Hydrogen Production and Application in The Energy Transition

Moses Jeremiah. Barasa Kabeyi
moseskabeyi@yahoo.com; mkabeyi@uonbi.ac.ke
Industrial Engineering Department, Durban University of Technology,
Durban South Africa

Oludolapo Akanni.Olanrewaju
oludolapoo@dut.ac.za
Industrial Engineering Department, Durban University of Technology,
Durban South Africa

Abstract

Global energy is a very significant energy with demand gradually increasing making it a key solution to tackle global greenhouse gas emissions and global temperature rise. Production technologies for hydrogen are commercially available, while some are still under development. In hydrogen is a renewable secondary energy source, and feedstock, and tool to meet greenhouse gas emissions targets and promote economic decarbonization. The unique properties of hydrogen make it a powerful enabler for energy transition, benefiting the energy system and end-use applications. Hydrogen gas has significant potential to play an important role in decarbonizing hard-to-electrify sectors of the economy, like long distance trucks in transport, aviation, and heavy manufacturing industries besides providing. Hydrogen and fuel cell technologies will enable this transition to a clean, low-carbon energy system resulting in greatly reduced greenhouse gas emissions and improved air quality. Green hydrogen energy provides clean energy, and the comprehensive utilization of hydrogen energy is crucial for the low-carbon transformation of the power sector. The production of hydrogen through water electrolysis powered by renewable energy reduces carbon emissions although it leads to an increase in demand for renewable energy generators. Appropriate planning of hydrogen storage can reduce the overall investment cost and promote a low carbon transition of the power system. Since hydrogen is a highly flammable fuel, to ensure safe operation and to timely detect a leakage, reliable safety sensors are applied. Indoor use of hydrogen detectors is recommended for indoor fueling operations. There are safety sensors on the market that can be used for the successful deployment of hydrogen technology. For hydrogen to take its rightful place in the energy transition, as with other energy technologies is sufficient development of the technology itself. Most hydrogen today is produced by steam reforming of natural gas, but green hydrogen can be manufactured by electrolysis using renewable electricity and use of renewable feedstock like biomethane.

Keywords:
carbon footprint; electrolysis; green hydrogen; renewable energy; sustainability

Introduction
195 countries signed a legally binding agreement on December 12, 2015: at Paris, to keep global warming well below 2°C which requires countries' globally to decarbonize world's energy system. This energy transition faces challenges.as significant renewable energy must be installed and integrated, while securing the supply and resilience of the power system is demanding(Hydrogen Council 2017). Among potential renewable energies identified for the transition, hydrogen is a versatile, clean, and safe energy carrier that can be used as fuel for power generation or in industry as feedstock for production of various chemicals and products. Gren hydrogen can be produced from renewable electricity and from carbon-abated fossil fuels. Hydrogen is emissions free at the point of use, can be can be stored and transported at high energy density in liquid or gaseous form for various applications including energy storage in fuel cells to generate heat and electricity or a transport fuel(Hydrogen Council 2017). Hydrogen is among the most important low-carbon technologies more so with the introduction of carbon peaking and carbon neutral targets, and enforcement of policies that promote hydrogen energy technology(Ran et al. 2022). The application of

hydrogen is concentrated in four principal areas, namely: electricity, industry, transport and building heating, as well as use as a feed for industrial raw materials, energy storage and alternative fuels. The demand for hydrogen has been in a steady growth stimulating research into physical component and the integrated energy system with hydrogen. Physical components for hydrogen energy include electrolysers, the hydrogen fuel cell, and the storage and transport carriers(Kabeyi & Olanrewaju 2022a; Ran et al. 2022).

Hydrogen is this one of the e simplest and most abundant elements on the planet earth combining readily with other chemical elements, and found as part of another substance, like water, hydrocarbon, or alcohol as well as in natural biomass like plants and animals hence considered as an energy carrier and not energy source. The global annual production of hydrogen is about 55 million tons with increasing consumption growing at about 6% per year. About 50% of the global demand for hydrogen is met by steam reforming of natural gas, about 30% from oil/naphtha reforming from refinery/chemical industrial off-gases, 18% from coal gasification, 3.9% from water electrolysis, and 0.1% from other sources. Although electrolytic and plasma processes show high efficiency for hydrogen production, the processes are energy intensive processes(Kalamaras & Efstathiou 2013).

Hydrogen is a clean energy carrier that with potential applications in power generation, automotive application as transportation fuel, fuel for industrial boilers, and even for commercial and residential heating. Since most of the hydrogen is produced currently is from catalytic steam reforming of natural gas, which is fossil there is growing need for use of renewable materials (Guoxin & Hao 2009). The utilisation of hydrogen is concentrated in four principal areas of industry, electricity, transport and building heating. It is also used as industrial raw materials, used as a means of energy storage and alternative fuels for transport and power generation.(Ran et al. 2022). It is desirous to have a regional electricity-hydrogen integrated energy system that couples electricity and hydrogen to improve renewable energy utilization and a double layer mixed integer planning model aimed at reducing the levelized cost of hydrogen by optimizing the proportion of wind and photovoltaic power generation installed in the system and the electricity purchased via the grid. An integrated expansion plan for electricity, natural gas, and hydrogen systems can contribute to the decarbonization of energy systems and identify a mix of technologies that meet energy demands and emissions with optimal economics(M. J. B. Kabeyi & O. Olanrewaju 2023; Ran et al. 2022).

The transition towards a carbon-neutral future relies on renewable hydrogen because of its spatio-temporal storage and sector coupling potential, which makes it identifies as an energy vector. However, hydrogen's large-scale deployment faces many unresolved issues like least-cost production challenges, optimal facility siting, and overall implications on power and energy systems. Expansion planning provides an opportunity to analyze the various issues in the holistic context of energy systems(Kabeyi & Olanrewajun 2022d; Klatzer et al. 2022). Energy sustainability can be improved by using hydrogen for energy related applications to substitute fossil fuels. The common methods for hydrogen production are electrolysis or methane reforming (SMR) and autothermal reforming (ATR) for syngas production (Antonini et al. 2020). The technologies can use biomethane, as a substitute natural gas to provide a lower carbon and renewable hydrogen for transport and power generation. Use of biomethane also provides a hedge against growing demand for fossil fuels particularly the natural gas and hence play a leading role in the energy transition.(Kabeyi & Olanrewaju 2022b; Saur & Milbrandt 2014).

Hydrogen Production

Hydrogen is produced from various carbohydrates, e.g. natural gases, coal, oil and oil products that are associated with CO_2 emissions although it can be derived from renewable power source, or biochemical processes and biomass. The global hydrogen demand is about 115 Mt/a in the form of 60% pure hydrogen, and 40% hydrogen mixed with other gases. About 75% of pure hydrogen is produced from natural gas (75%) and coal (23%), with electricity and oil accounting for the balance. Hydrogen derived from fossil resources is called grey, or blue, if carbon capture technologies while hydrogen from nuclear power is pink hydrogen. Green hydrogen produced from renewable energy sources (Kabeyi & Olanrewaju, 2022e; Klatzer et al. 2022).. The global production of hydrogen is currently dominated by fossil fuels, with the most significant contemporary technologies being the steam reforming of hydrocarbons like coal and natural gas, while electrolysis of water, an energy demanding process is the greener option. (Kalamaras & Efstathioum 2013). The various methods for hydrogen production are discussed in this section.

Steam Methane Reforming

Hydrogen can be produced steam methane reforming (with and without carbon capture and storage (CCS),In this process, methane is used as a feedstock and as energy source for steam generation. Methane and steam are first converted to syngas, which is rich in carbon monoxide and hydrogen and has some residual methane. The process occurs at 700–900 °C, and 20–40 bar. This is followed by a water-gas shifting (WGS) process in which carbon monoxide and steam form carbon dioxide and hydrogen. Carbon dioxide and residual methane are separated from hydrogen by downward pressure swing adsorption (PSA).

Reforming process leads to Synthesis gas (syngas) which is a mixture of hydrogen and carbon monoxide. H_2 and CO. Syngas is a raw material for production of many long chain hydrocarbons through fermentation, Fischer-Tropsch fuels and methanol to gasoline technology conversion. (Ashraf et al. 2015)

Dry reforming

In dry reforming, CO and H_2 are produced by reaction of methane (CH_4) and carbon dioxide (CO_2). However, the endothermic reaction minimizes reduction of CO_2 emissions, because the carbon dioxide (CO_2) emitted by fuel combustion generate the heat required for the reaction needs to be accounted for. Dry reforming also satisfies basic requirements of many processes in Fischer–Tropsch synthesis, as an efficient route for producing synthesis gas production yielding a H_2/CO ratio close to 1(Alves et al. 2013) .

The main limitation of Dry reforming compared with steam reforming is that it produces a lower syngas ratio (H_2/CO=1), The H_2/CO ratio is influenced by water gas shift reaction (WGS), which lowers the ratio because of reverse reaction which converts hydrogen to water. The H_2/CO ratio can be kept between 1 and 2 through partial oxidation of methane as shown in equation below through feeding water which promotes forward water gas shift reaction. The process also lowers process energy demand since partial oxidation is exothermic (Ashraf et al., 2015). The temperature range for dry reforming process 700–1000°C(Ashraf et al. 2015).

$$CH_4+CO_2 \rightarrow 2CO+2H_2 \qquad \Delta H^0 = 247 \text{ kJ/mol}$$

Since the feed has got lower O/C and H/C ratios, dry reforming tends to form carbon deposition hence need to carry out the process at a higher temperature (Ashraf et al., 2015).

Steam reforming and water shift reaction

In steam reforming methane is combined with water vapor to produce CO and H_2 in the in the presence of a catalyst, in a reaction that is endothermic process at a temperature between 650 and 900 °C, to produce hydrogen yield of 60–70%(Alves et al. 2013).. The chemical reaction is demonstrated by a two-step reaction demonstrated below.

$$CH_4+H_2O \rightarrow CO+3H_2 \qquad \Delta H^0 = 206 \text{ kJ/mol}$$

$$CO+H_2O \rightarrow CO_2+H_2 \qquad \Delta H^0 = -41 \text{ kJ/mol}$$

The process of steam reforming is often followed by a water shift reaction to improve hydrogen generation(Kabeyi & Olanrewaju 2022a, 2022f; Moses Jeremiah Barasa & Oludolapo 2023).

Partial oxidation reforming (POR)

The partial oxidation reforming is used to generate hydrogen at reduced energy cost since the process is moderately exothermic as opposed to steam reforming which is highly endothermic. In partial oxidation reforming, methane oxidized partially to H_2 and CO at atmospheric pressure and temperature of 700 and 900 °C. Complete conversion yields H_2/CO ratio of about 2 and reduced soot formation. A decrease in CO selectivity makes methane to react with oxygen to form carbon dioxide (CO_2) hence complete combustion which is strongly exothermic leading to formation of hot-spots in the reactor bed and coke deposition on the catalyst(Alves et al. 2013).This process involves oxidation of methane to syngas

$$CH_4+0.5O_2 \rightarrow CO+2H_2 \qquad \Delta H^0 = -25.2 \text{ kJ/mol}$$

Partial oxidation reforming (POR) is an exothermic reaction. The reduce on energy consumption, the process can be combined with either dry reforming or stream reforming which are endothermic.

Autothermal Reforming (ATR)

Internal heating of a reactor is more efficient than external heating, and exothermal process is more economical. The partial oxidation reaction of methane as in POR is exothermic but the product has lower H_2/CO compared too endothermic steam reforming(Alves et al. 2013). Autothermal Reforming combines the two processes i.e., POR and SR and occurs in presence of carbon dioxide. In ATR, a thermal zone exists in the reactor in where partial oxidation takes place to produce heat needed for steam reforming in the catalytic zone. The process is efficient as it requires no external heating while at the same time it is attractive because of the speed of the reactor stop and restart. The process also has higher yield of hydrogen and consumes less oxygen compared to partial oxidation reaction. The process also reduces formation of hot-spots hence no need to deactivate the catalyst(Alves et al. 2013).

Gas Switching Reforming

This is an alternative to SMR which is a novel process, cost effective intrinsic CO_2 capturing process. In gas switching reforming air and fuel (methane and water) enter a single reactor alternately where an oxygen carrier material which also acts a catalyst is oxidized or reduced, respectively. The oxidation stage involves the oxygen carrier being heated by the exothermic reaction, and the heat is utilized in reduction stage, the heat is utilized for methane reforming, to produce hydrogen and CO_2. GSR can be combined with combined cycle hydrogen turbines for to directly utilize hydrogen in the power generation, while excess hydrogen could be stored or supplied to a dedicated hydrogen system(Kabeyi & Olanrewaju, 2022e; Klatzer et al. 2022).

Electrolysis

Hydrogen derived from renewable sources plays a marginal role with global production of less than 0.4 Mt/a, although there is significant potential for large-scale hydrogen production from renewable power is envisaged. Electrolysis makes use of electricity to split water into hydrogen and oxygen. Electrolyser technologies applied include alkaline electrolysis (AEL), proton exchange membrane electrolysis (PEMEL), and solid oxide electrolysis cells (SOEC). Of the three technologies, with the alkaline electrolysis (AEL), being the most mature technology have industrial scale efficiency of about 65% on the basis of lower heating value. The process is however limited by limited startup and ramp-up dynamics which are reflected by the lack of application. The PEMEL technology is approaching market maturity, and a 6 GW PEMEL plant was commissioned for operation in Linz, Austria. Such plants produce up to 1200 m^3 hydrogen per hour, with the ability to ramp and start up within seconds, enabling them to provide grid services. They operational flexibility of PEMEL has the potential to produce hydrogen at the lowest cost in the future. The solid oxide electrolysis cells (SOEC) are still under development at demonstration stage. They operate at high temperatures of (700–1000 °C) leading to start-up times and a relatively short useful life of 8000–20000 h). It is the overall hydrogen demand and policy measures that influence the hydrogen production technologies selected (Kabeyi & Olanrewaju, 2022c; Klatzer et al. 2022).

Hydrogen Production Using Nuclear Energy

A potentially efficient method for hydrogen production may be attained by raising the water temperature before splitting its molecules in electrolysis or thermochemistry at a temperature range of 700°C to 1000°C. Since the current LWRs and near-term, water-cooled ALWRs produce temperatures below 350°C, they cannot be used for this process. However, coolants for Generation IV reactors concepts can attain higher than 700°C and can be coupled to thermochemical plants. The use of nuclear reactors to supply the heat needed in the steam methane reforming (SMR) process is potentially more economical than water splitting Nuclear-assisted SMR would minimize the use of natural gas in the process as and minimize the CO_2 emissions. (Kalamaras & Efstathiou 2013).

High-Temperature Electrolysis of Steam

In this process, increased demand for thermal energy is offset reduction in the electrical energy demand, thus improving overall thermal-to-hydrogen heat conversion efficiency. Higher temperatures lower cathodic and anodic over voltages making high-temperature electrolysis of steam (HTES) advantageous from both thermodynamic and kinetic standpoints. The HTES overall efficiency appears less sensitive to temperature than the thermochemical processes(Kalamaras & Efstathiou 2013).

Thermochemical Reactions

Of the several hundred possible reactions, two identified candidate thermochemical cycles for hydrogen production from water (i.e., cycles that enable chemical reactions to take place at high temperatures) with high potential for efficiency and practical applicability to nuclear heat sources are the sulfur-iodine (S-I) and calcium-bromine-iron (Ca-Br) cycles. Additionally, Argonne National Laboratory (ANL) identified the copper-chlorine (Cu-Cl) thermochemical cycle as another option which is a hybrid sulfur-based process that does not require iodine but has a single electrochemical process. However, nuclear power reactors emit trace amounts of radionuclides, chiefly noble gases which cause small doses of radiation to persons offsite, the total annual risk of which is less than one part in 1 million.

Cost of Hydrogen Production

Steam reforming remains the most widely used and cheapest hydrogen production method accounting for close to half of lobal production. The price for hydrogen is about 7 USD/GJ. The partial oxidation of hydrogen also provides a comparable price for hydrogen, but the capture of , greenhouse gases generated by thermochemical processes leading to price increase by 25–30% (Kalamaras & Efstathiou 2013). The main component of the cost of hydrogen is the cost of fuel or electricity used to produce the hydrogen. Cost evaluation shows that hydrogen from all reforming and gasification equipped with and without carbon capture is cheaper than renewable hydrogen. Solid fuel/coal gasification with capture will remain cost competitive in the current and in anticipated net-zero emissions scenarios.(Kalamaras & Efstathiou 2013).

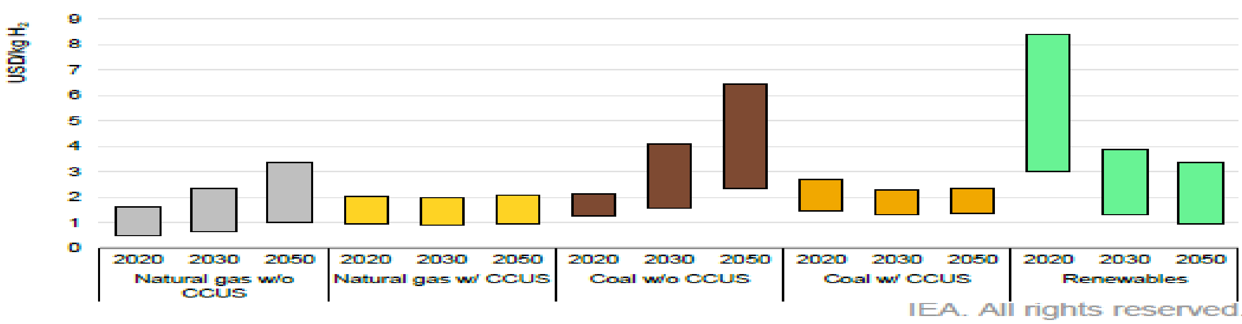

Figure 1. Levelized cost of hydrogen production by technology in 2020, and in the Net zero Emissions Scenario, 2030 and 2050 (Kalamaras & Efstathiou, 2013)

Figure 1 shows hydrogen production costs for the major methods of producing hydrogen, namely natural gas reforming (without and with carbon capture and storage [CCUS]), use of renewables, coal gasification (with and without CCUS). The costs are further compared to those costs associated with the net zero emissions scenarios for 2030 and 2050. It is shown that the cost of hydrogen produced from natural gas remains steady and most competitive. The cost of renewable hydrogen is currently high, but it is expected to drop by 2030, and further drop by 2050.

Feedstock For Hydrogen Production

Hydrogen is the most widespread chemical element on the earth and as molecular dihydrogen (H_2) can be obtained from several sources both renewable and nonrenewable using different production processes. The significance of renewable hydrogen production has increased due to increase in the pure hydrogen demand, fossil fuels depletion, concerns over greenhouse gas emissions and global climate change. The availability of capital, desired hydrogen amount and purity hydrogen and the composition of available biogas will influence the selection of reforming processes(Saur & Milbrandt 2014).

Biogas

Biogas has significant potential for production of hydrogen through a variety reforming processes whose selection is guided by the composition of biogas, required purity of hydrogen, required volume, and process cost and availability of funding. The catalyst poisoning effect of hydrogen sulphide limits the use of biogas as a raw material for hydrogen manufacture. By partially treating biogas to remove H_2S and 30–45% vol. carbon dioxide, the dry reforming process is appealing since it takes advantage of the of carbon dioxide to intrinsically act as oxidant in dry reforming. Use of biogas with CO_2/CH_4 ratio less than 1 requires alternative supply of oxidant to produce synthesis gas. Oxygen addition by DOR method is a potential route for hydrogen production from biogas, whose aim is to increasing the H_2/CO ratio(Kabeyi & Olanweraju 2022; Lyng & Brekke 2019).

Through steam reforming, biogas can be used to manufacture green hydrogen, in a process where a catalyst refines and separates the hydrogen from the gas stream(Admin 2020; Kabeyi & Olanrewaju 2022f). The most common method used to manufacture hydrogen is by steam-reforming of natural gas, followed by pressure-swing adsorption to remove impurities. However, small reformers like those used for combined heat and power with biogas plants are in commercial operation(Admin, 2020). Upon removal of carbon dioxide and water molecules, the methane (CH_4) left from biogas can be used for hydrogen synthesis and bio-fuel production. Methane can be split to hydrogen molecules (H_2) in a process that can be done in a steam/methane reformer. In the process, high pressure and temperature steam is combined with the methane (CH4) to produces flow of hydrogen molecules and CO molecules(Kabeyi & Olanrewaju 2022a; Karuppiah & Azariah 2019).

Biomethane

Biomethane may be used in form of Bio-CNG, is compressed biomethane having similar properties to with compressed natural gas (CNG) used as an alternative fuel for automotive application with better economy and lower emissions. The production of Bio-CNG requires the removal of impurities like water, nitrogen (N_2), oxygen (O_2), hydrogen sulphide (H_2S), ammonia (NH_3) and carbon dioxide (CO_2) from biogas for composition to be >97% CH_4, <2% O_2 at a pressure 20–25 MPa. Bio-CNG occupies less than 1% of its volume at standard atmospheric pressure and temperature(Li, 2014; Lyng & Brekke 2019).

Biomethane has a significant application in fuel cell technologies for application are used for applications like power generation whereby fuel cells use hydrogen for power generation just like batteries. Other applications are Hydrogen-powered FCEVs which is environmentally attractive since they have no tailpipe emissions which makes them extremely clean as transport option to fossil fuel powered vehicles (Saur & Milbrandt, 2014).Fuel cell technology in power generation is emission free and hence attractive (NaturalGas.org, 2013).Biomethane is a source of renewable hydrogen, making hydrogen a green energy resource(Kabeyi & Olanrewaju, 2022a; Moses Jeremiah Barasa & Oludolapo, 2023). Biomethane can be used as a substitute for natural making the process renewable. Therefore, it is technically feasible to develop an integrated system which produces grid electricity and hydrogen for further electricity production from fuel cells and process applications in manner that yields negative greenhouse gas emissions. These promises to be a power pathway in the global transition to sustainable energy and electricity as well as sustainable development(Saur & Milbrandt 2014).

Natural gas

Hydrogen is produced by natural gas reforming/Gasification which produces synthesis gas, a mixture of hydrogen, carbon monoxide, and a small amount of carbon dioxide through reacting natural gas with high-temperature steam. The carbon monoxide in syngas is reacted with water to produce additional hydrogen in this process(Kabeyi & Olanrewaju 2022a). The production of hydrogen by steam-reforming of natural gas is an established low-cost option for hydrogen production(Blok et al. 1997).

Coal

Coal gasification is used to produce hydrogen from coal, in a process that uses steam and oxygen to break molecular bonds in coal and form a gaseous mixture of hydrogen and carbon monoxide. It is easier to remove carbon dioxide and pollutants from gas obtained from coal gasification compared to coal combustion. In another method, low-temperature and high-temperature coal carbonization is applied. The coke gas made from pyrolysis (oxygen free heating) of coal consists of about 60% hydrogen, while the rest is methane, carbon monoxide, carbon dioxide, ammonia, molecular nitrogen, and hydrogen sulfide (H_2S). Hydrogen ca then be separated from other components of coke gas using the pressure-swing adsorption process. (Blok et al. 1997; Guoxin & Hao, 2009; Kabeyi 2019).

Petroleum coke

Petroleum coke can be converted to syngas which is rich in hydrogen through coal gasification. Other constituents are hydrogen, carbon monoxide and H_2S from the sulfur in the coke feed. Gasification process is used to produce hydrogen from almost any carbon source(Blok et al. 1997).

Depleted oil wells

Hydrogen can be extracted by injecting appropriate microbes into depleted oil wells to allow them to extract at low production costs are low. Concentrated CO_2 is produced by this method that could in principle be captured(Blok et al. 1997).

Water

The electrolysis of water splits water into hydrogen and oxygen and contributed a meagre 0.1% of hydrogen production in 2020. The process of hydrogen production by electrolysis is 70–80% efficient i.e. the conversion loss is 20–30% compared to steam reforming of natural gas whose thermal efficiency is 70 to 85%. The electrical efficiency of electrolysis is projected to reach 82–86% by 2030, as progress in this area continues. The temperature at which water electrolysis occurs is 50–80 °C (120–180 °F), while steam methane reforming requires takes place at 700–1,100 °C (1,300–2,000 °F). The main difference between electrolysis and methane reforming is the primary energy i.e. electricity for electrolysis and natural gas for steam methane reforming(Blok et al.1997)

Electrolytic cells are of their main types, solid oxide electrolyze cells (SOECs), polymer electrolyte membrane cells (PEM) and alkaline electrolysis cells (AECs)., with alkaline electrolysers being traditionally are cheaper in terms of investment, but are less efficient.. They make use of nickel catalysts. The PEM electrolysers, are more expensive since they use more expensive platinum group metal catalysts but are more efficient and can operate at higher current densities. Large scale hydrogen production can make them more economical and cheaper on basis of economies of scale and higher efficiency (Blok et al. 1997).

Application Of Hydrogen Fuel

Hydrogen (H_2) is predominantly used in the chemical industry for production of ammonia and methanol, with significant potential applications in industry, transportation, and power generation. Hydrogen is expected to become a significant fuel for the energy transition. Hydrogen has many applications like conversion of heavy petroleum fractions into lighter ones through hydrocracking, aromatization process, hydrodesulfurization and the production of ammonia via the Haber process which is the primary industrial method for the production of synthetic nitrogen fertilizer widely used in agriculture. Hydrogen is also used as a fuel in fuel cells power generation and potentially as a transportation fuel.

Industrial applications

Almost all hydrogen produced in the US is used by industry for refining petroleum, treating metals, producing fertilizer and other chemicals, and processing foods. The industry has safely used hydrogen for decades in the following applications: Common industrial applications of hydrogen include petroleum refining, glass purification, manufacture of semiconductors, aerospace applications, fertilizer production, Welding, annealing and heat-treating metals, pharmaceuticals production, used as a coolant in power plant generators, and hydrogenation of unsaturated fatty acids in vegetable oil.

Application in Transportation

Hydrogen might become an energy carrier for transport applications by application of fuel cells(Blok et al. 1997).. Since diesel remains the most dominant energy resource used in transportation there is a need to shift to renewable and low carbo sources of energy, like hydrogen (Machado et al. 2021), since the transport sector is a significant contributor of emissions accounting for about 14% of the global anthropogenic greenhouse gas emissions(Boden et al. 2017).

The use of hydrogen in transportation can reduce emissions from engines which are widely used in transportation. The hydrogen fuel cells can provide an alternative to internal combustion (IC) engines due to the clean exhaust emissions, fuel renewability and higher efficiencies compared to conventional fossil fuel engines. Except for the challenge of waste heat removal, hydrogen fuel cell vehicles have a potential to gain widespread acceptance except for existing challenges like waste heat removal in mobile applications(Fly & Thring, 2013).

Since hydrogen has a relatively low energy density compared to other fossil fuels, conversion of hydrogen into alternative fuel products, e.g. synthetic natural gas (SNG) or ammonia, is an option being considered. These processes require CO_2 or nitrogen as feedstock e.g.CO_2 from coal-fired power plants can be fed to P2G facilities. Methanation is part of a hydrogen technology chain (TC) used to produces, stores and utilize SNG in an OCGT. The process involves capture of carbon and feeding back to the methanation process. An option is to use CO2 from the direct air capture process as feedstock for the methanation process. The efficiency of electrolysis and subsequent SNG or ammonia synthesis is generally between 45–50%. It seems feasible to establish a continental long-distance transport of hydrogen/natural gas blends or SNG via pipelines, followed by a dedicated hydrogen pipelines and liquefied hydrogen/SNG/ammonia transport could emerge. (Fly & Thring 2013).

Application In Power Generation

Hydrogen is an ideal raw material for a sustainable energy transformation, but with the challenge being where and how to get hydrogen from renewable sources. Renewable hydrogen can be produced using renewable energy sources and usually produced via water electrolysis(Admin, 2020). Continued Integration of an increasing share of intermittent power sources above 40% of the electricity mix creates a need for operational flexibility. Hydrogen offers valuable advantages as it avoids CO_2 and particles emission, and can sustain largescale deployment almost everywhere, and can be made available everywhere. Hydrogen is used to improve the efficiency and flexibility of the energy system(Hydrogen Council 2017).

In electricity generation hydrogen can be utilized in fuel cells, e.g. proton exchange membrane fuel cells (PEMFC) and solid oxide fuel cells (SOFC), hydrogen-fired gas turbines (HGTs). Fuel cells technically reverse the electrolysis process from the reaction between hydrogen and oxygen (air) in a redox process . Power generation from hydrogen requires the state-of-the-art efficiencies of about 50–60%. The PEMFCs offer quick start-up and flexible operation, and so far, demonstration projects with 500 kW capacity have been achieved. The SOELs, and SOFCs fuel cells are limited in their start-up and ramping. These systems can also run on alternative fuels, like biogas and biomethane(Moses Jeremkah Barasa Kabeyi & Akanni O Oludolapo, 2020; Moses Jeremiah Barasa Kabeyi & Akanni O Oludolapo, 2020).. The high operating temperatures of fuel cells can be exploited to produce hydrogen via steam and carbon dioxide reforming for efficient hydrogen fuel production Hydrogen gas turbines which are still evolving can run on 100% hydrogen and will provide benchmark costs for upgrading gas power plants 10, 25 or 100% hydrogen, respectively. The efficiencies of 60% for combined cycle hydrogen turbines (CCHTs) is expected compared with 35-40% for open cycle hydrogen turbines (OCHTs)(Kabeyi & Olanrewaju, 2021; Moses Jeremiah Barasa Kabeyi & Akanni O Oludolapo, 2020).

Electrolysis Can Convert Excess Electricity into Hydrogen During Times of Oversupply.

Hydrogen can be applied to provide back-up power during power supply deficits or can be used in other sectors like transport, industry or residential, hence it valorizes excess electricity, with the potential of valorization of otherwise curtailed renewable energy being huge e.g. in Germany alone, in a scenario with 90% renewables, curtailment of more than 170 TWh/year is projected for 2050, which is equivalent to about half the energy needed to fuel the German passenger car fleet with hydrogen. Valorization will thus create an opportunity for about 60 GW of electrolysis capacity for economical operation. This will depend on grid improvement in grid interconnectivity. Hydrogen serves as a source of centralized or decentralized primary or backup power. Power from hydrogen (or one of its compounds) can be switched on and off quickly just like gas which helps deal with sudden drops in renewable energy supply. In addition, electrolysers may provide ancillary services to the grid, such as frequency regulation. Hydrogen is also used in specific fuel cell CHPs in industry and buildings thus provides a link between heat and power generation. (Hydrogen Council 2017).

.

Hydrogen can be used in long-term, carbon-free seasonal storage unlike batteries, super-capacitors, and compressed air which can support balancing, but they lack either the power capacity or the storage timespan needed to deal with seasonal imbalances. Although the pumped hydro provides an alternative to hydrogen for large-scale, long-term energy storage; accounting for 95% of global power storage (162 GW worldwide), the remaining untapped potential is affected by local geographic conditions and is limited to about 1% of annual global energy demand (0.3 EJ) which is not enough to deal with seasonal demand difference e.g. Germany energy has about 30% higher demand in winter than in summer, while renewable generation is typically 50% lower in winter than in summer. In such a case, hydrogen remains a novel way to store energy with more and more large, hydrogen- based storage projects being planned, announced, or launched globally in countries like Denmark, Canada, Japan, and the Asia-Pacific region. The underground storage of large volumes of hydrogen is an -established practice with limited technological barriers. The cost of cost of hydrogen storage is projected reduce from €140/MWh (power to power) in 2030 for hydrogen stored in salt caverns compared to projected cost for pumped hydro storage of €400/ MWh in 2030..Hydrogen enable a more economical integration of large amounts of intermittent energy sources in the system and develop the much needed power system flexibility to maintain the resilience of the system(Hydrogen Council 2017).

Serve As Feedstock Using Captured Carbon.

Hydrogen-based chemistry can be used as a carbon sink and complement or decarbonize parts of the petrochemical value chain. Crude oil is today used as feedstock for manufacturing industrial chemicals, fuels, plastics, and pharmaceutical goods. Almost all these products contain both carbon and hydrogen. The application of carbon capture and utilization (CCU) technology as part of a circular economy or an alternative to carbon storage requires green hydrogen to convert the captured carbon into usable chemicals like methanol, methane, formic acid, or urea. This application of hydrogen would make CCU a viable alternative for other hard-to-decarbonize sectors like steel and cement production and would contribute to the decarbonization of part of the petrochemical value chain. The use of hydrogen and captured carbon for production of chemical feedstocks is still under research and development phase. Methanol production is, although local factors make it cost-competitive with an electricity price of EUR 30/MWh. In Germany, a combining carbon from steel production emissions with hydrogen from excess electricity to produce chemicals. (Hydrogen Council 2017)

Act As System Buffer to Increase Resilience.

Hydrogen can align global energy storage with changing energy demand, with its high energy density, long storage capacity, and variable uses making it suitable to serve as an energy buffer and strategic reserve. The energy system has a backup capacity of about 90 EJ (24% of final annual energy consumption and is almost exclusively held by fossil energy carriers. As electricity consumers switch to alternative energy carriers, application of fossil fuels as backup will reduce, since this buffer serves only applications that consume fossil fuels. The most efficient buffer should mix energy carriers that reflect end-use applications in include a mix of fossil fuels, biofuels/biomass/synthetic fuels, and hydrogen(Hydrogen Council 2017)

Handling And Transportation of Hydrogen

Hydrogen storage and transportation remain a challenge today, with storage currently done on a relatively small scale in tanks while large-scale storage envisioned include storage in caverns, Feasible storage facilities for hydrogen include are storage tanks, caverns, hydrogen trucks and hydrogen pipelines. These hydrogen storage systems can be assessed based on a state of charge concept like charging/discharging efficiencies, losses, hydrogen demand of compressor unit, and minimum storage reserve required. Hydrogen trucks are a special type of storage which also offers a means used for transportation. .(Klatzer et al. 2022)

Hydrogen Transportation

All these hydrogen technologies are still under studies and whichever hydrogen storage technologies will prevail on the pathway towards a hydrogen economy is still not clear. Important, decisive factors are establishment of hydrogen demand, the evolution of hydrogen production, the transport cost, price of feedstocks, etc. Therefore, any integrated power, natural gas, and hydrogen models for analysis should consider broad portfolio of hydrogen technologies and policy regulations which may influence the of hydrogen to be produced. .(Klatzer et al. 2022)

Since pipelines are by far the most deployed transport infrastructure resulting from technological maturity, high transport capacities, and cost competitiveness for distances below 2500 km, it is envisaged that by 2050, about one-third of renewable hydrogen will be internationally traded and via pipelines. It is further estimated that up to 69% of European natural gas transmission pipelines could be repurposed to transporting hydrogen fuel, or natural gas/hydrogen blends.(Klatzer et al.2022)

Hydrogen pipelines can be classifying as high-pressure transmission or high/medium/low pressure distributions systems, but we currently have no unified standard for pressure levels. Both systems are linked through controllable pressure valves to ensure appropriate gas flow rates at the distribution level. Blending hydrogen and natural gas is envisaged in the transition, but current blending rates are just between 1% up to 10% by volume e.g., in Austria, blending of up to 10% of carbon-neutral hydrogen is allowed.

Compressor units (CUs) are also considered in integrated power and natural gas expansion planning literature. Compressors ensure adequate gas flow rates by compensating pressure drop along a hydrogen typically in an interval of 100–200 km. for gas transmission, multistage radial flow turbo-compressors with a compression ratio between 1.2 and 1.5 may be considered. The compressors may be powered by electric drives or gas turbines consuming part of the transported gas. As a rule, in general, compressor units are exclusively installed at transmission system level since pressure in the distribution system are often enough to meet natural gas demand. Since hydrogen has lower density than natural gas compressor units for hydrogen transportation are currently a crux, due to its lower density compared to natural gas. Modelling compressor units present challenges because the mathematical formulation is non-linear and non-convex.

Studies indicate that the existing natural gas infrastructure can contribute to the transition towards a hydrogen economy, particularly at the early stages when demand for hydrogen is still relatively low such that making hydrogen dedicated transport systems pose an economic risk. Therefore, an integrated expansion planning should utilize the well-developed natural gas infrastructure while considering its technical and regulatory limitations, like maximum blend rates. Also to be considered is the broad technology portfolio for future transmission expansion(Klatzer et al. 2022).

Hydrogen storage

Hydrogen requires storage at terminals like refueling stations, transport, and users like ships, trucks, and vehicles. High storage volumes limit the use of hydrogen in mobile applications like transportation because it reduces space for load services. High pressure increases volumetric density, which renders storage an important technology for the advancement of H_2-based solutions. Hydrogen storage requires high-pressure tanks (350–700 bar) and, as a liquid, cryogenic temperatures below −252.8 °C (H_2 boiling point). The gas may be stored on the surfaces of solids (by adsorption) or within solids (by absorption). Liquid H_2 (LH_2) is generally stored in double-wall, vacuum super-insulated tanks. (e.g., ammonia)(Araújo & de Medeiros 2023)

The variations of hydrogen storage are developed based on operating time, and needs of users e.g. the metal hydrides, range from mature systems in specific designs, as applied in submarines where they were used for a long time, to experimentally obtained systems which have not yet entered the market . Metal hydride hydrogen storage systems and compression technologies are efficient in small-to-medium scale energy storage systems The hydrogen demand influences size and type of hydrogen storage (Kovač et al. 2021). Figure 2 shows the various storage pathways for hydrogen.

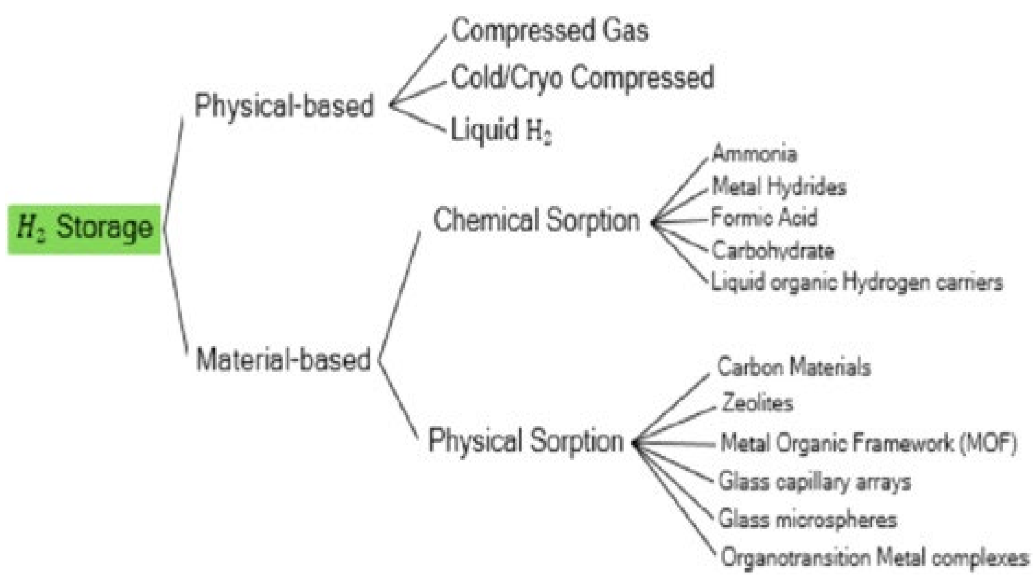

Figure 2. Hydrogen storage methods(Kovač et al., 2021)

From figure2. It is noted that hydrogen storage can be classified into physical i.e., liquid, compressed or cold/cryo compressed methods or on basis of material used i.e., chemical sorption or physical sorption. The compression the compression technology is classified as mechanical and non-mechanical compression (Kovač et al. 2021)

Planning And Modelling for Hydrogen Energy Future

Flexibility is a key requirement for highly renewable power systems. The Modelling energy storage systems and demand-side management requires a chronological (hourly) temporal framework which implies additional computational burden, that can be mitigated by reduction techniques, like representative periods or decomposition methods. Such a framework can mitigate short-term uncertainty when combined with ramping constraints, but modelling stochasticity is recommended to be an integral part of expansion planning(Klatzer et al. 2022).

Hydrogen and its variations technically extend the portfolio of energy carrier options making optimal sitting of power generation alongside hydrogen production and consumption units a complex undertaking as well as the choice of energy transmission technology. A state-of-the-art integrated power, natural gas, and hydrogen expansion planning models should be considered to facilitate decision making in network-based power and gas flows, e.g., via DC-OPF and steady-state gas flow equation which can be extended to include detailed line pack modelling to utilize pipeline storage capacity. There exists a knowledge gap in terms of beneficial effects of line pack on integrated expansion planning against its implied computational burden. Other gaps are in transmission of natural gas and hydrogen blends, blend rates, and constraints for the energetic properties of blends. There is also a policy constraint that should allow specifying the type/color of hydrogen to be produced (or not). There are limited holistic integrated expansion planning models that consider all the issues raised in terms of knowledge gap.(Klatzer et al.2022).

Formulation of gas flow

At the center of integrated power and gas models is the formulation of gas flow where applied formulations include transport models, steady-state, or dynamic gas flows. The most basic modelling concept that can be adopted is a transport model that disregards physical laws for gas flows but only establishes lower and upper bounds. Its simplistic nature provides convenience, and minimal modelling and solution efforts particularly in in long-term models. The integer relaxation for truck scheduling and SMR unit commitment has benefits in terms of computational time with little impact on the overall optimal system cost. (Klatzer et al. 2022).

A comparison of physical characteristics of high-pressure gas flows, requires more sophisticated approaches starting with the Darcy-Weisbach equation where the steady-state flow equation for a horizontal pipeline is derived. This is a highly non-convex and non-linear formulation.

The friction factor, λ, (or f in American literature), which is a function of Reynolds number plays a key role for pipeline gas flows. The Reynolds number, Re, is generally based on average values, pipe roughness, ε, and internal diameter, D. The relationship of these parameters is represented in a Moody diagram , characterized by a zone for laminar flows ($Re < 2.320$) and one for turbulent flows ($Re > 2.320$). The Moody diagram differentiates between smooth, rough, and rough pipes. The friction factor is commonly described by the Colebrook-White equation. However, this implicit formulation requires iterative solution methods and thus, is not very practical for planning models. Gas system parameters, like pressure ranges, pipeline parameters, physical gas parameters etc., are often only vaguely/partially specified or not at all, making comparison of different approaches and case study results difficult. The range of application for the practical equations is subject to several limitations. To this end, we are applying the steady-state flow equation, and an explicit friction factor is recommended. The emergence of natural gas and hydrogen blends makes it more relevant to consider detailed gas parameters (Klatzer et al. 2022).

Challenges of Gas flow modelling challenges

Power system expansion planning models are commonly formulated as linear programming or MILPs. Hence detailed modelling of pipeline gas flows needs linearization of the non-linear and non-convex steady-state gas flow From a practical point of view, linear formulations do not require unconventional solvers(Klatzer et al., 2022).

Considering Linepack

The main difference between power transmission lines and pipelines is the storage capacity referred to as line pack which plays an important role in gas grid operation by offering operational flexibility in terms of balancing demand fluctuations. Injection of hydrogen at the transmission level will increase the importance of linepack. (Klatzer et al., 2022). The linepack can be quantified as the volumetric amount of gas that is stored in a pipeline at a given point in time under certain pressure and temperature conditions(Klatzer et al., 2022). Considering linepack necessitates reformulation since the relation between linepack and average pressure is based on non-quadratic pressure variables. (Klatzer et al., 2022). Depending underlying temporal framework additional linepack constraints can be useful e.g., specifying initial linepack at time $k = 0$, which makes sense otherwise linepack behaves like additional demand, leading to an initial 'charging' of the pipeline, thus increasing the number of pipelines. In a chronological hourly structure, neglecting this is likely to only have minor effects on overall modelling results because continuous gas demand results in linepack not falling below a minimum value. In the case of representative periods this is different as the effects of neglecting initial linepack increase not only with the number of pipelines but also with the number of representative periods (Klatzer et al. 2022).

In future, Linepack is likely to become even more relevant for integrated power, hydrogen, and natural gas systems. Linepack storage could provide additional flexibility, e.g. for large-scale hydrogen generation plants. Only a small fraction of integrated expansion planning models considers detailed linepack at the moment as it represents additional computational challenges. The modelling of linepack in case of natural gas/hydrogen blends, will require additional binary variables in order to ensure identical direction of natural gas and hydrogen flows, thus further increasing computational burden(Klatzer et al. 2022).

Sustainability Of Hydrogen Energy

Hydrogen has also recently emerged as a clean fuel that is capable of operating thermal power plants. This creates room for future plants to operate by blending natural gas with synthetic fuels including hydrogen. Hydrogen s through steam methane reforming (SMR). SMR requires carbon capture and storage (CCS) technologies since CO_2 is produced during the process. The cost of production of Hydrogen production from natural gas ranges is between 0.5-1.7 USD/kg. Although using CCS technologies to reduce the CO_2 emissions it adds to the cost of production up to 1-2 USD/kg. Production of renewable hydrogen through electrolysis costs around 3-8 USD/kg which is higher but the cleanest method of producing hydrogen. The production cost of Hydrogen is expected to reduce globally as its adoption gathers momentum(Ceylon Electricity Board 2023).

Cost and Carbon Emission

Investment in hydrogen equipment increases investment costs and O&M costs; in the process of achieving the goal of carbon neutrality, by substitution of grey hydrogen in industry, transport, and heating with electricity is necessary. The carbon emission reduction from replacing grey hydrogen with green hydrogen is calculated by referring to the 1kg of hydrogen produced from coal to produce 20 kg of CO_2.(M. J. B. Kabeyi & O. A. Olanrewaju, 2023b, 2023c; Ran et al. 2022)

Levelized Cost of Hydrogen

A sustainable energy system needs green electricity and green molecules as well to move from fossil to electrified chemical industry (chemistree). A promising LCOE of H_2 is found in all importing scenarios with an average of 5.20 €/kgH_2. Transport of hydrogen transport via pipelines (0.14 €/kg/1000 km) is noted as optimal solution for the studied cases. Further investigation is required for importing RE via other types of molecules and e-fuels such as ammonia, methanol, and methane from the Middle East and North Africa (MENA) to the EU(M. J. B. Kabeyi & O. A. Olanrewaju, 2023a; Zayoud et al. 2022)

Results and Discussion

Hydrogen has significant potential as a source of energy with applications in industry, transportation, power generation and heating. Replacing grey hydrogen with green hydrogen will significantly reduce a large amount of carbon dioxide in the hydrogen production process. The importance of hydrogen storage has emerged gradually as the share of renewable energy in the power system increases. Forecasts indicate a continued rise in the demand for hydrogen in the future. Planning for the future power structure with consideration of water electrolysis powered by renewable energy to hydrogen production could reduce a significant amount of carbon emissions. The low carbon energy transition cannot only consider the traditional electric load, but also the electric load from hydrogen demand in other sectors like the industry sector. Considering electrolysis for hydrogen production increases electrical load which increases demand for renewable energy sources, hence the need for more investment in renewable power capacity expansion like wind power and photovoltaics.

The main goal of the hydrogen energy transition, is to achieve a carbon-neutral hydrogen society, based on green hydrogen, . Green hydrogen is produced via water electrolysis using renewable electricity. As the production and s share of green hydrogen grows globally, hydrogen is expected to be price competitive to the grey hydrogen production, which is produced from fossil fuels. within a decade. The cost parity can be achieved through increase in technical efficiency, equipment cost reduction and reduction in material prices, and manufacturing scaled up to achieve economies of scale. which are currently in progress in several countries. The production of hydrogen via alkaline water electrolysis is a mature technology with commercially available megawatt (MW) scale installations, while production systems based on proton exchange membrane (PEM) and solid oxide (SO) electrolyzers are also at advanced stages of maturity (Kovač et al. 2021)

Most hydrogen used today is produced by steam reforming of natural gas or from coal gasification. The growing demand for large volumes of low-emission hydrogen for the Net Zero emissions target creates new opportunities for nuclear power through many ways, including coupling nuclear reactors with electrolysers while other methods that create hydrogen directly from nuclear power without electrolysis are under development. High-temperature thermochemical hydrogen production, use heat directly derived from nuclear reactors to split water into hydrogen and oxygen at a system efficiency greater than 40%, which is higher than advanced electrolysis models whose efficiency limited to 30%(IEA 2022).

The study showed that hydrogen-based vehicles can be used in marine, railways and aerospace industry and hence hydrogen-based fuel cell vehicles should be commercialized globally. Challenges facing hydrogen applications include the distribution and storage of hydrogen. Undeveloped hydrogen technologies have a high implementation cost for proper commercialization, which discourages vehicle manufacturers from adopting the technology(Klatzer et al. 2022).. Different countries should coordinate their energy requirements for the future to promote the use of hydrogen as a transition energy resource. Policy and regulatory measures and as well as funding for research and commercialization initiatives will pave the way for the take-off steps toward a hydrogen economy.

Hydrogen Production

Steam-methane reforming and electrolysis (splitting water with electricity) are common methods for hydrogen production. By source or methods, hydrogen can be referred to as green hydrogen, blue hydrogen, brown hydrogen and even yellow hydrogen, turquoise hydrogen, and pink hydrogen. Desulphurization of feedstock is often the first since sulfur tends to poison catalysts. In steam reforming, syngas is produced Next in an endothermic process that requires heating (da Rosa & Ordóñez, 2022). The processes in hydrogen production are summarized in figure 3 below.

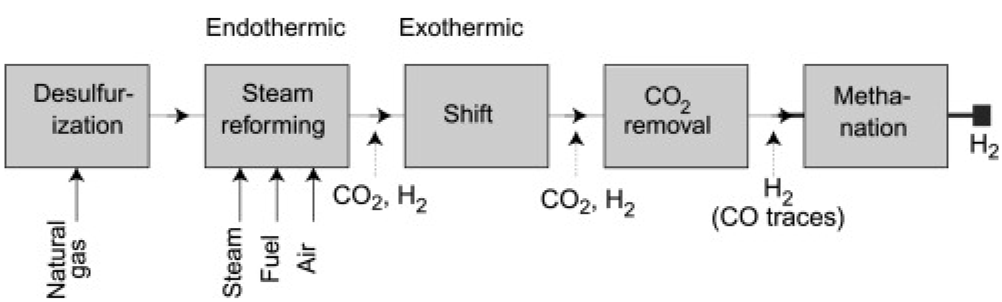

Figure 3. Processes I hydrogen production.

The shift reaction in the production process eliminates most of the CO in a process that releases substantially less heat than what is required to drive the reforming (or decomposition) reaction. The exothermic reaction profits from operation at low temperatures due to equilibrium considerations. This creates unfavorable kinetics of the reaction hence attention is now given to the development of good catalysts with early catalysts used being based on nickel, cobalt, or iron oxide at temperatures above 700 K. The modern copper-based catalysts enable operation at temperatures below 520 K. The gas leaving the shift has large amounts of CO_2 mixed with hydrogen which necessitates its removal step. The final step involves the removal of residual CO,, otherwise, it would alter the catalyst in the ammonia synthesis process(da Rosa & Ordóñez 2022).

Feedstock For Hydrogen Production

The various sources and feedstock for hydrogen production are summarised in figure 4 below.

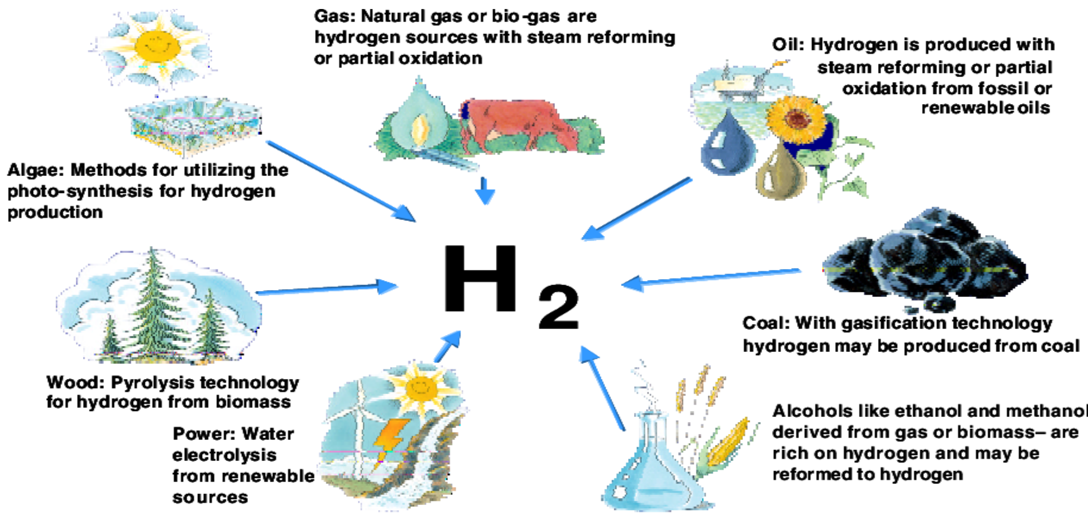

Figure 4. Various sources and feedstock for hydrogen production.

From figure 4, the feedstock and methods for hydrogen production include coal, alcohols like ethanol and methanol through reforming, solid biomass like wood through pyrolysis technology, natural gas, and oil through reforming.

Hydrogen Contribution by Source

The production of hydrogen is the family of industrial methods for generating hydrogen gas with four main sources for the commercial production of hydrogen namely natural **gas, oil, coal, and electrolysis of water**, which account for 48%, 30%, 18% and 4% of global manufacture respectively. The global hydron production by source is summarized in figure 5 below.

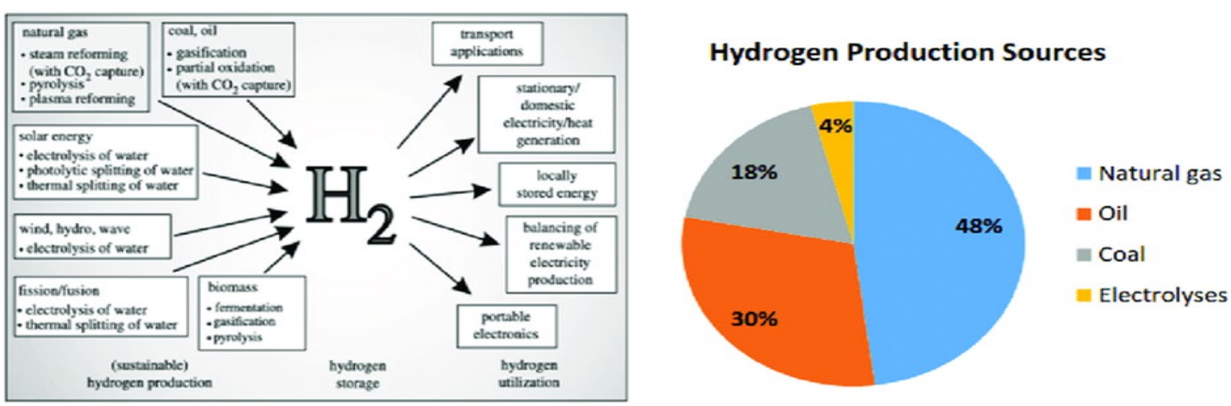

Figure 5. The global share of hydrogen production by source

From figure 5, it is noted that natural gas is the main feedstock for hydrogen production accounting for close to 48%, followed by oil at 30%, coal accounting for 18% and electrolysis 4%.

Hydrogen Storage

It is possible to store hydrogen as a liquid or a gas, in pure or molecular form without any physical or chemical relationship with other materials. Atomic hydrogen can be chemically bound or absorbed by another element while molecular hydrogen can be absorbed by a material. Hydrogen storage can be classified based on how hydrogen storage systems interact with each other. The hydrogen storage technologies are classified into three categories, as shown in Figure 6 below:

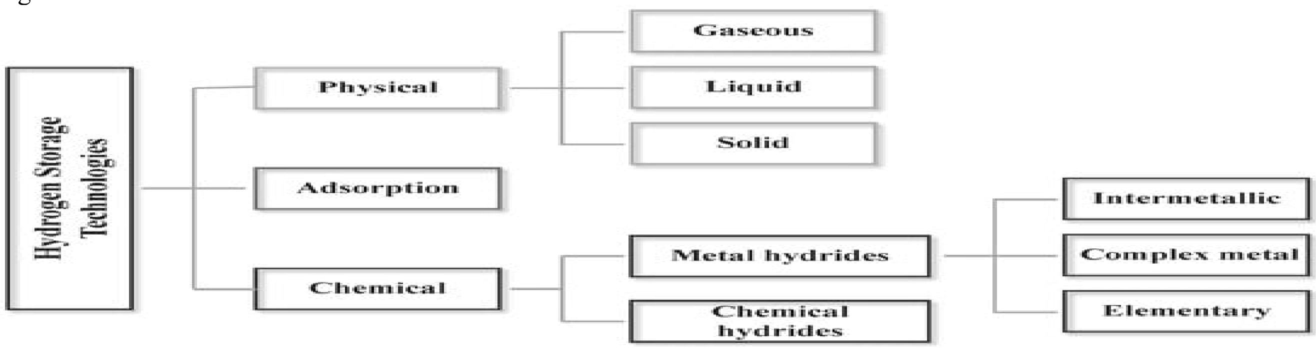

Figure 6. Storage technologies(Bairrão et al., 2023).

From figure 6, it is noted that hydrogen storage technologies are broadly classified into chemical, physical and adsorption methods.

For chemical storage, it is important to distinguish between metal and chemical hydrides since they have differences in chemical storage qualities. The names indicate that metal hydrides contain metal atoms to which hydrogen can attach directly or through a complicated ion chain. Chemical hydrides, are made up of nonmetallic atoms such as oxygen, carbon, nitrogen, and hydrogen(Bairrão et al. 2023)

Application Of Hydrogen

Hydrogen energy has various applications in many industries and sectors as summarized in figure 7 below.

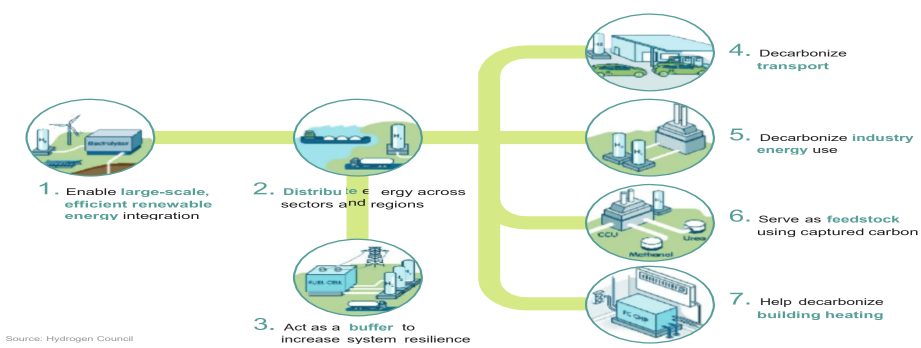

Figure 7. Various applications of hydrogen

From figure 7, it is noted that hydrogen has multiple direct and indirect uses energy for the transition by mainly enabling large-scale effective nuclear energy integration to the energy systems by acting as a buffer to increase energy system resilience and to distribute energy across sectors and geographical regions. Hydrogen can be used to decarbonise all sectors like buildings, feedstock, industry, and transport sector.

Challenges

There are various obstacles that should be overcome before the full benefit of hydrogen in the energy transition can achieved. They include insufficient recognition of its importance for the energy transition, lack of of mechanisms to mitigate and share the long-term risks of the initial large-scale investments, poor coordination across stakeholders, absence of fair economic treatment of a developing technology, and limited technology standardization and harmony to drive economies of scale(Hydrogen Council 2017).

Many hydrogen investments require a long horizon, a long period of f 10 to 20 years particularly the early years and require infrastructure investments before the consumer demand can grow. The lack of clear and binding emission reduction targets or stimuli for specific sectors additionally discourages potential investors from long term risks. Applications immobility need a coordinated effort across industries to address the market mismatch between infrastructure deployment and hydrogen demand(Hydrogen Council 2017)

Social Aspects

As governments appreciate the potential and necessity of hydrogen technology development, more resources are invested in R&D, education, product manufacturing, etc. Society's willingness to support the hydrogen economy is quite important and must be taken into consideration. Likewise, projects should be clear about the ultimate motive in a carbon-neutral society, direct be accessible, and convince the populace enough to receive support. How hydrogen implementation will affect people's lives is important and should leave a big effect on energy equality and social practices. (Kovač et al. 2021).

Safety

Hydrogen is an odorless, colorless, tasteless, and non-toxic gas that is 14 times lighter than air, having rapid diffusion (diffusion coefficient in NTP air is 0.61 cm^2/s) and buoyancy. He density of hydrogen is 0.08987 kg/m^3 at 0 °C and 1 atm, making it necessary to store under high pressure The gas is highly flammable with a lower flammability limit (LFL) of 4.1% and an upper flammability limit (UFL) of 74.8% in the air conditions of 25 °C temperature and 1 atm. It has an explosion range between the lower and upper limit. The Safety measures include gas detection systems and portable monitors equipped with alarms usually set at 20% and 40% LFL. The characteristics of hydrogen change when mixed with other gases based according to the volume percentage, thermodynamic properties, and ambient conditions e.g., a mixture of hydrogen/methane in 70/30 vol % in comparison to pure hydrogen has lower flame speed (142 cm/s) and detonation of the explosive mixture with air (20%), lower UFL, and slightly bigger LFL (34% and 4.5%, respectively). It also has a higher ignition temperature compared with pure hydrogen. A mixture of air and hydrogen has eight times greater maximum burning velocity from natural gas/air and propane/air mixture. (Kovač et al. 2021).

The risks in hydrogen storage include H_2 embrittlement, and the worst-case incident scenario is LH_2 storage rupture when a boiling liquid expanding vapor explosion (BLEVE) is expected. BLEVE's hazards include a blast wave, fireball, and projectile. The safety challenges in storage on the consumer side (e.g., oil refiners) has traditionally favored it's in situ production. A feasible option for hydrogen transport is by converting into a chemical carrier (e.g., ammonia)(Araújo & de Medeiros, 2023). Leakage of a flammable or detonable mixture can lead to a fire or detonation. Gas leakage when ignited can lead to deflagration and detonation hazards, whose amplitude is a function of factors like amount of hydrogen released, the air conditions, space limitation, location, and strength of the ignition source. The risk of detonation or fire is low in open spaces, but higher in closed spaces.

To ensure safe operation and to timely detect a leakage, reliable safety sensors are applied. Indoor use of hydrogen detectors is recommended for indoor fueling operations. There are safety sensors on the market that can be used for the successful deployment of hydrogen technology. Integrated use of Failure Mode and Effect Analysis (FMEA), HAZard OPerability Analysis (HAZOP), and Fault Tree Analysis (FTA) are strongly advised for prevention of hazards. The use of FMEA reduces the possibility of deficiencies, identifying the areas that are more prone to failure occurring. FMEA on the other hand reduces them by application of appropriate corrective actions. HAZOP analysis is applied is used to analyze While HAZOP analysis applied in incident identification and potential scenarios, whereas FTA analysis is used to analyze the probability of their happening. Incorporation of well-established practices in future projects, and personnel training and education in hydrogen safety, are becoming standard in hydrogen safety engineering(Kovač et al. 2021).

Strategies

The energy transition of any kind can't happen won't be achieved without implementing the political solution, developing national strategies and action plans with clear agenda, development methodology, adequate legislation, and financing. Many countries and political entities have put in place national plans for the integration of hydrogen into an energy transition, in the form of the upgrade by upgrading national energy plans with RES and clean energy production. Hydrogen use has spread out across the globe from most urban places to places with quality hydrogen development away from R&D centers, like is the case with Patagonia(Kovač et al. 2021)

Recommendations

The following policy actions are recommended to enable hydrogen contribution to the energy transition:

i.) Provide long-term and stable policy frameworks to enable transition in all sectors i.e., energy, transport, industry, and residential.

ii.) Develop coordination and incentive policies that support deployment of hydrogen energy solutions and adequate private sector investments.

iii.) Ensure strong coordination in the transport sector among governments, car manufacturers, infrastructure providers, and consumers of transport sector products and services.

iv.) Reform the energy sector in terms of feed-in tariffs, manage net of curtailment, seasonal balancing of capacity, remuneration and taxation, with due regard of benefits of hydrogen to the energy system.

v.) Provide financial instruments to motivate private sector investment by mitigating risks through instruments like public guarantees for early movers.

vi.) Harmonise industry standards across sectors and regions to enable hydrogen technologies and capitalize on cost reduction(Hydrogen Council, 2017)

Conclusion

as environmental concerns grow due to greenhouse gas emissions and environmental sustainability, hydrogen has emerged as a fuel for multiple applications transport, power generation, and heat production. hydrogen and fuel cell technologies potential to enable this transition to a clean, low-carbon energy system in a transformation that will result in significant reduction in greenhouse gas emissions and better air quality hydrogen can store and move energy, enabling exportation but its application in the energy sector remains restricted, The grates obstacle to the wider application of hydrogen is its since renewable hydrogen can be produced by splitting water which is an energy-intensive process with most of electricity globally coming from fossil fuel and nonrenewable sources. Since currently energy needed to produce renewable hydrogen is more than the energy in hydrogen, hydrogen is more as an energy carrier rather than an energy source. Hydrogen is a renewable, emission-free fuel when created with renewable energy sources like solar and wind.

Since hydrogen is a highly flammable fuel, to ensure safe operation and to timely detect a leakage, reliable safety sensors are applied. Indoor use of hydrogen detectors is recommended for indoor fueling operations. There are safety sensors on the market that can be used for the successful deployment of hydrogen technology. The growth of hydrogen technology is already at a satisfactory level for its complete involvement in the energy transition strategies with several ongoing R&D projects estimating a rapid increase in hydrogen usage. The hydrogen has grown significantly proving the significant potential of hydrogen technology with focus set solve legislation, market growth, preparing industries and economics for the growth of hydrogen-based systems, and promoting global interconnection and cooperation of various sectors and regions to integrate hydrogen energy.

For hydrogen to take its rightful place in the energy transition, as with other energy technologies is sufficient development of the technology itself. Years of R&D of hydrogen technology seem to finally pay off. Hydrogen technology can positively cope with concurrent technologies for most applications, and even offer undoubtedly better products and services, although cost parity has not been reached yet in all aspects. As the scale of product increases, production costs will become economically profitable. The main goal of the hydrogen energy transition, is to achieve a carbon-neutral hydrogen society, based on green hydrogen, . Green hydrogen is produced via water electrolysis using renewable electricity. As the production and s share of green hydrogen grows globally, hydrogen is expected to be price competitive to the grey hydrogen production, which is produced from fossil fuels. within a decade. The cost parity can be achieved through increase in technical efficiency, equipment cost reduction and reduction in material prices, and manufacturing scaled up to achieve economies of scale. which are currently in progress in several countries.

References

Admin, A. (2020, September 15, 2020). *Green hydrogen from biogas*. H2 International. Retrieved 1 July 2022 from https://www.h2-international.com/2020/09/15/green-hydrogen-from-biogas/

Alves, H. J., Bley Junior, C., Niklevicz, R. R., Frigo, E. P., Frigo, M. S., & Coimbra-Araújo, C. H., Overview of hydrogen production technologies from biogas and the applications in fuel cells. *International Journal of Hydrogen Energy*, *38*(13), 5215-5225, 2013. https://doi.org/https://doi.org/10.1016/j.ijhydene.2013.02.057

Antonini, C., Treyer, K., Streb, A., Mijndert, v. d. S., ac,, Bauer, C., & Mazzo, M. , Hydrogen production from natural gas and biomethane with carbon capture and storage – A techno-environmental analysis. *Sustainable Energy & Fuels*, *2020*(4), 2967. https://doi.org/https://doi.org/10.1039/D0SE00222D

Araújo, O. Q. F., & de Medeiros, J. L. , Hydrogen in the energy transition: some roles, issues, and questions. *Clean Technologies and Environmental Policy*, *25*(7), 2071-2073, 2023. https://doi.org/https://doi.org/10.1007/s10098-023-02593-1

Ashraf, M. T., Schmidt, J. E., & Bastidas Oyanedel, J. R. (2015, 2015). *Conversion Efficiency of Biogas to Liquids Fuels through Fischer-Tropsch Process.* 23rd European Biomass Conference and Exhibition, http://www.etaflorence.it/proceedings/?detail=11205

Bairrão, D., Soares, J., Almeida, J., Franco, J. F., & Vale, Z., Green Hydrogen and Energy Transition: Current State and Prospects in Portugal. *Energies*, *16*(1), 2023.. https://www.mdpi.com/1996-1073/16/1/551

Blok, K., Williams, R. H., Katofsky, R. E., & Hendriks, C. A., Hydrogen production from natural gas, sequestration of recovered CO2 in depleted gas wells and enhanced natural gas recovery. *Energy*, *22*(2), 161-168,1997. https://doi.org/https://doi.org/10.1016/S0360-5442(96)00136-3

Boden, T. A., Marland, G., & Andres, R. J., *Global, Regional, and National Fossil-Fuel CO2 Emissions* O. R. N. L. Carbon Dioxide Information Analysis Center, 2017. https://cdiac.ess-dive.lbl.gov/trends/emis/overview_2014.html

Ceylon Electricity Board. (2023). *Long term generation expansion plan 2023-2042*. Ceylon Electricity Board. file:///C:/Users/ASUS/Downloads/LTGEP%202023-2042.pdf

da Rosa, A. V., & Ordóñez, J. C. , Chapter 10 - Hydrogen Production. In A. V. da Rosa & J. C. Ordóñez (Eds.), *Fundamentals of Renewable Energy Processes (Fourth Edition)* (pp. 419-470),2022. Academic Press. https://doi.org/https://doi.org/10.1016/B978-0-12-816036-7.00021-X

Fly, A., & Thring, R. H. , System thermal and water balance in an evaporatively cooled PEM fuel cell vehicle. In *Vehicle Thermal Management Systems Conference Proceedings (VTMS11)* (pp. 267-277), 2013. Woodhead Publishing. https://doi.org/https://doi.org/10.1533/9780857094735.6.267

Guoxin, H., & Hao, H. (2009). Hydrogen rich fuel gas production by gasification of wet biomass using a CO2 sorbent. *Biomass and Bioenergy*, *33*(5), 899-906. https://doi.org/https://doi.org/10.1016/j.biombioe.2009.02.006

Hydrogen Council. (2017). *How hydrogen empowers the energy transition*. H. Council. https://hydrogencouncil.com/wp-content/uploads/2017/06/Hydrogen-Council-Vision-Document.pdf

IEA. *Nuclear Electricity*. I. E. Agency, 2022. https://www.iea.org/reports/nuclear-electricity

Kabeyi, M. J. B. (2019). Evolution of Project Management, Monitoring and Evaluation, with Historical Events and Projects that Have Shaped the Development of Project Management as a Profession. *International Journal of Science and Research (IJSR)*, *8* (12). https://doi.org/10.21275/ART20202078

Kabeyi, M. J. B., & Olanrewaju, A. O. (2021, 7-8 Oct. 2021). Performance analysis and evaluation of Muhoroni 60 MW gas turbine power plant. 2021 International Conference on Electrical, Computer, Communications and Mechatronics Engineering (ICECCME),

Kabeyi, M. J. B., & Olanrewaju, O. , Diesel to gas engine power plant conversion: a review and preliminary design for an operting power plant. *Journal of Energy Management and Technology*, *7*(2), 103-115, 2023. https://doi.org/https://doi.org/10.22109/jemt.2022.292982.1312

Kabeyi, M. J. B., & Olanrewaju, O. A. (2022a). Biogas Production and Applications in the Sustainable Energy Transition. *Journal of Energy*, *2022*(8750221), 43. https://doi.org/https://doi.org/10.1155/2022/8750221

Kabeyi, M. J. B., & Olanrewaju, O. A. (2022b, April 5-7, 2022). *Conversion of diesel and petrol engines to biogas engines as an energy transition strategy* 4th African International Conference on Industrial Engineering and Operations Management, Nsukka, Nigeria. https://ieomsociety.org/proceedings/2022nigeria/448.pdf

Kabeyi, M. J. B., & Olanrewaju, O. A. (2022c, July 26-28, 2022). *Energy and environment: oportunities and challenges for the energy transition* Fifth European Conference on Industrial Engineering and Operations Management, Rome, Italy. https://ieomsociety.org/proceedings/2022rome/427.pdf

Kabeyi, M. J. B., & Olanrewaju, O. A. (2022d). Performance evaluation of Kipevu-III 120 MW power station and conversion to dual-fuel power plant. *Energy Reports*, *8*(16), 800-814. https://doi.org/https://doi.org/10.1016/j.egyr.2022.11.064

Kabeyi, M. J. B., & Olanrewaju, O. A. , Sustainable Energy Transition for Renewable and Low Carbon Grid Electricity Generation and Supply [Review]. *Frontiers in Energy Research*, *9*(743114), 1-45, 2022. https://doi.org/https://doi.org.10.3389/fenrg.2021.743114

Kabeyi, M. J. B., & Olanrewaju, O. A. (2022f). Technologies for biogas to electricity conversion. *Energy Reports*, *8*(Supplement 16), 774-786, 2022. https://doi.org/https://doi.org/10.1016/j.egyr.2022.11.007

Kabeyi, M. J. B., & Olanrewaju, O. A. , The levelized cost of energy and modifications for use in electricity generation planning. *Energy Reports*, *9*, 495-534, 2023. https://doi.org/https://doi.org/10.1016/j.egyr.2023.06.036

Kabeyi, M. J. B., & Olanrewaju, O. A. (2023b). Life cycle assessment of energy sources and applications. *AIP Conference Proceedings*, *3018*(1), 020015. https://doi.org/10.1063/5.0171603

Kabeyi, M. J. B., & Olanrewaju, O. A. , Life cycle carbon emissions of energy sources. *AIP Conference Proceedings*, *3018*(1), 020017,2023. https://doi.org/10.1063/5.0171605

Kabeyi, M. J. B., & Olanweraju, O. A. (2022, March 7-10, 2022). *Sustainability Assessment for Non-Combustible Renewable Power Generation* 12th Annual Istanbul International Conference on Industrial Engineering and Operations Management, Istanbul, Turkey. https://ieomsociety.org/proceedings/2022istanbul/429.pdf

Kabeyi, M. J. B., & Oludolapo, A. O. (2020, 5-7 December 2020). *Development of a Biogas Plant with Electricity Generation, Heating and Fertilizer Recovery Systems* 2nd African International Conference on Industrial Engineering and Operations Management, Harare, Zimbabwe. http://ieomsociety.org/harare2020/papers/82.pdf

Kabeyi, M. J. B., & Oludolapo, A. O. (2020, 5- 7 December 2020). *Optimization of Biogas Production for Optimal Abattoir Waste Treatment with Bio-Methanation as Solution to Nairobi Slaughterhouses Waste Disposal* 2nd African International Conference on Industrial Engineering and Operations Management, Harare, Zimbabwe. http://ieomsociety.org/harare2020/papers/83.pdf

Kabeyi, M. J. B., & Oludolapo, A. O. (2020, 14-17 December 2020). *Performance Analysis of an Open Cycle Gas Turbine Power Plant in Grid Electricity Generation* 2020 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM), Singapore, Singapore. https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=9309840

Kalamaras, C. M., & Efstathiou, A. M. (2013). Hydrogen Production Technologies: Current State and Future Developments. *Conference Papers in Energy*, *2013*, 690627. https://doi.org/10.1155/2013/690627

Karuppiah, T., & Azariah, V. E. (2019). Biomass Pretreatment for Enhancement of Biogas Production. . In *Anaerobic Digestion.* IntechOpen. https://doi.org/https://doi.org/10.5772/intechopen.82088

Klatzer, T., Bachhiesl, U., & Wogrin, S. (2022). State-of-the-art expansion planning of integrated power, natural gas, and hydrogen systems. *International Journal of Hydrogen Energy*, *47*(47), 20585-20603. https://doi.org/https://doi.org/10.1016/j.ijhydene.2022.04.293

Kovač, A., Paranos, M., & Marciuš, D. (2021). Hydrogen in energy transition: A review. *International Journal of Hydrogen Energy*, *46*(16), 10016-10035. https://doi.org/https://doi.org/10.1016/j.ijhydene.2020.11.256

Li, Y. (2014). *Converting Biogas to Transportation Fuels*. https://ohioline.osu.edu/factsheet/AEX-653.2

Lyng, K.-A., & Brekke, A. (2019). Environmental Life Cycle Assessment of Biogas as a Fuel for Transport Compared with Alternative Fuels. *Energies*, *12*(3), 532. https://www.mdpi.com/1996-1073/12/3/532

Machado, P. G., Teixeira, A. C. R., Collaço, F. M. A., & Mouette, D. (2021). Review of life cycle greenhouse gases, air pollutant emissions and costs of road medium and heavy-duty trucks. *WIREs Energy and Environment*, *10*(4). https://doi.org/ https://doi.org/10.1002/wene.395

Moses Jeremiah Barasa, K., & Oludolapo, A. O. (2023). Biomethane Production and Applications. In A. Prof. Sevcan (Ed.), *Anaerobic Digestion - Biotechnology for Reactor Performance and Environmental Sustainability* (pp. 45). IntechOpen. https://doi.org/http://dx.doi.org/10.5772/intechopen.11205

NaturalGas.org. (2013, 20 September 2013). *Natural Gas and the Environment*. NaturalGas.org,. http://naturalgas.org/environment/naturalgas/

Ran, L., Mao, Y., Yuan, T., & Li, G. , Low-Carbon Transition Pathway Planning of Regional Power Systems with Electricity-Hydrogen Synergy. *Energies*, *15*(22), 8764,2022. https://www.mdpi.com/1996-1073/15/22/8764

Saur, G., & Milbrandt, A. (2014). *Renewable Hydrogen Potential from Biogas in the United States*. https://www.nrel.gov/docs/fy14osti/60283.pdf

Zayoud, A., Coppitter, D., Verleysen, K., Dias, V., Laget, H., Jeanmart, H., & Contino, Francesco (2022). *Importing renewable energy to EU via hydrogen vector: Levelized cost of energy assessment* ECOS 2022 - The 35th International Conference On Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy System, https://flexnconfu.eu/wp-content/uploads/2022/07/ECOS2022-165_final.pdf

Biography:

Moses Jeremiah Barasa Kabeyi is currently a doctoral researcher in the Department of Industrial Engineering at Durban University of Technology. He earned his B.Eng. degree in Production Engineering and MSC in Mechanical and Production Engineering (Energy) from Moi University, in Kenya, MA in Project planning and Management from University of Nairobi, in Kenya and Diplomas in Project management, Business management and NGO management respectively from The Kenya Institute of Management. He has worked in various factories including sugar manufacturing at Nzoia Sugar Company Ltd, pulp and paper at Pan African Paper Mills EA Ltd, and power generation at the Kenya Electricity Generating Company (KenGen) in Kenya, in an industrial career of 16 years before moving into teaching. He has taught in various universities in Kenya including University of Nairobi, Technical University of Mombasa, and Egerton University and currently on study leave. His research interests are power generation, fuels and combustion, internal combustion engines and project management and sustainability. He is registered with the Engineers Board of Kenya (EBK) and Institution of Engineers of Kenya (IEK) and has published several journal papers.

Oludolapo Akanni Olanrewaju is currently a Senior Lecturer and Head of Department of Industrial Engineering, Durban University of Technology, South Africa. He earned his BSc in Electrical Electronics Engineering and MSc in Industrial Engineering from the University of Ibadan, Nigeria and his Doctorate in Industrial Engineering from the Tshwane University of Technology, South Africa. He has published journal and conference papers. His research interests are not limited to energy/greenhouse gas analysis/management, life cycle assessment, application of artificial intelligence techniques and 3D Modelling. He is an associate member of the Southern African Institute of Industrial Engineering (SAIIE) and NRF rated researcher in South Africa.