As well as try to ensure the safety, reliability, and interoperability of low voltage electrical equipment.

However, in practical actual voltage levels specifications differ from these general standards and guidelines provided by institutes with the application, manufacturer's specification, and local regulation authorities (Csanyi, 2017).

The low voltage product comprehends a board range of devices in different applications equipped with its unique features. Common examples include circuit breakers, designed to detect excess current resulting from short circuit faults or overload conditions. They cut off the current flow to safeguard the circuit and mitigate potential hazards. Switches and disconnectors enable safe interruption in the system for essential maintenance or circuit isolation for safety. Contactors function as electrically controlled switches, utilizing a lower-power circuit to switch much higher power. Relays play a vital role in sensing faults within the system and providing necessary data to safely control the system. Altogether low voltage products contribute to uphold the stability and safety system to ensure efficient operation (“Low Voltage Products and Systems,” n.d).

3.4.2 LV products approach in P2G and G2P process

Low voltage products play a vital role in green hydrogen production with efficient and safe procedures and convert green hydrogen back to useful energy via fuel cell technology. Therefore, circuit breakers, disconnectors, fuse gears and combination of variety of low voltage products brings proper management of the power control, safety, and efficiency requirement of the solution (“Safety Aspects of Green Hydrogen Production on Industrial Scale,” n.d).

Process of P2G, where electrolyser requires electrical power to perform conversion process as well as G2P process, fuel cells generate electrical power using green hydrogen. Therefore, two main systems highly rely on low voltage products in the control of the system while subsystems like gas compression and flow control system, heating and cooling systems and auxiliary systems also requires several low voltage products to fulfil total system reliability and safety.

Production of green hydrogen is based on renewable sources such as wind and solar, therefore depends on the type and the level of power output of the energy source. Power conditioning is done using transformers and inverters to meet the specific required low voltage DC power supply for the electrolyser system. Produced green hydrogen compression, storage and supply to fuel cells typically based on the type of the fuel cell need to manage safe and efficient manner with proper control and monitoring, where the low voltage products help in controlling compressors and handling units (Amireh et al., 2023).

In the power to gas stage circuit breaker and disconnectors are used to connect electrolysers ensuring secure and controlled power supply from the renewable power sources. In the other hand electricity generated by fuel cells connection to the electrical network similarly circuit breakers and disconnectors are equipped. While fuse gears and relays protect the system and enhance the control, monitoring to assure the protection of the whole solution. Therefore, research and continuous improvement in low voltage products and their utilization in P2G and

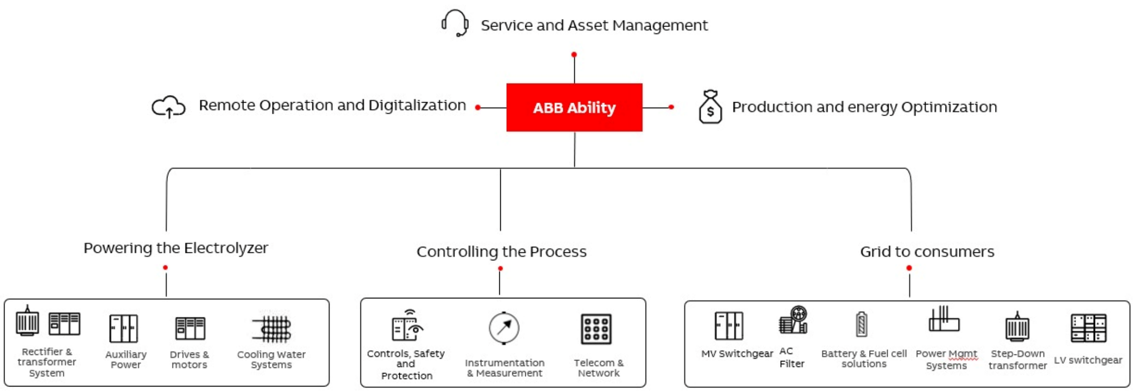


Figure 31: ABB Capability (ABB)

G2P processes is essential to enhance the efficiency and the reliability of the solution with the critical power quality requirements. This includes improvements in material, technology and systems (Dobó & Palotás, 2016).

ABB currently has the capability to deliver products and services in many stages of the P2G-G2P solution (Figure 32). However, a better understanding of the raising requirement of the field is crucial to target the particular requirement while catering the best solution.

4.0 Market study

4.1 Introduction

Green hydrogen production by water splitting hydrogen atoms from water molecules using renewable energy experienced noticeable growth all around the globe during recent time. This market growth effects on several industries due to its significant technical, economical and ability to support social wellbeing characteristics. The use of hydrogen as an energy carrier has shown its potential to support the transition of the global economy to a green energy future, although there are hurdles to overcome regarding infrastructure development, economic barriers, and the process of adopting hydrogen (Böhringer & Rosendahl, 2010). This chapter presents the current market for green hydrogen especially in power generation using fuel cell technology.

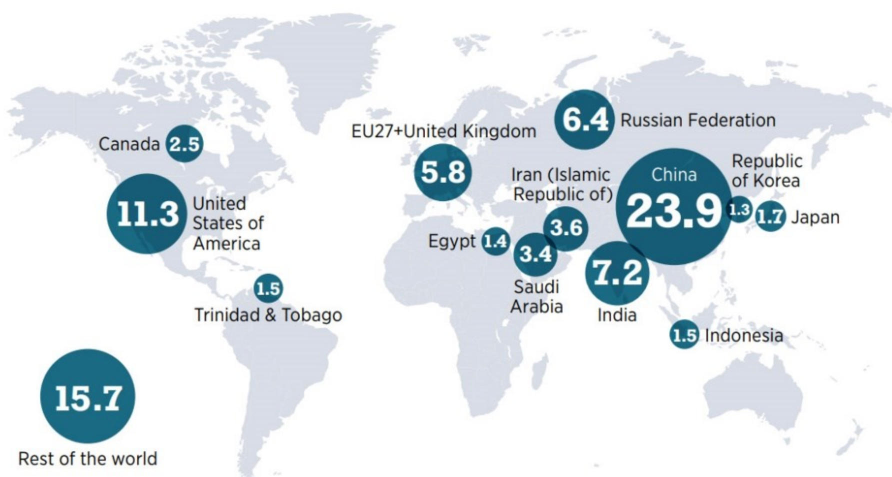


Figure 32: Hydrogen consumption in 2020 (million tonnes per year) (Geopolitics of the energy transformation)

The hydrogen economy is built up with stakeholders who produce hydrogen and up to different end users, policy makers, regulators, and other businesses along with vast supply chain. At the moment, most of the hydrogen production depends on fossil fuel base energy sources. Around 47% of the world's hydrogen requirement is fulfilled by energy generated using natural gas, 27% covered by coal and 22% as a byproduct of oil production. At the end of 2021, which means more than 95% of hydrogen is produced by gasification and steam reformation and 4% of hydrogen was produced using electrolysis. However, only 1% of hydrogen was green due to the world renewable ("Hydrogen," 2022).

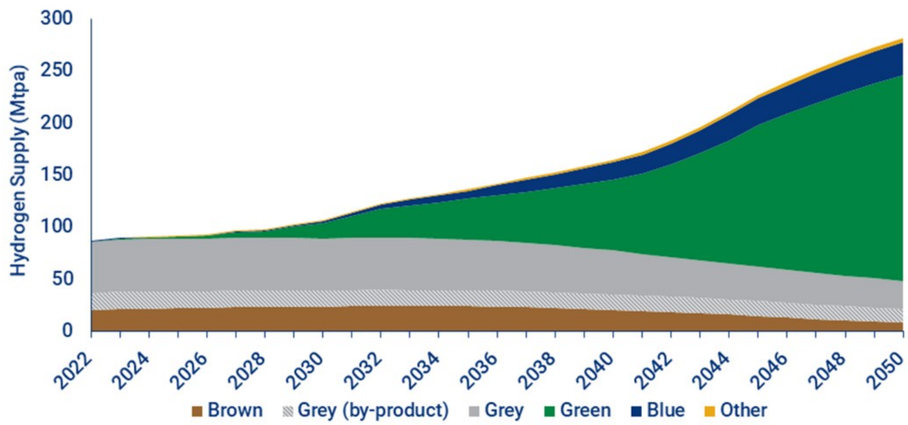


Figure 33: Global hydrogen production respectively the energy source from 20222-2050 (Wood Mackenzie)

energy share being 33%. Hydrogen is not a newly introduced technology. Ever since 1975 the world hydrogen demand has grown over three times. (IEA, 2019)

In 2022 global hydrogen production capacity reach over 109,000 tons per annum (King, 2023). Word hydrogen market value is estimated in 2021 as USD 150.2 billion, and with compound annual growth rate of 5.6% expected to reach USD 220.37 in 2028 (Direxion Hydrogen ETF). Even though, with various policies and agreements to reduce high carbon concentration hydrogen production methods such as brown and gray hydrogen are being affected overall global hydrogen production rate until 2030 according to Figure 34, there will be not much visible transition to green hydrogen. Major players like Air Liquide, Nel, Linde main hydrogen production method is steaming reformation which is gray hydrogen. Even though gray hydrogen is their main product these companies contribute to blue and green hydrogen production up to some level.

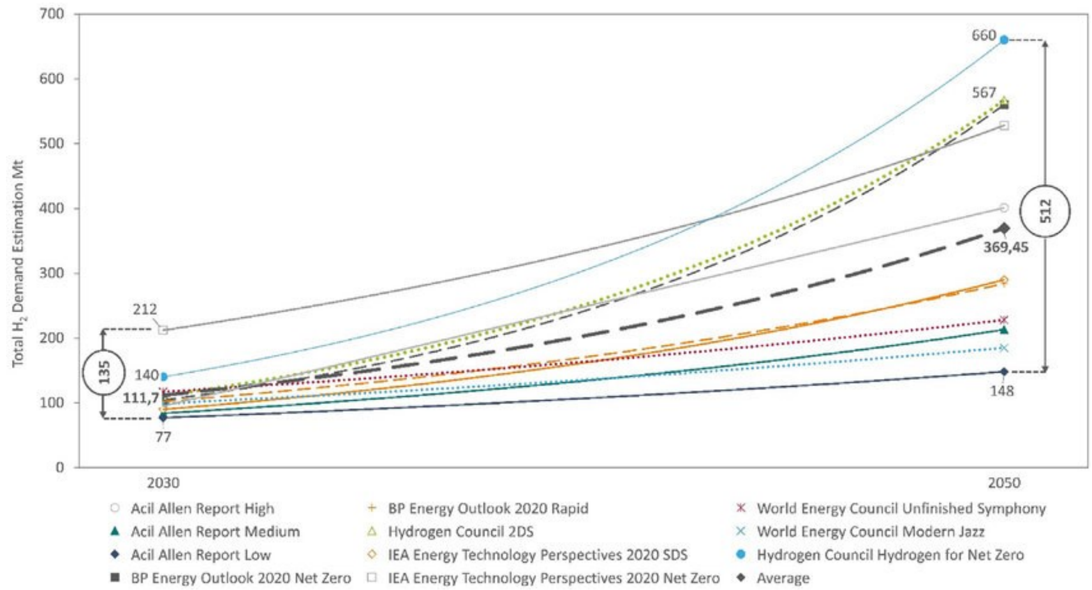


Figure 34: Comparison of different studies with global hydrogen demand based on different scenarios (Wappler et al.,2022)

According to Wappler et al. (2022) the production of green hydrogen comparison over 18 different several studies about the future of the green hydrogen it is shown that the production of green hydrogen could differ based on several factors such as, most of the studies based on its own niche, feasibility of the realistic implementation, different implementation methods and procedures. That explain why the prediction of hydrogen production substantially vary in 2020 between 77-212 Mt per annum and 148-660 Mt per annum, in 200 which shows over 10% compound annual growth rate different in in both predations.

CAGR = (Ending year/beginning year) $^{1/\text{number of years}}$ - 1

Acil Allen report low (CAGR): $(148/77)^{1/20}$ - 1 ≈ 0.04 → 4%

Hydrogen council hydrogen for net zero (CAGR): $(660/140)^{1/20}$-1 ≈ 0.15 → 15%

Therefore, is it visible that despite of the other dependant factors when considering the growth of the hydrogen market, when considering overall performance and demand can expect to see considerable growth of green hydrogen market in coming decades.

4.2 Driving Factors

1. Increasing demand for renewable energy

All around the word, governments and private sectors building more solar parks, wind farms and hydroelectric power plants to generate power as global warming and climate change continue to lead hazardous to comfortable and healthy lifestyle of living beings.

Increasing interest for renewable energy became critical point in the sustainable development and growth of the economy. Systemic review of 46 articles 2010-2011 exhibits that renewable energy does not affect the economic growth of both developed and developing countries (Bhuiyan et al., 2022). World renewable energy growth shows positive impact on regional economic growth while promoting stability in the energy supply. Furthermore, several studies support the fact that while leading improvements in environmental quality renewable energy shows strong positive relationship (Chen et al., 2020) (SOAVA et al., 2018). From 27% in 2019, in 2020 the global renewable electricity generation came up to 29%, in 2021 is has expanded by more than 8% leads to reduce fossil fuel demand. According to IEA by 2025 30% of world electricity requirement will comes renewable energy sources.

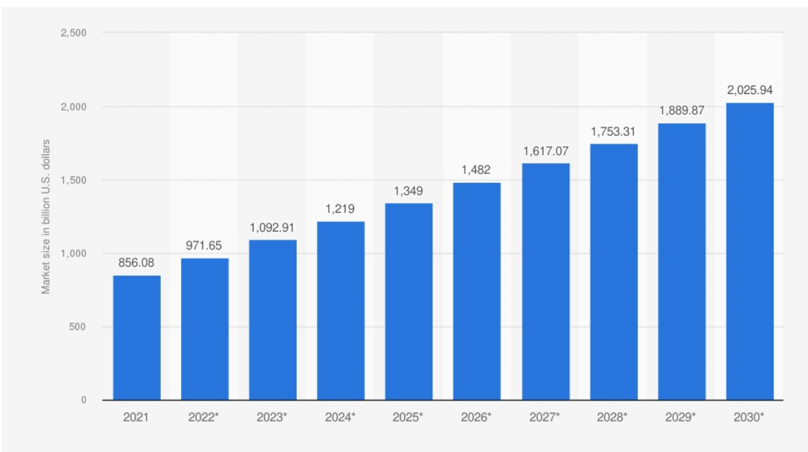


Figure 35: Renewable energy market size worldwide in 2021, with a forecast for 2022 to 2030(in billion U.S. dollars) (Statista 2024)

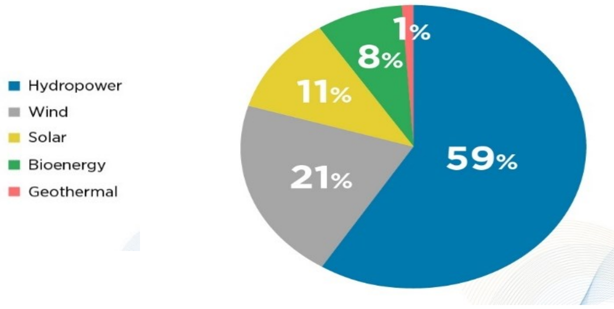


Figure 36: Share of renewable energy in world by source in 2020 (IRENA, 2022)

With strong developments in renewable energy technology and major investments, there is a significant falling cost of renewable energy which are driving factor for wide spread of renewable energy sources. Past decade solar and wind power became more cost competitive and affordable. Therefore, solar and wind gain much more attraction compared to fossil fuels (Charabi & Abdul-Wahab, 2020) (Muneer et al., 2022).

The global average levelized cost of electricity from solar photovoltaic systems experienced a significant decline, dropping from 378 USD/MWh to 68USD/MWh between 2010 and 2019. This is an impressive 85% of reduction in price. During the same period offshore wind decreased from 181 USD/MWh to 129 USD/MWh while onshore cost decreased from 149 USD/MWh to 67 USD/MWh, respectively 29% and 55% drop in the price. Highly efficient solar panels, large wind

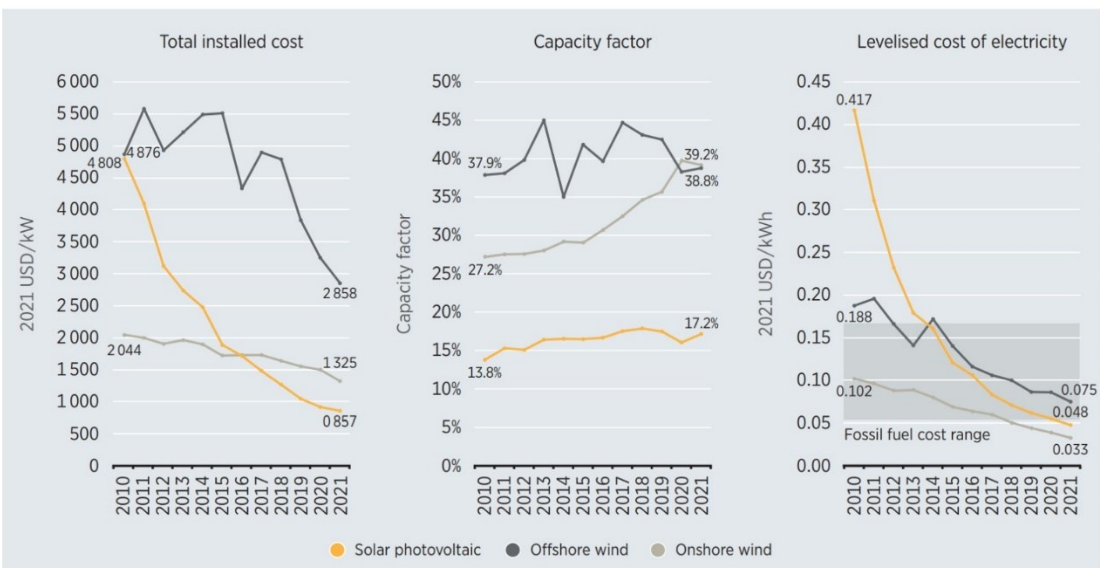


Figure 37:Global weighted average total installed costs, capacity factors and LCOE of newly commissioned utility-scale solar PV, onshore, offshore wind 2010-2021 ("Renewable energy statistics 2022 - IRENA – international renewable," 2021)

turbines, improved installation procedures and low capital cost led to decrease in the renewable energy price point (The price of solar power has fallen by over 80% since 2010. here's why 2021).

2. **Government and policy support:**

The increasing adoption of renewable energy around the globe has significant effect from the government support and policies. Research exhibits continuous government subsidies and incentives influence growth of renewable energy systems. The global future of clean energy investment: the annual review 2022 by the international renewable agency (2022) indicate that the total investments for renewable power sector increased by 12% in 2020 which is up to 1.2 trillion USD with expectation to see the growth to around USD 1.2 trillion. IN 2020, government spending on energy research and development increased by 10%, reaching nearly 44 billion USD. During this period, clean energy, particularly renewable energy, accounted for an impressive 81% share. This showcases the governments' propitiation of clean energy as shown in figure 39.

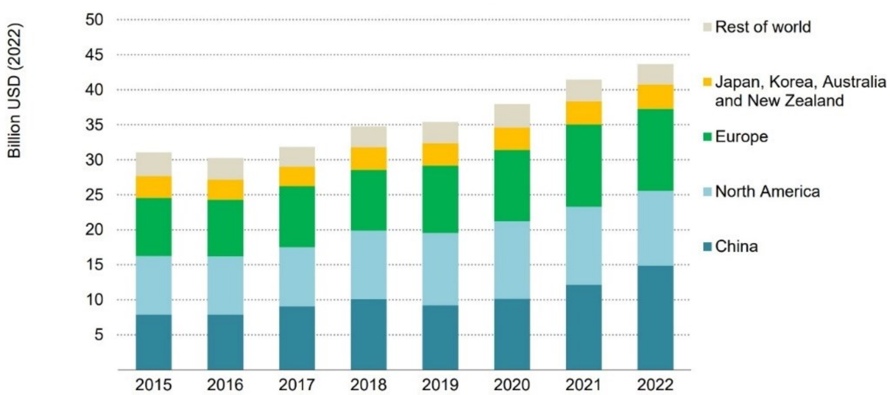
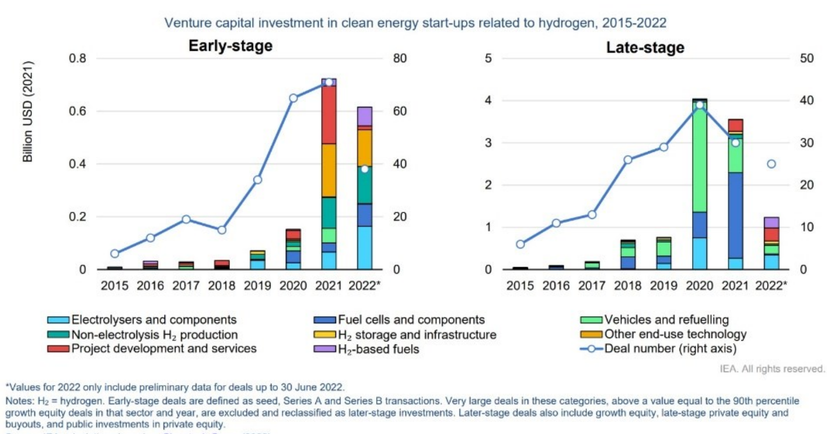


Figure 38: Spending on energy R&D by governments, 2015-2022 (IEA, 2023)

Governments and regional union's curtailment and policy in the adoption of renewable energy for both upstream and downstream support have been boosting the renewable energy sector. Furthermore, to support governments and policy makers to follow globally recognized policy framework to achieve clean energy, IRENA, IEA and Renewable Energy policy network for the 21st century have joined forces and presents "Renewable Energy Policies in Time of Transition" in 2018. This publication covers renewable energy policy options covering global development trends, sector specific policies as well as measures for integrating various renewable resources into the power system ("Renewable energy policies in a time of transition," 2018). However, these policies and regulations differ a lot based on the region and the country due to their legislations based on geography and the capacity of the governments' contribution towards the transition procedure and providing proper security for energy system and stakeholders. Due to global and regional targets to achieve zero emission governments and policymakers are bound to take necessary actions based on their targets (Blumberga et al., 2014). Moreover, implementation of subsidies, incentives and policy framework are essential for governments to act accordingly to commit to the overall success of the renewable energy solutions (Suh & Yoon, 2020).

4.3 Key market players and iconic projects

When Studying market of P2G and G2P can identify key players from several segments which are green hydrogen manufacturer, electrolyser manufacturers, fuel cell manufactures and electricity generators by fuel cell using green hydrogen. Identifying key players, market share and their strategies in green hydrogen production is essential to understand the operation and contribution to the green hydrogen market. Green hydrogen producers pay a vital role in the total market structure and the transition to green future (Villalba-Herreros et al., 2023).



According to IEA Global Hydrogen Review 2022 (2) 33 publicly traded companies identified as whose success depends on the increasing demand for low emission hydrogen. These companies' sector of operation varies from electrolyser and fuel cell manufacturers, low emission hydrogen and ammonia project developers, hydrogen distribution infrastructure developers and hydrogen fuel vehicle manufacturers. Furthermore, the whole segment valued at USD 33 billion which is over 10 times compared to five years ago and 4 times greater than end of 2019 ("Global Hydrogen Review 2022," 2022).

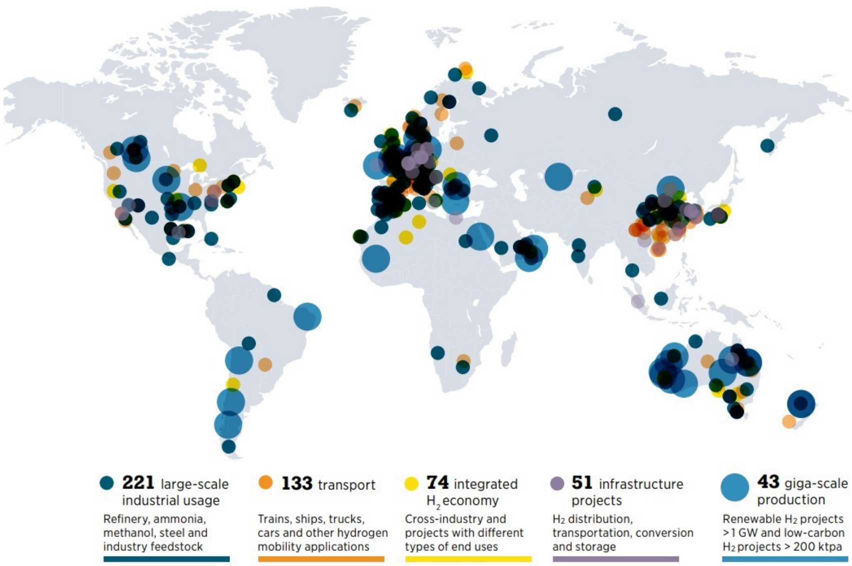


*Figure 39: Clean hydrogen projects and investment as of November 2021 ("*Geopolitics of the energy transformation," 2021*)*

Global green hydrogen, blue hydrogen and other clean hydrogen related projects announced by 2030 reached about 160 USD billions of investments (figure 40).

However, 4% of announced electrolysis and low emission hydrogen projects have taken final investment decision. In 2022 China total installed capacity reached 200MW and with expectation to reach 1.2GW by the end of 2023 which represent 50% of global installed capacity, Europe as the second largest and followed by North America (IEA,2023). 2022 hydrogen demand reached the historical high of 95Mt with 3% increase year on year. In other hand as illustrate in figure 41, for the growth and strengthen the establishment low emission hydrogen firms with proper valuation requires better government involvement with more favourable policies (IEA,2023).

*Figure 40: a. Comparison of monthly return of hydrogen companies and funds by Market capitalisation of hydrogen companies and funds (*World Energy Investment 2023 - .NET framework *2023)*

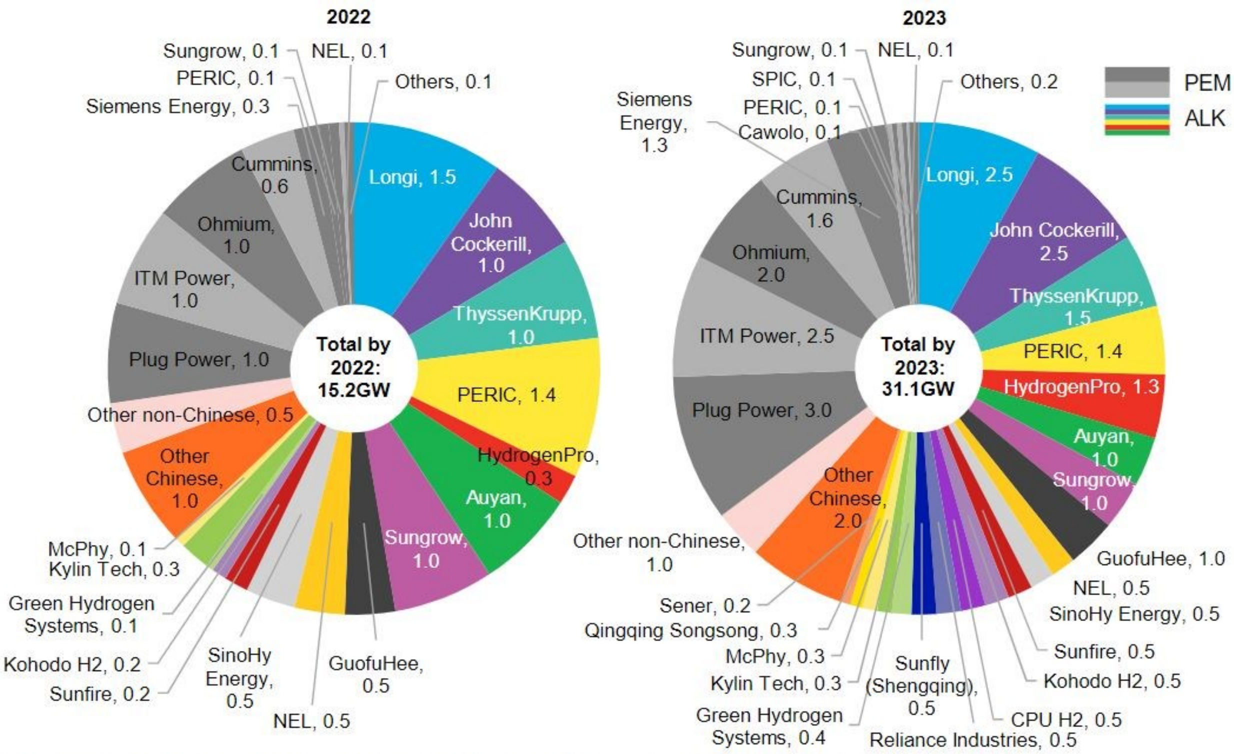


Figure 41: Annual Electrolyser manufacturing capacities

(A breakneck growth pivot nears for green hydrogen 2022) (Company findings, BloombergNEF, Values refer to year end capacities)

With respect to the growth of green hydrogen market, the capacity of electrolyser manufacturing emerging (Figure 42). Around the globe companies manufacturing electrolysers increased their annual manufacturing capacity by 15.2GW to 31.1 GW from 2022 to 2023. Based on these figures the growth rate is approximately 104.6%. Furthermore, figure 43 compares how few companies from above data perform over the year to contribute to this improvement in electrolyser manufacturing industry. Also, several companies like CPU H2, Sunfly, Sener, and some joint ventures have been established to support the growth of the clean energy industry.

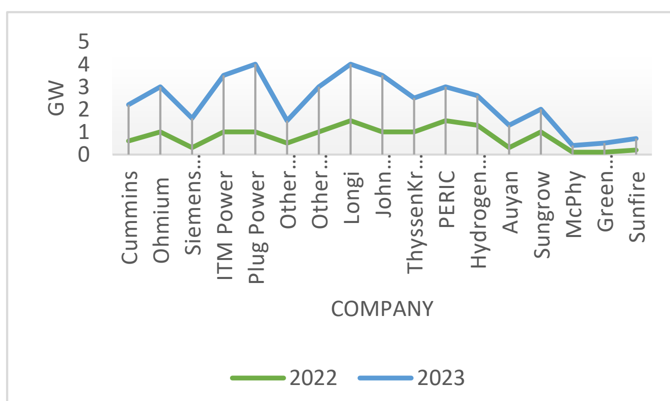


Figure 42: Comparison of individual commitment

4.4 Economic and Environmental benefit

Green hydrogen production and use of fuel cells in power generation has shown significant impact on economy and environment. Green hydrogen capabilities as an energy carrier and use as of fuel indicate the viability of green hydrogen in energy industry. Fuel cells capability to operate as power generating units as distributed power generating devices and mobile power units has advantage of delivering clean power while contributing to environmental protection and economic benefits (Hamukoshi et al., 2022). Green hydrogen versatile feature is one key component that makes it highly effective in economic and environmental aspects in various sectors such as energy storage, power generation and power system balancing, transportation, agriculture, and heavy industries. Significant advantage of adoption of green hydrogen is it commitment to uphold both economic value and environmental protection equally at the same time.

1. Economic benefits

Studies like Di Micco et al. (2022) on site solar powered refuelling station for green hydrogen production and distribution solution's technological performance against cost factor present the viability of green hydrogen and fuel cells performance and it's economic and environmental benefits. With high demand and dependability on energy, while interest towards more renewable energy comes with risk of intermittency and variability. With existing energy storing techniques are not sufficient to rely on therefore, use of green hydrogen as energy soring and fuel cells to power conversion technology enhance the energy security ("Hydrogen benefits and considerations," n.d). Since the price of green hydrogen effect the economic growth to achieve the benefits, according to the IRENA "HyDeal" project named as world largest green hydrogen project with aim to deliver 100% green hydrogen by 2030 across Europe at €1.5/kg (Hydeal, n.d). Several projects around the world taking necessary steps to enhance the wide spread of adoption to green hydrogen. As we understand the market growth in under introduction to green hydrogen market, development of green hydrogen and fuel cell market lead to create new job opportunities

Figure 43:Hydrogen commitment with scaling up (Hydrogen Council 2017)

in various sectors can be seen as one big step in economic benefits. According to Hydrogen council, (2017) by 2050 hydrogen would meet 18% of total final economy demand with creating sustainable economic growth.

2. **Environmental benefits**

Over conventional fossil fuel-based power generation, green hydrogen fuel cell system for electricity generation offers several environmental benefits. Mainly this solution is emission free from harmful greenhouse gases which cause to air pollution, by-products are clean, and solution is sustainable. According to IEA, (2021) Net Cero Emission (NZE) scenario by 2050 impact of implementation of green hydrogen is modest in 2030 and vast in the long term. Furthermore, NZE scenario indicates current (2022) average emission intensity of CO_2 from hydrogen production which is 12-13.4kg CO_2 –eq/Kg expect to drop down to 6-7.5kg CO_2 –eq/Kg by 2030 (Net zero by 2050 - .NET framework 2021).

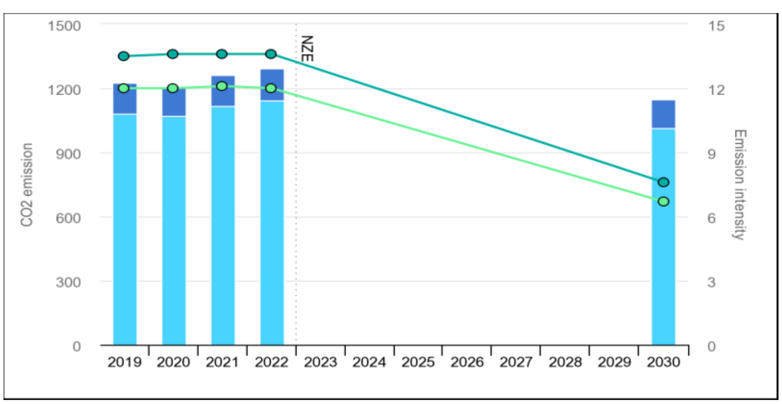


Figure 44: CO2 emission and NET Zero targets (Net zero by 2050 - .NET

	Economic benefit	Environmental Benefit
Energy storage	Excellent energy storage medium as a solution to store excess energy form intermittent renewable sources and enhance energy security, reduce dependency on fossil fuels.	By-products are only water/vapour and heat which is clean and environmentally friendly
Electrolyser efficiency	The efficiency is compared to other hydrogen production methods is lower and cost is higher. Expected to see cost reduction and efficiency increment with research and development.	Highly beneficial for environment since electrolyser hydrogen production is zero carbon emission process.
Fuel cell efficiency	Fuel cells high efficiency considering only conversion of chemical energy to electricity compared to traditional combustion engines.	Capability to operate in different operating temperatures and reliability with silent and compact operation in variety of application.
Cost reduction	Overall cost is currently higher than traditional fossil fuel systems, however expecting to decline over the time with techno-economy development.	Extraction of fossil fuel costly as well as highly effect the ecosystem, therefore fuel cell systems could help to conserve environment while reducing cost.

Table 4: Economical and environmental benifits with clean hydrogen

As mentioned in Dillman & Heinonen, (2023) there are limitations and lacking studies about the carbon footprint of hydrogen production and use. Therefore, it highlights that the global energy models' potential changes to achieve economy decarbonisation and limiting global warming to 1.5 °C is challenging.

5.0 Data Driven Approach to Green hydrogen; Power to Gas to Power

Besides the influence of market value for green hydrogen and the total solution, efficiency of the overall gas to power to gas system is the major critical factor affect the widespread implementation. However, this overall efficiency may affect various possibilities to integrating green hydrogen systems with other systems with such gas network (Gondal, 2019). Several studies taken place to see the importance of improving efficiency and possibilities to improve the efficiency of the green hydrogen systems by integrating feed water hydrogen heating by nuclear power plants and examining challenges of connecting intermitted power sources (Aminov & Egorov, 2020), (Settino et al., 2022). In other hand, the cost of the solution at the moment compared to other systems is high. Hence, the price of electricity generated using green hydrogen as backup or distributed power source considered to be expensive.

Efficiency:

Exergy efficiency as defined by Park & Jang, (2016) stands for the ratio of electrical output power to maximum achievable work output of the system. Stack efficiency refers to the efficiency of an individual fuel cell stack or electrolyser stack. System efficiency is the generic system efficiency of the total procedure from the production green hydrogen to THE use of green hydrogen in fuel cells to generate electricity with including all supporting ancillary processes.

Typically, efficiency losses are visible in any system when the system deviates from the ideal performance characteristics, which is known as polarization. Correspondingly, the efficiency of electrolysers and fuel cells is significantly affected by primary polarization factors (i.e., activation polarization, ohmic polarization, diffusion polarization and concentration polarization). Activation polarization (Trattner et al., 2021) occurs where the reaction takes place due to the resistance of the electrochemical interfaces, and the required activation energy as well. Factors like the type of catalyst, electrode material and reaction kinetics affect the activation polarization. Resistance for the ions and electrons to move through electrolyte and electrode known as ohmic polarization, which is due to the conductivity of the materials and the electrolyte thickness (eere,n.d). Concentration polarization happens with the reduction of the reaction rate with depletion of reactants and concentration at electrode-electrolyte interface. Mainly due to limitation is mass transportation and diffusion coefficients (Oener et al., 2020). According to IRENA, (2020) diffusion polarization also occurs due to mass transfer limitations, specifically reactance and removal of products from the electrodes which again reduce the reaction rate. Apart from these primary polarization factors there are several other factors that influence the stack efficiency and lead to system efficiency of the system.

5.1 Green hydrogen production stage

Electrolysis is the method we consider producing green hydrogen. Even though the electrolysis process is being around for hundreds of years. As it took years to solar and wind energy to become cost effective and wide adoption, electrolysis industry is also under development and growth in the industry is required. IEA Net Zero Emission by 2050 scenario tracking of clean energy progress 2023 show that the installed electrolyser capacity grew by 20% while the manufacturing capacity of electrolyser grew by more than 25%. With project under development and expected commission date in the current pipeline by the end of 2023, capacity of electrolyser could reach to 3GW, which is four times increase compared to the 2022 capacity (IEA, 2023).

Efficiency of the electrolyser performance is dependent on various factors and operating condition, which is eventually affect the overall performance of the power to gas system. Components and operating condition effect on PEM electrolyser are identified Ahmed et al. (2022) as electrolyte membrane, catalyst layer for the oxygen evolution reaction and hydrogen evolution reaction, gas diffusion layer and bipolar plates. From operating conditions’ side, operating temperature is crucial which has effect on ionic conductivity leads to very current density and flow rate of electrolyte (Niroula et al., 2023).

Operating temperature of the electrolyser influence the performance of the electrolyser in various manners. When the temperature of the electrolyser increased, the required voltage can decrease while lead to improve the performance (El Jery et al., 2023). However, this event could lead to fast martial degradation, increasing the conductance of the electrolyte. Overtime maximizes the resistivity of electrodes and leads to offset the benefits. Considering the cost of the electrolyser, increasing temperature is not beneficial (Han et al., 2015). Faraday's efficiency is the measure of how effectively an electrolyser convert electrical energy into chemical energy. Theoretically, it is defining as the theoretical gas produced to actual gas produce in ideal operation of electrolyser. However, according to (Yodwong et al., 2020) both PEM and alkaline electrolysers exhibits that decreasing the electrolyte resistance leads to high crossover currents that will lower the faraday's efficiency.

Conductivity of the electrolyte strongly affects the performance of the electrolyser Matsuzaki et al. (2019) because it is responsible to facilitate the electrochemical reaction to happen. Conventional oxide-ion conducting materials have lower conductivity compared to proton conducting solid electrolyte however proton conducting electrolyte is more environmentally friendly (Matsuzaki et al., 2019), (Mojaver et al., 2020). Furthermore, temperature increase the mobility of ions increases, leads to high electrolyte conductivity and stable flux helps to raise the efficiency of the electrolyser (Rahman et al., 2008), (Topriska et al., 2015).

The electrolyse performance impacts significantly through gas accumulation, efficiency and contact resistance (Ebbesen et al., 2014), by proper control operating pressure has the capability to significantly improved system level performance of the electrolyser (Flura et al., 2021). SO, electrolysers kinetic and diffusion rates of the electrochemical reaction increase with pressure leads to improve the efficiency due to high mobility of ions' transfer of electrons and protons across electrolyte, also this increases the open circuit voltage, which boosts the performance (Hauch et al., 2020), (Jensen et al., 2016). Correspondingly, PEM and Alkaline electrolysers in several studies and experiments shows how the performance improved under high pressure conditions while stabilizing the performance of the electrolyser (Sood et al., 2020).

Catalyst material has a crucial impact on the performance of the electrolysis process¸ by the material, deposition methodologies, and the electrolysis technology. Based on the technology of electrolyser, catalyst that operates at low over potential helps with better electrical conductivity affect current distribution in the cell and improve the overall efficiency (Durst et al., 2014), (Arminio-Ravelo et al., 2020). Most common catalyst materials are noble-metal oxides, which are rare and costly however, non-noble metals like cobalt used in some cases as an alternative catalyst. Catalyst plays a role in both two half-cell reactions that are hydrogen and oxygen evolution reactions (Wang et al., 2021). Hence, use and selection of catalyst is crucial due the cost and the performance variation.

Current density of the electrolysers effect on its performance and efficiency evaluated in various studies and it is proven that different types of electrolysers have differentiate the effect of their performance with the current density with respectively to other factors as well. As well, increment of current density up to the potential level leads to production of green hydrogen with more competitive manner in the industries. Alkaline electrolysers at high current densities lead to increase cell voltage and decrease efficiency by high rate of generation of gas bubbles blocking the access to catalysts (Kou et al., 2020). Similarly, PEM electrolysers at high current densities decrease the efficiency of the operation with mass transport losses and internal ohmic resistance, which are main sources of irreversible (Carmo et al., 2013). However, solid oxide electrolyser as electrolysers operating at high temperature shows less sensitivity towards high current densities and in certain cases overall efficiency goes up as well when mass transport and reduce activation over-potentials (Hauch et al., 2008). Influence of current density in certain scenarios leads to improve efficiency. However, it is essential to consider other operation parameters to see the threshold level of current densities based on different scenarios.

Cell voltage is also another critical factor that has significant influence over the efficiency of the electrolyser operation, which represent the electrical potential required to drive the electrolysis reaction. Cell voltage, effect differently for different types of electrolysers. Owing to the increase over-potential and polarization losses in alkaline electrolysers at high cell voltage reduce the operation efficiency according to (Zeng & Zhang, 2010). Similar to alkaline, PEM electrolysers also exhibit high influence over the cell voltage and higher the cell voltage results to increase energy consumption and leads reduction of efficiency cause to elevated over-potential and resistance of membrane and electrodes (Carmo et al., 2013). However, SOC electrolysers show similar less sensitivity to cell voltage like the variation of current density due to high operating temperature. In that case low cell voltage is desirable to achieve high efficiency and minimise energy consumption (Hauch et al., 2008).

There are several factors that have comparatively low effect on the efficiency and the performance of the electrolyser based on the level of precision and operating conditions. According to Mazloomi & Sulaiman, (2012) to arrangement characteristics of the electrodes, unwanted side reactions, and electrical behaviour exhibits less impact compared to the temperature and electrolyte quality. Furthermore, anode and cathode pressure which has direct effect on mass transport impact is relatively low and pressure change in accepted range not significantly visible in the change of performance and efficiency of the electrolyser (Mamoon et al., 2015). Gas diffusion layer considers an essential component in several types of fuel cells and initial design of gas diffusion layer has critical impact on electrolyser efficiency since it is responsible for efficient transportation of gas. However, after finalized design small adjustments and changes will have negligible effect on the electrolyser performance (Omrani & Shabani, 2017). It is visible that the performance and the efficiency of the electrolyser exhibits interconnection of various factors as well as the type of the electrolyser. Even though despite the level of impact from different factors respectively, the combined influence of various factors has considerable effect on the overall performance and the effectiveness of the electrolyser.

Factors	Alkaline Electrolyser	PEM Electrolyser	Solid Oxide Electrolyser
Operating Temperature	Controlled low temperature, increase temperature under certain limits improve efficiency by reducing required voltage.	Controlled moderate temperature, increase temperature under certain limits improve efficiency by reducing required voltage.	High temperature facilitates uniform temperature distribution and offer higher efficiency.
Electrolyte Conductivity	-Liquid electrolyte: accommodate high conductivity. -Required high conductivity for efficient ion transport	-Proton exchange membrane: controls the conductivity -Effects ohmic losses	-Solid oxide material: Supports to ion conductivity.
Catalyst material	-Nonprecious metals -Moderate effect	-Precious metals -High effect with stability control	-Ceramic materials -High effect with contributing to stability
Catalyst Activity	Low to moderate	High	High
Current Density	High current density can improve efficiency but leads over potential and reliability.	High current densities increase the efficiency with low over potential and rapid response.	High current densities achieved better efficiency even though leads to increase energy consumption.
Cell Voltage	Operates at high cell voltage, to improve efficiency cell voltage could lower.	Operate at low voltage, high current density with low cell voltage	Due to high temperature possible to achieve high

		provides better efficiency.	efficiency at low cell voltages.
Electrode Characteristic	Effect over potential and efficiency, Nickel based electrode improve the stability and efficiency.	Even though the platinum group metal expansive reduce over potential and improve efficiency	High operating temperature requires robust material and by controlling ion transport contribute to the efficiency.

Table 5: Factors effecting different types of electrolyser

Therefore, understanding the impact of various factors on electrolyser efficiency and performance is a complex process. In the calculation of electrolyser efficiency there are several methods being used in different studies Faraday efficiency, energy efficiency, and voltage efficiency.

$$\text{Faraday Efficacy} = \frac{\text{Actual Gas Production (mol)}}{\text{Actual Gas Production (mol)}} \text{X}100\%$$

Equation 2: Faraday efficiency

Faraday efficiency is one of the key methods to evaluate the performance of the electrolyser performance. Based value as expected gas production according to the Faraday's law to the actual gas production ratio the efficiency of operation calculates. This measure indicates the efficiency of conversion of electrical energy into chemical energy. Several studies done based on Faraday's method on various applications across different electrolyser types (Ulleberg, 2003).

Energy efficiency is a concept that considers the ratio of total electrical energy input to useful chemical energy output. Energy efficiency reflects the efficiency of the electrolyser system

$$\text{Energy Efficacy} = \frac{\text{Chemical Energy Output (J)}}{\text{Electrical Energy Input (J)}} \quad \text{X100\%}$$

Equation 3: Energy efficiency

highlighting several critical metrics like operating voltage, operating pressure and emphasize the importance of improving critical factors in the development of the performance of the electrolyser (Jia et al., 2016). As well, Burhan et al. (2018) addressed the system design optimization of energy efficiency to achieve desirable efficiency and Persson et al. (2020) address how energy efficiency parameter addresses various challenges in the modelling and development phase while maintaining the efficiency levels.

The voltage efficiency is denoted by the ratio between theoretical cell voltage and actual cell voltage. Theoretical voltage is the ideal case of operation without any losses in the specific electrolyser type and theoretical cell voltage value is the applied voltage to perform electrolysis in certain operating conditions under several losses (Moreno-Hernandez et al., 2017). Studies emphasize the importance of voltage efficiency when changing parameters and how that effect vary based on the type of the electrolyser (Sun & Hsiau, 2019), (Patru et al., 2019).

$$\text{Voltage Efficacy} = \frac{\text{Actual Cell Voltage (V)}}{\text{Theoretical Cell Voltage (V)}} \quad \text{X100\%}$$

Equation 4: Voltage efficiency

Current efficiency is concentrated on the efficiency of use of charge in the electrolysis process which based on the electrochemical process performance. Current efficiency ratio is developed with the theoretic charge requirement according to the Faraday's law to the actual charge requirement to produce specific quantities of hydrogen (Patru et al., 2019).

$$\text{Current Efficacy} = \frac{\text{Actual Charge Passed (C)}}{\text{Theoretical Charge Passed (C)}} \text{X100\%}$$

Equation 5: Current Effiency

5.2 Power to Gas conversion using fuel cells stage

The fuel cell technology is known as clean and efficient technology used to convert green hydrogen to electricity energy. Fuel cell technologies enables the direct transformation of chemical energy (green hydrogen) to electrical energy (Liu, 2023). Widespread adoption of renewable energy sources with large scale electrolyser systems to produce green hydrogen at an economical viable rate encourages the integration of fuel cells to produce clean electricity and support the energy security. However, advancement in materials and design procedures of fuel cell parallel with electrolyser technology taken the focus of research to embrace the technical readiness of green hydrogen as the alternative to replace fossil fuels and advantage in several applications (Fatih et al., 2008) (Staffell et al., 2019).

According to (Cebolla & Davie, (2019) Global, installed large stationary fuel cell systems that are being used for distributed generation and combined heat power applications. More than 800MW of systems are installed globally, while United States and South Korea accounting for the largest portion. Market of the fuel cell power generation system is dominated by Molten Carbonate Fuel Cell (MCFC), Solid Oxide Fuel Cell (SOFC), and Phosphoric Acid Fuel Cell (PAFC). However, PEM and Alkaline have limited share which is contrary to electrolyser market. Although PAFCs have shown strong growth rates over the past few years, MCFCs still hold the largest share and there are also upcoming projects employing MCFC technology (Cebolla & Davies, 2019).

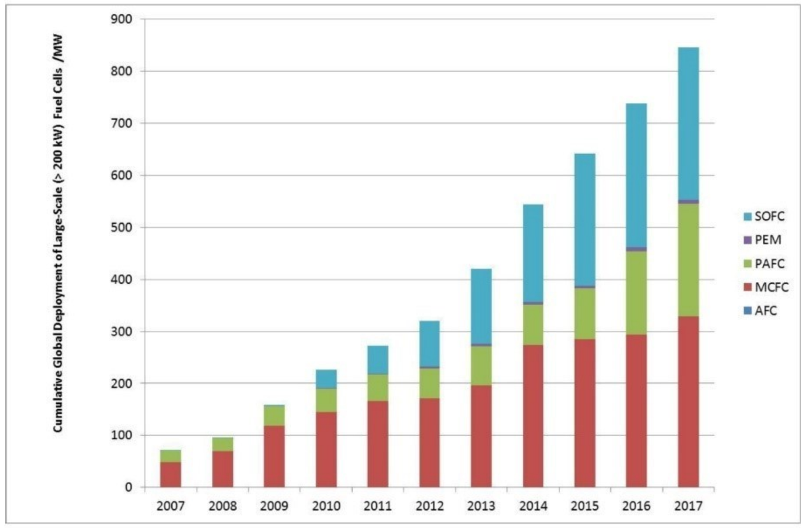


Figure 45: Cumulative global development of large-scale stationary fuel cells (Ronnefeld et al., 2019)

Operation performance and efficiency of the fuel cell influenced by various factors in different levels at different operating conditions. Like electrolysers, fuel cells' performance and efficiency effect by the type of the fuel cell, operation condition, and multitude of factors such as fuel quality, catalyst performance, mass transport, water management, pressure, operating current density, (Winkler et al., 2010) (Wang et al., 2011).

Temperature effect on fuel cell performance and efficiency mainly depend on the fuel cell typical operating temperature. For example, SOFC, MCFC which operate at high temperatures, are highly efficient and less sensitive to contamination (Li et al., 2019). In contrast PEM, Alkaline fuel cells as relative low operating temperature fuel cells even though the increased temperature leads to ionic conductivity, which increase the efficiency of the fuel cell, due to other factors such as reactant gas relative humidity, reaction pressure and challenging thermal management affect the overall efficiency of the fuel cell (Ma & Cai, 2022). Thus, it is evident that the different types of fuel cells demonstrate varying efficiencies to temperature changes. In addition to efficiency, temperature also affects fuel cell lifetime, start-up time, output range, robustness, etc.

When understanding the influence on the efficiency of fuel cells by the quality of fuel, it is important to consider the quantity of impurities which determine purity levels of hydrogen. The quality requirement for fuel cell determined based on the type, electrical efficiency, size of the fuel cell, and operation temperature (Staiger et al., 2017). According to Murugan & Brown (2014), the presence of impurities such as carbon monoxide leads to dilute the fuel and creation of diffusion barrier, catalyst deactivation, and in PEM slowdown of proton transfer speed are caused to reduce the efficiency of the system. A study emphasizes the importance of the purity of hydrogen to maintain a stable and efficient power output when varying the electric response in the load change (Doi et al., 2013). The severity of the effect cause due to the purity of the fuel depends on the type of the fuel cell and in general the high temperature fuel cell shows low sensitivity compared to moderate and low temperature fuel cells.

Catalyst commitment for reactions at an anode- hydrogen oxidation (HOR) and at the cathode- oxygen reduction reaction (ORR) significantly influences the overall efficiency and performance of the fuel cell. Catalyst works to enhance the oxygen reduction reaction, which is slower process than the hydrogen oxidation reaction, but both reactions are actively important for the fuel cell operation (Ejikeme et al., 2016). Therefore, the two reactions enhance the reaction kinetic of the overall process while reducing the overpotential (extra voltage requirement for the electrochemical reaction) with the suitable catalyst material (Nørskov et al., 2004). The choice of catalyst is critical since catalyst material must facilitate strong support for the reactions while maintaining better durability. However, to achieve these requirements is challenging in some fuel cell type since the cost of an ideal catalyst material hinders the commercialization (Du et al., 2016).

Water management of fuel cell is the crucial and complicated factor that linked with heat management, electrode saturation levels and control systems of fuel cells which leads to affect the performance, efficiency and durability of the fuel cells. Additionally, changes in operating conditions such as humidity, temperature, and pressure highly affecting the balance of water in fuel cells (Weber & Newman, 2004). Water management in fuel cell comes to action in various ways since it has effect on fuel cell performance from different dimensions. Maintaining membrane hydration and control humidity, controlling water vapour to avoid water condensation in gas channel and smooth product flow, prevent excessive water collection at the cathode and anode, which could impact the performance due to potential flooding and, control temperature for water vapour content is identified as critical factors affect the fuel cell performance end efficiency with the management of water process (Zhou et al., 2023) (Wang et al., 2021).

Mass transportation process refers to the movement of reactant gases, which are hydrogen and oxygen to the respective locations, optimal proton transportation and removal of excess water. Therefore, mass transportation is vital to ensure the smooth operation while achieving better efficiencies in the fuel cell operation. Efficiently delivering hydrogen and oxygen to anode and cathode where the electrochemical reaction take place without concentration degradation to avoid limitations in the rate of the reaction ensure the optimal performance of the fuel cell (Jaouen et al., 2002). Minimizing ohmic losses important to maintain the efficiency of the fuel cell, then effective transport of proton enables high proton conductivity and as we discussed earlier excess water removal that is also one dimension of mass transportation, which is important to endure the efficiency of the fuel cell performance (Gao et al., 2023).

Similarly, it is difficult to categorize any factors that are completely negligible for fuel cell performance. However, there are some factors identified as have very small effect on the fuel cell performance and efficiency compared to the other factors. According to Wang et al. (2011) Gas diffusion layer use in fuel cell in particular, PEM fuel cell membrane thickness has relatively low effect on the fuel cell performance and the efficiency. Furthermore, some factors that have major effects on the efficiency and the performance of some types of fuel cells have less effect on some other type of fuel cell. For example, temperature has a great impact on PEM fuel cells, while the impact of temperature on SO fuel cells is negligible. Similarly, hydrogen purity depends on the advancement of the technology and the design of the fuel cells, modern fuel cells come with a higher acceptable threshold for hydrogen purity compared to the old designs (Jaouen et al., 2002). Therefore, it is evident that the efficiency and the performance of the fuel cell from various factor depend on the type of the specific fuel cell, the other operating parameter, and interconnection of different factors.

5.3 Case studies and real-world scenarios

In the context of power to gas to power case studies, demonstrate the vital importance of the improvement and support in performance of the solution. The widespread adoption of this innovative solution associate with the distributed power generation as well as backup power requirements necessitate continuous improvements in the operation efficiency. A thorough examination of academic literature reveals the prevailing condition of the system power lagging in enhancing system scalability and cause high conversion losses.

Case	Case Study	Type		Capacity		Efficiency		
		Electrolyser	Fuel cell	Electrolyser	Fuel cell	Electrolyser	Fuel cell	Overall
Case 1	Efficiency analysis of a solar photovoltaic array coupled with an electrolyser power unit: a case study	Bipolar Alkaline	PEM	5kW	1kW	70%		0.93-5.01%
Case 2	Electrolyzer Performance Analysis of an Integrated Hydrogen Power System for Greenhouse Heating. A Case Study	Alklaine Barometric	PEM	2.5kW	2kW	45-67%		
Case 3	Development of renewable energy based green hydrogen and oxygen production and electricity generation systems for sustainable aquaculture	PEM	PEM					12.20%
Case 4	Solar electricity storage through green hydrogen production: A case study	PEM	PEM	3kW		50-70%		19%
Case 5	Pilot-scale hydrogen energy utilization system demonstration: A commercial building case study on on-site green hydrogen production and use	PEM	PEM	26kW	14kW			27%

Figure 46: Case Study Comparison (Appendix 1)

Study 1 - Efficiency analysis of a solar photovoltaic array coupled with an electrolyser power unit: a case (Shiroudi et al., 2015)**:**

Study presents an efficiency analysis of a solar photovoltaic array couples with an electrolyser power unit with comprehensive review of the solar hydrogen system. Study use mix of empirical method, efficiency calculation and data analysis. Observing the variation in solar radiation intensity with hydrogen production efficiency and overall efficiency of the system. The 5kW electrolyser system incarnate with 10Kw solar PV system and 1.2Kw PEM fuel cell system. Since study has the main focus on the solar radiation intensity the other factors effecting the total efficiency such as electrolyser performance are not highlighted in the finding. However, the key finding of energy efficiency of the overall system which ranges from 0.93% to 5.01% reflect the idea that the use of renewable energy in power to gas to power overall efficiency is relatively low compared to other backup power and distributed power sources.

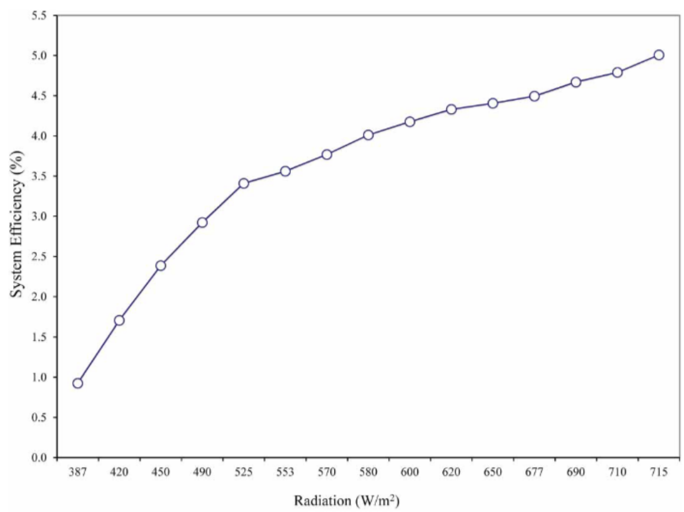


Figure 47: Dependence of system efficacy upon the solar radiation intensity (Shiroudi et al., 2015)

Study 2 - Electrolyser Performance Analysis of an Integrated Hydrogen Power System for Greenhouse Heating. A Case Study (Pascuzzi et al., 2016):

Integration of hydrogen power system for green house heating investigated in this case study and observed the factors effecting the performance utilizing mathematical model and empirical method. Mathematical model evaluates the performance of the alkaline electrolyser as the operating voltage as a function of current density and other factors like temperature, pressure and concentration. Furthermore, evaluated the consider the other external factors like solar radiation and location of the project. Empirical method supports the study with observed measurement of the project different factors in different operating conditions. Which includes the measurement of hydrogen production rate, power requirement of electrolyser, and electrolyser Faradic efficiency.

The nonlinear relationship of energy efficiency of the electrolyser and hydrogen production rate (Increment of 45% energy efficiency in the hydrogen flow rate range of 0.05-0.5 Nm^3h^{-1}) highlight the dynamic and variable nature of the system operation with reflecting the influence with multiply of multiple factors on the system efficiency.

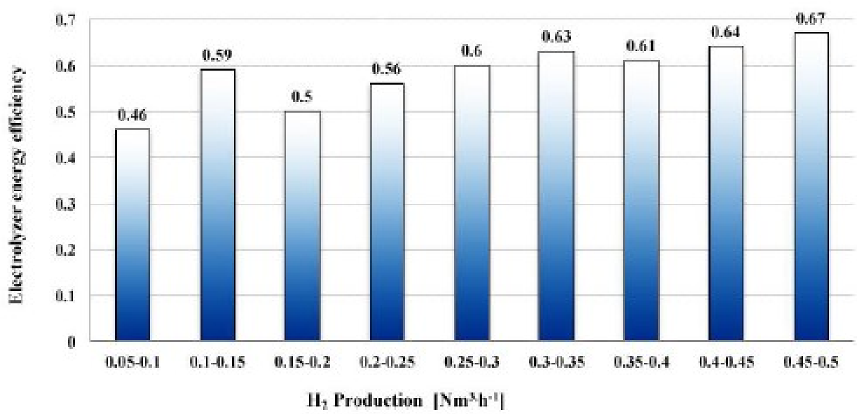


Figure 48: Electrolyser energy efficacy Vs. hydrogen production (Pascuzzi et al., 2016):

However, electrolysers operate in the transient state continuously over the whole test period and did not reach the steady state condition. Similar to the (study 1) great fluctuation of solar PV radiation affects the stable power input to the electrolyser system. Study specifies the consideration of fuel cell efficiency contribution likely considered to the system overall efficiency and performance is not available in the study. Due to the linear effect of various factors and change of solar radiation effect understood as the barrier to achieve steady state operation and to suggested to install a battery system as a short-term energy buffer to stabilize the electrolyser input power to improve the system.

Study 7 - **Development of renewable energy based green hydrogen and oxygen production and electricity generation systems for sustainable aquaculture** (Erdemir & Dincer, 2024):

Study present system development, system assessment and comprehensive analysis of the findings with simulations and several tools. Matlab Simscape utilized to assess the performance and efficiency of the system. Assess of both energy and exergy efficiency of renewable based green hydrogen and oxygen production system and fuel cell power supply for sustainable aquaculture. Study is strengthening with empirical work done to evaluate the performance of the proposed system with investigation in five cities from different countries. Factors that affect the performance of the system are identified as solar radiation input, solar plant capacity, ambient temperature, system design and control, and operational conditions.

$$Effiency_{en} = \frac{\sum_t W_{net} + m_{O2}h_{O2}}{\sum_t E_{in}}$$

Total system exergy efficiency observed reached 65% demonstrates the effectiveness of solution in aquaculture system. Proposed system intention to identify the possibility of operating aquaculture activities fully depend on green energy system. The system is evaluated under location differentiation to observe how contribution to sustainable development according to the United Nation's Sustainable Development Goals (SDGs). Capital cost, lack of quality and trained personnel, importance of environment impact evaluation, and economic analysis are highlighted as challenges. Therefore, study suggests that it is important to address this lack of confident areas prior to commercialization of the solution.

Study 18 - Solar electricity storage through green hydrogen production: A case study (Fopah-Lele et al., 2021):

Application of green hydrogen production as the solar electricity storage potential investigate in the study. Development and validation of a model with numerical and experimental observations to assess the technical and economic feasibility. This study is also depending on both empirical and non-empirical methods. The characterization of solar resources and validation of the model depends on experimental data collection which is empirical. On other hand study, rely on non-empirical theoretical model and numerical simulations in performance analysis of PV system, PEM electrolyser hydrogen production, and economic analysis.

Study present breakdown of efficiency in segment level with overall efficiency evaluation. PV module efficiency was around 17%-20% which over the manufacturer given value, 13%. Electrolyser efficiency oscillate between 50% to 70% also, DC/AC converter indicate the average efficiency of 85%.

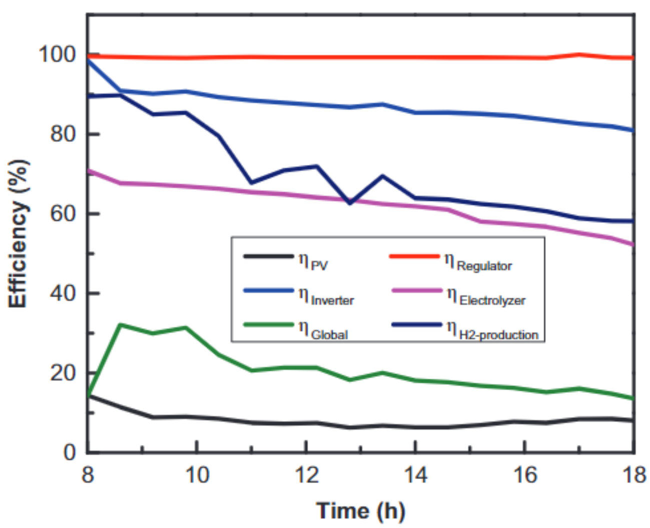


Figure 49: Different elements efficienies (Fopah-Lele et al., 2021)

The overall efficiency varies between 65% to 85%. However, the average overall efficiency is around 19%. Efficiency measurement methods involves the calculation of annual ratio between energy consumed by electrolyser to produce hydrogen and total energy produced by PV units. Most importantly study emphasise the lack of information in efficiencies, lack of knowledge in storage technologies, and techno-economic factors lags the development of effective and efficient solar hydrogen production system.

Study 20 - Pilot-scale hydrogen energy utilization system demonstration: A commercial building case study on on-site green hydrogen production and use (Segawa et al., 2022):

Study focuses on practical application of pilot scale green hydrogen utilization system for energy requirement for building. Investigated the performance of the system under various weather conditions and carbon dioxide emission reduction capabilities. Evaluation of practical application on demonstration scale pilot project, the study follows empirical methodology. Comparison evaluation of the improved system with PV only system and relocating to see the effect of weather on the system are main objective of the project.

The system efficiency is calculated comparing the amount of electricity consumed by the system with amount of hydrogen produce. Overall efficiency of P2G-G2P process calculated as 27%. However, it is mentioned that when the efficiency value calculates unit of hydrogen production and fuel cell power assumed based on the market values in 2020. Another major target is to identify how this proposed advance system contribute to reduce carbon dioxide emission. From the results it is identified that the proposed system reduces carbon dioxide emission by more than 12% compared to PV only system.

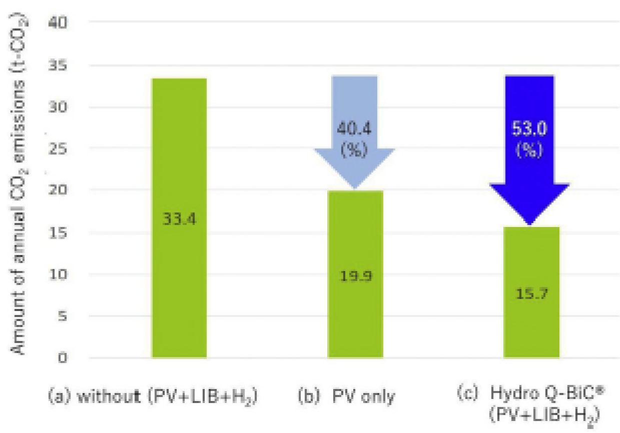


Figure 50:Annual CO2 emission comparison (Segawa et al., 2022):

Study identified several challenges in the implementation of this solution. Weather changes leads to drastic effect on the performance by reducing PV output and leads to utilize grid power to produce hydrogen. Therefore, study point out the importance of having real time monitoring, prior simulation, integration of heat utilization system and improve hydrogen storage capacity. Overall findings promote and encourage the utilization of hydrogen energy system in the building industry.

Scenario 1 - GenCell and Enapter integrate alkaline fuel cell and electrolyser (GenCell, 2020), (Sampson, 2020)

The project utilizes Enapter 5 kW of electrolysers and GenCell 5 Kw of fuel cells. Project is installed and tested at GenCell headquarters in Israel. The modular and scalable anion exchange membrane electrolysers from Enapter which produce hydrogen at the rate of 500NL/hour per module. Electrolyser form Enapter comes with 80% of efficiency. The fuel cell from GenCell capable of converting hydrogen to electricity at an efficiency of 52%. Therefore, according to GenCell they achieved the overall efficiency of 41.6%. Furthermore, it was mentioned that the project was successful in performance wise as well as electrolysers produce high quality good amount of hydrogen too. This test project demonstrates the capability to utilize hydrogen fuel cells for hybrid and backup power solutions to strengthening the power requirements in sustainable way.

Scenario 2- New Research Collaboration to Advance Megawatt-Scale Hydrogen Fuel Cell Systems (NREL, 2022):

National Renewable Energy Laboratory (NREL) and Toyota build up a research-based collaboration to identify and demonstrate the possibility of megawatt scale hydrogen fuel cell system. The project is located at NREL's Flatirons campus in Arvada, Colorado, USA.

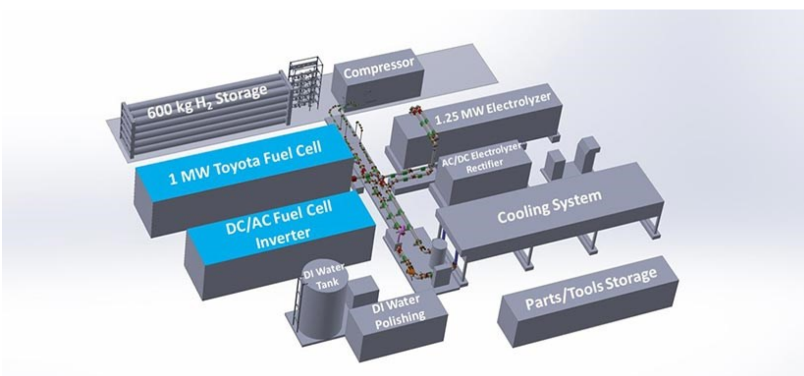


Figure 51: Plant layout (Image by Jeff Mohr, NREL)

The project contains 1.25MW PEM electrolyser system and 1MW PEM fuel cells. The solution is capable of producing up to 600kg of hydrogen per day and stored in the 600kg hydrogen storage system. Electrolyser has efficiency of 55% at production rate of 22kg/hr and total power consumption of 1.33MW. Fuel cells when consuming hydrogen at the rate of 60kg/hr and producing 1MW of net power exhibits efficiency of 50%. These values are based on the storage 600kg of Hydrogen which provides buffer of 27 hours and 10 hours respectively for electrolysers and fuel cells. AC/AC round trip system efficiency is calculated as approximately 27% under specific operation conditions. Considering the project; performance in real world conditions, acquiring necessary components and technology and achieving grid stabilization are identified as major barriers.

Scenario 3 - H2 Grid for industrial energy independence – Germany (Hensoldt, 2023), (Enapter, 2023)**:**

The project is built in standard 20ft ISO container which is possible to relocate easily. The project being led by the German Federal Ministry for Economic Affairs and Climate Action (BMWK) aiming to develop hydrogen infrastructure in Germany. Project consist of alkaline electrolysers which can produce up to 4Nm^3 of hydrogen per hour (20kW). For hydrogen production renewable power supplied to electrolysers by solar PV system with plan of producing 2.6-3.3kg of hydrogen per day. Hydrogen storage is with the capacity if 34kg at 500 bar. In the electricity generation side project uses a 60kW of fuel cells from PowerCell Sweden. The project expects 60% energy autonomy and from the environment conservation perspective reduction of 33 tons of CO2 emission yearly. In addition to handle surplus of renewable energy generation system contain short term battery storage of 96kWh. However, the system efficiency calculation method is not clearly present, but the overall energy efficiency of the hydrogen value chain estimated to be around 50%. Apart from regenerating electricity using the produce hydrogen solution includes refuelling station with refiling capacity of 1000 kg of hydrogen in 30 minutes.

Scenario	Type		Capacity		Efficiency		
	Electrolyser	Fuel cell	Electrolyser	Fuel cell	Electrolyser	Fuel cell	Overall
Scenario 1	AEM	Alkaline	5kW	5kW	80%	52%	41.20%
Scenario 2	PEM	PEM	1.25MW	1 MW	55%	50%	27%
Scenario 3	Alkaline	PEM	20kW				50%

Figure 52: Scenario Comparison

6 Discussion and Strategic Approach

6.1 Discussion

Utilizing existing data delves into the comprehensive analysis of P2G-G2P sector. Study presents an understanding of green hydrogen production, use of green hydrogen to electricity generation including green hydrogen market, electrolyser technology and fuel cell technology. In these sections reviewing most recent, existing research papers, case studies and real-world scenarios to gain through understanding.

Market growth and trend

The study recognizes the substantial market growth in green hydrogen sector with several key driving factors effecting the growth. The growth of market predictions has variation (Wappler et al.,2022) based on the consideration of different factors in each scenario. According to Acil Allen report under low level consideration around 4% CAGR is visible during 2030 -2050-time period. Also, every different scenario exhibits the growth of green hydrogen market underline that importance of addressing diving factors accordingly.

Efficiency consideration

Cost of renewable energy is identified as the major effect of green hydrogen production process. However, efficiency consider as one of the pivotal factors that influence the P2G-G2P solution (IRENA 2020). The understanding and examination of electrolyser and fuel cell efficiency conduct with a review of case study and real-world scenarios. Study identified and highlighted the importance of incorporation of academic studies with real world scenarios Figure 54. There is room for improvement in efficiency in the overall process chain. For low voltage product manufacturers and other supporting sectors, it is important to understand the status of the technology.

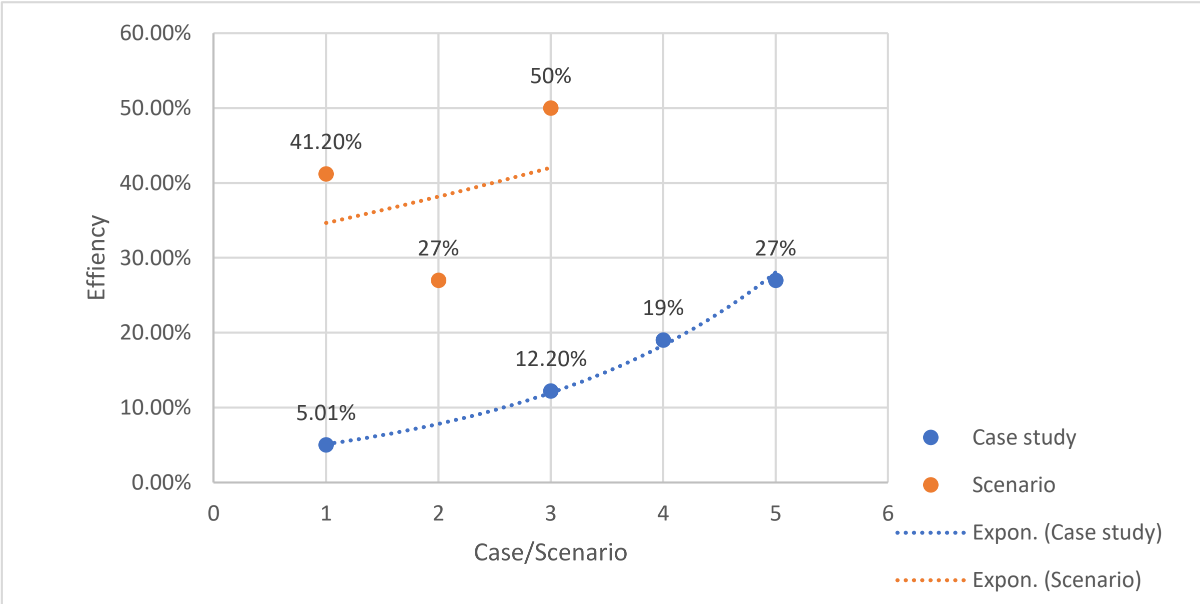


Figure 53: Efficiency comparison (Case study vs. Real world scenario)

Plan the improvements and development required from their products based on the market situation. If there is a gap between real world scenarios and academic studies, application and contribution of academic studies to the industry face difficulties.

6.2 Strategic approach

Based on the study findings and interaction with service providers in the green hydrogen industry identified the various stakeholders.

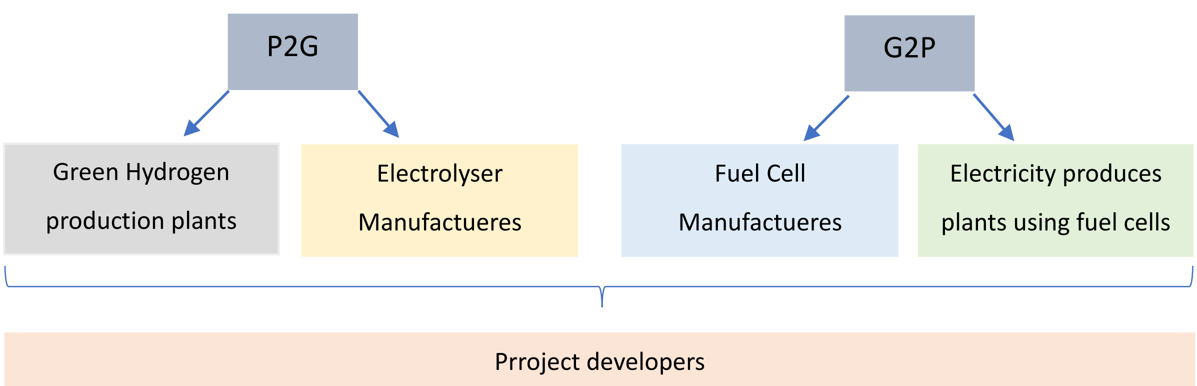
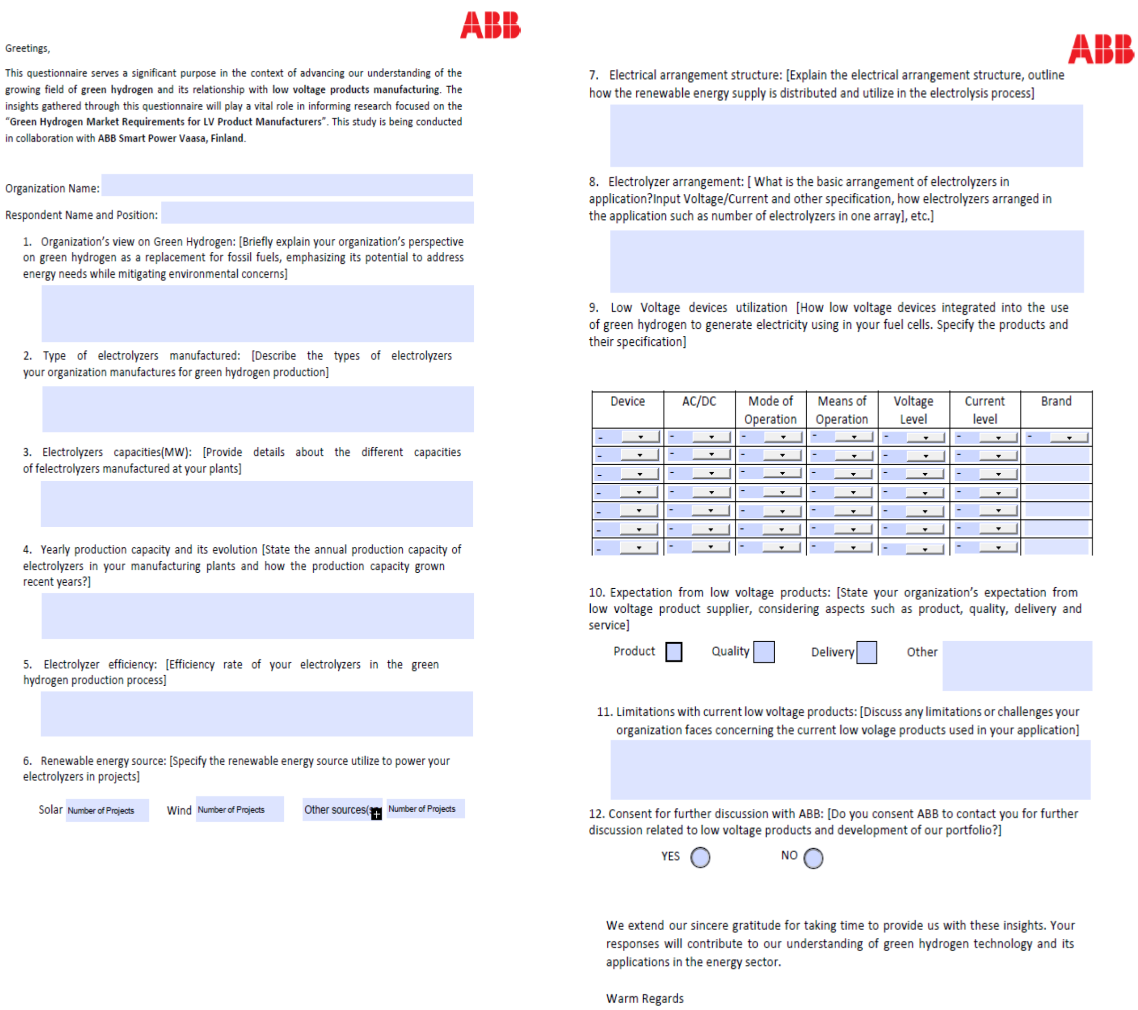


Figure 54: Stakeholders involved in P2G-G2P (Compiled by author)

Figure 55, illustrate the identified key stakeholders involved in the P2G-G2P segment of green hydrogen. As an integral part of the research work a questionnaire form has been designed to collect and monitor green hydrogen market concerning technology, efficiency, pricing and trends. Development of questionnaire to assess market trends and values serve industry in decision making (Tvaronavičienė et al., 2014). The use of questionnaire to collect technology details, efficiency, operation and market trends in specific industry can be highly beneficial. Therefore, considering the various stakeholders involved questionnaires crated with the goal of collect details from the real-world scenarios. The details collected can be utilize in industrial professions



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Greetings,

This questionnaire serves a significant purpose in the context of advancing our understanding of the growing field of **green hydrogen** and its relationship with **low voltage products manufacturing**. The insights gathered through this questionnaire will play a vital role in informing research focused on the **"Green Hydrogen Market Requirements for LV Product Manufacturers"**. This study is being conducted in collaboration with **ABB Smart Power Vaasa, Finland**.

Organization Name:

Respondent Name and Position:

1. Organization's view on Green Hydrogen: [Briefly explain your organization's perspective on green hydrogen as a replacement for fossil fuels, emphasizing its potential to address energy needs while mitigating environmental concerns]
2. Type of electrolyzers manufactured: [Describe the types of electrolyzers your organization manufactures for green hydrogen production]
3. Electrolyzers capacities(MW): [Provide details about the different capacities of felectrolyzers manufactured at your plants]
4. Yearly production capacity and its evolution [State the annual production capacity of electrolyzers in your manufacturing plants and how the production capacity grown recent years?]
5. Electrolyzer efficiency: [Efficiency rate of your electrolyzers in the green hydrogen production process]
6. Renewable energy source: [Specify the renewable energy source utilize to power your electrolyzers in projects]

Solar Number of Projects Wind Number of Projects Other sources(Number of Projects

ABB

7. Electrical arrangement structure: [Explain the electrical arrangement structure, outline how the renewable energy supply is distributed and utilize in the electrolysis process]
8. Electrolyzer arrangement: [What is the basic arrangement of electrolyzers in application?Input Voltage/Current and other specification, how electrolyzers arranged in the application such as number of electrolyzers in one array], etc.]
9. Low Voltage devices utilization [How low voltage devices integrated into the use of green hydrogen to generate electricity using in your fuel cells. Specify the products and their specification]

Device	AC/DC	Mode of Operation	Means of Operation	Voltage Level	Current level	Brand
-	-	-	-	-	-	-
-	-	-	-	-	-	
-	-	-	-	-	-	
-	-	-	-	-	-	
-	-	-	-	-	-	
-	-	-	-	-	-	
-	-	-	-	-	-	

10. Expectation from low voltage products: [State your organization's expectation from low voltage product supplier, considering aspects such as product, quality, delivery and service]

Product ☐ Quality ☐ Delivery ☐ Other

11. Limitations with current low voltage products: [Discuss any limitations or challenges your organization faces concerning the current low volage products used in your application]
12. Consent for further discussion with ABB: [Do you consent ABB to contact you for further discussion related to low voltage products and development of our portfolio?]

YES ○ NO ○

We extend our sincere gratitude for taking time to provide us with these insights. Your responses will contribute to our understanding of green hydrogen technology and its applications in the energy sector.

Warm Regards

Figure 55: Questioner based on electrolyser manufacturer (Appendix 2)

to adjust according to the requirements in the sector. As well as serve academic studies to monitor and compare the current status when proceeding to laboratory level experiments.

6.3 Future Development

To obtain the full potential of collection of data using questionnaire there must be proper mechanism of evaluation of data and continues update as well. Therefore, I believe use of questionnaire template to monitor the requirement and trends in the market is necessary. Development of program to analysation of collected data to plot the status and trends in the market. This model would cater benefited approach to industrial professionals in decision making related to technical improvements as well as marketing strategies.

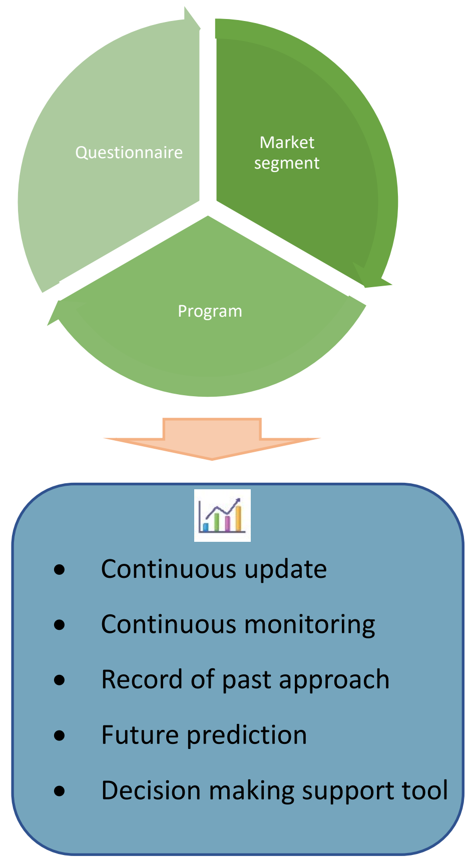

Figure 56: Future development plan

7 Conclusion

Production of green hydrogen using electrolysis and use this green hydrogen to produce electrical energy using fuel cell systems has potential to play a significant role in the future energy mix. Even though this interesting technology to store excess renewable energy, hindered due to several challenges. Identify market value influence from efficiency of the overall process, it is pivotal to consider various factors impact the efficiency of the electrolyser and fuel cells systems.

This thesis considers understanding the blooming technology using hydrogen in power generation systems. Hydrogen acting as power storing units and distribution hybrid power supply systems which is known as combination of P2G and G2P solutions of hydrogen. Major advantage of this solution is this method is being fully carbon free. However, as a supporting sector like low voltage product manufacturer, does not have certain knowhow to proceed their developments to bring advancement to the solution. This thesis provides comprehensive exploration of green hydrogen production to generation of electricity. The study has highlighted key aspects of green hydrogen, operational intricacies of electrolysers and fuel cells, conducting market analysis and identifying critical factors influencing efficiency of the system.

As the output of the research work the questionnaire from serve as a tool to support the data collection. Enabling the smooth interaction with stakeholders in identifying the requirement and monitoring the market. This mechanism enables the possibility to understand the market behaviour and refine strategies to evolve industry dynamics.

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Appendices

Appendix 1.

#	Study	Brief the study	Electrolyzer Type	Electrolyser Capacity	Efficiency Measurement Method/ Model	Electrolyser Efficiency (%)
1	Efficiency analysis of a solar photovoltaic array coupled with an electrolyser power unit: a case study	Study investigate a solar hydrogen energy system. Demonstrate the feasibility of using hydrogen as solar energy storing medium and evaluvate system overall performance.	Bipolar Alkaline from Hydrotechnik (Germany)	5kW	**Overall eff** $\eta_{overall} = \frac{Q \cdot E}{S \cdot A}$, A- PV array total surface (m^2) Q- hydrogen	70%
2	Electrolyzer Performance Analysis of an Integrated Hydrogen Power System for Greenhouse Heating. A Case Study	Study investigate a greenhouse heating suystem integrating solar panels, electrolyser, hydrogen storage, fuel cell and geothermal heat pump. Examined the electrolyser's energy efficiency during winter season.	Alkaline barometric electrolyser	2.5kW	Energy efficiency/Faradic efficiency	Energy efficiency: 45%-67% Faradic efficiency: higher than 90% for certain operational
3	Techno-economic Analysis of a More Efficient Hydrogen Generation System Prototype: A Case Study of PEM Electrolyzer with Cr-C Coated SS304 Bipolar Plates	Prototype use PEM electrolyser withthe aim to produce hydrogen more efficient and economically utilizing septic mixture and super strong magnets.	PEM	3.5kW	-	4.5 times more effficient than the hydrogen production systems in the world
7	Development of renewable energy based green hydrogen and oxygen production and electricity generation systems for sustainable aquaculture	Proposal for a renwabal driven system to produce hydrogen for power generation and oxygen for fish farm while aligning with sustainable goals	PEM		Overall efficiency= Net energy output/total energy input using energy and	
14	Flexible production of green hydrogen and ammonia from variable solar and wind energy: Case study of Chile and Argentina	Present techno-economic modl for flexible green hydrogen and ammonia production using solar and wind energy.	Alkaline		Assumed	70%
16	PERFORMANCE OF HYDROGEN PRODUCTION PROCESS USING SOLAR ENERGY	Investigate the solar driven water electrolyzer efficiency with impact of operational parameters	Alkaline		Energy Efficiency (hydrogen energy/input energy)	90%
10	Performance assessment of solar-powered high pressure proton exchange membrane electrolyzer: A case study for Erzincan	Investigate a solar powered high pressure PEM electrolyser for hydrogen production	PEM	-	System efficiency measured using dynamic model developed	
18	Solar electricity storage through green hydrogen production: A case study	Investigate the potential of hydrogen production for enegry storage using solar power	PEM	115L of Hydrogen/day and Operates within 45W to 300W power	Energy efficiency	50%-70%
19	Dynamic Investigation and Optimization of a Solar-Based Unit for Power and Green Hydrogen Production: A Case Study of the Greek Island, Kythnos	Study propse a solar power energy system for electricity and green hydrogen production	PEM	-	Energy efficiency & exergy efficiency	-
20	Pilot-scale hydrogen energy utilization system demonstration: A commercial building case study on on-site green hydrogen production and use	Evaluvated the affectiveness of green hydrogen energy utilization sysetm to reduce CO_2 emission in building without only PV system	PEM	26kW		

#	Overall Efficiency	Operational temperature °C	Operational voltage	Operational current	Electrolyte	Cell/Stack Type	Energy Source	System Configuration/ Scale	Hydrogen purity	Technological Advancements
1	$\eta_{overall} = \frac{Q \cdot E}{S \cdot A}$ Range of 0.93%-5.01	PV cell: 34°C-40°C	25V max	From 0-250A	28% alkaline (KOH) solution	10 series connectedd electrolyser stack	Solar Energy -10kW	Small scale prototype energy system	99.99%	Study aimed to demostrate the thechnical feasibility of using hydrogen as a solar energy storage medium and use of fuel cells as the electricity generation using.
2	-	Upto 80°C	62.02V	40A	stationary 25%-30% wt KOH solution	33 biplora circular cell connected in series	Solar Energy- Capacity not specified but mentioned that electrolyser	Small scale prototype energy system	High	>Improvement f the battery bank aranagement to improve electrolyser efficiency. >Optimizing electrolyser operating parameters such as temperature, pressure and current density.
3	-	70°C-80°C	10V	30A	15% KOH solution	Consist of 12 cells		Small scale prototype energy system	-	Uitilizing Cr-C coated SS304 biplora plates, use of septic mixyure (urea, amonia, methyl alcohol) as a cost effective oprtion, Placing strong magnets on the outer surfac of the electrolyser cells to improve performance
7	Overall system efficiency -12.2% Exergy efficienc y- 66%	80°C					Solar - 50% of the capacity use in rlectroyser system	Small scale prototype energy system - Simulation Model	99.99%	1. Remote monitoring and control 2. Use Oxygen to improve the overal efficieny factor
14							Chlie: Wind- 6.8GW, Solar-1.5GW Argentina- Wind 640MW	Small scale prototype energy system		>Discuss about hybridization of Solar and Wind in green hydrogen and ammonia production
16	1.67%	-	38.07V	8.89A	30% KOG solution		Solar-225W	Small scale prototype energy system	High	1. Direct supply of supply of electrical power from PV cell to the water electrolyser
10	11-12%						Solar	Small scale prototype energy system	99.99%	1. Use of high pressure electrolyser 2.Advance modeling and simulations
18	65%-85% and averagage overall efficiency 19%	70°C-100°C					Solar	Small scale prototype energy system - Simulation Model	99.99%	1. Optimization of same land sapce for total system 2. Improvement of sotage capacity to improve system performance
19	Energy efficiency - 14.52% Exergy efficiency - 15.48%	50°C-80°C					Solar	Small scale prototype energy system	99.99%	1. Combined solar thermal collector 2. Optimization of real world conditions
20	27%						Solar energy - 64.75kW	Pilot scale energy system		1. Use of Li-ion batteries and hydrogen production with fuel cell to convert back to electricity in the same project. 2. Real time control and onitoring

#	Amount of hydrogen produced	Cost of produced hydrogen	Economic Incentives	Operational Lifetime	Location	Published year	Technological Challenges	Fuel cell type	Fuel cell system capacity
1	$\eta_{overall} = \frac{Q \cdot E}{S \cdot A}$, change upon the solar output		Not speified, but supported by Ministry of Energy-Renwable Energy Orgainisation of Iran	-	Taleghan renwable energies site in Iran	2017	Not specified But it is visible the requirement of improvement in the performance to improve the efficiency	PEM	1kW
2	0.05Nm^3h^{-1} to 0.5Nm3h-1		-	-	University of Bari, Valenzano, Italy	2016	Irregularity of solar source	PEM	2kW
3	with 1MW- 6m^3/h		-	-	-	2019	Requirement of more cost effective and efficient bipolar plates, catalyst, method to seperation and purification of hydrogen gas	N/A	
7						2024	1. Flucuating availability of renewables 2. Resources availability, technical capability and economic viability to perform the operation.	PEM	
14					Chilie and Argentina	2020	1. Variability of renewable energy spources 2.Intermediate storge cost and challenges in prduction process	N/A	
16						2018	1. Empersize the losses at the PV cell, connecion wires, abd electrolysis process which create significant gap between electrolyser efficiency and overall efficiency	N/A	
10					Erzincan, Turkey	2019		N/A	
18	115L/day	Levelized cost of hydrogen 1.09€/m^3		25 years	Cotonou, benin	2021	1. Limited storage capacity 2. Low efficiency of the system 3. Intermittency of solar 4. System complexity and cost	PEM	3kW with 50% efficiency
19	2356.5kg/year	15€-20€/kg			Kythnos, Greece	2022	1. Lack of technology compitance in the integration of energy storage systems 2. Ensuring both economic viability and energy demand simultaniously	N/A	
20					Fukushima Japan	2022	1. Improved real time control system to eliminate hydrogen production with grid power when weather condition chnages and differ solar power generation.	PEM	14kW

Appendix 2: Question form for Electrolyser Manufacture

Greetings,

This questionnaire serves a significant purpose in the context of advancing our understanding of the growing field of **green hydrogen** and its relationship with **low voltage products manufacturing**. The insights gathered through this questionnaire will play a vital role in informing research focused on the **"Green Hydrogen Market Requirements for LV Product Manufacturers"**. This study is being conducted in collaboration with **ABB Smart Power Vaasa, Finland**.

Organization Name:

Respondent Name and Position:

1. Organization's view on Green Hydrogen: [Briefly explain your organization's perspective on green hydrogen as a replacement for fossil fuels, emphasizing its potential to address energy needs while mitigating environmental concerns]

2. Type of electrolyzers manufactured: [Describe the types of electrolyzers your organization manufactures for green hydrogen production]

3. Electrolyzers capacities(MW): [Provide details about the different capacities of felectrolyzers manufactured at your plants]

4. Yearly production capacity and its evolution [State the annual production capacity of electrolyzers in your manufacturing plants and how the production capacity grown recent years?]

5. Electrolyzer efficiency: [Efficiency rate of your electrolyzers in the green hydrogen production process]

6. Renewable energy source: [Specify the renewable energy source utilize to power your electrolyzers in projects]

Solar Number of Projects Wind Number of Projects Other sources(Number of Projects

7. Electrical arrangement structure: [Explain the electrical arrangement structure, outline how the renewable energy supply is distributed and utilize in the electrolysis process]

8. Electrolyzer arrangement: [What is the basic arrangement of electrolyzers in application?Input Voltage/Current and other specification, how electrolyzers arranged in the application such as number of electrolyzers in one array], etc.]

9. Low Voltage devices utilization [How low voltage devices integrated into the use of green hydrogen to generate electricity using in your fuel cells. Specify the products and their specification]

Device	AC/DC	Mode of Operation	Means of Operation	Voltage Level	Current level	Brand
-	-	-	-	-	-	-
-	-	-	-	-	-	
-	-	-	-	-	-	
-	-	-	-	-	-	
-	-	-	-	-	-	
-	-	-	-	-	-	
-	-	-	-	-	-	
-	-	-	-	-	-	
-	-	-	-	-	-	
-	-	-	-	-	-	
-	-	-	-	-	-	
-	-	-	-	-	-	
-	-	-	-	-	-	

ABB

10. Expectation from low voltage products: [State your organization's expectation from low voltage product supplier, considering aspects such as product, quality, delivery and service]

Product ☐ Quality ☐ Delivery ☐ Other

11. Limitations with current low voltage products: [Discuss any limitations or challenges your organization faces concerning the current low volage products used in your application]

12. Consent for further discussion with ABB: [Do you consent ABB to contact you for further discussion related to low voltage products and development of our portfolio?]

YES ○ NO ○

We extend our sincere gratitude for taking time to provide us with these insights. Your responses will contribute to our understanding of green hydrogen technology and its applications in the energy sector.

Warm Regards