ICEST-2K24 [International Conference on Engineering, Science and Technology]
In Association with
International Journal of Scientific Research in Science, Engineering and Technology
Print ISSN - 2395-1990 | Online ISSN : 2394-4099 (www.ijsrset.com)

Synthetic Fuels – A Review

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ABSTRACT

For almost ten years, researchers have been studying artificial fuels in an effort to identify alternative energy sources. There has been a focus on intensifying the transition recently because the world's climate circumstances are quickly drawing to an end. A wide range of substances known as synthetic fuels can be used in place of more conventional fuels like petrol and diesel. This paper offers a thorough analysis of synthetic fuels, emphasizing their categorization and methods of manufacture. After providing a thorough introduction, the article essentially categorizes the main synthetic fuels that are now produced on an industrial basis. In order to assist readers grasp the fundamental science underlying synthetic fuels, this article goes on to describe their feedstock's and manufacturing methods in further detail and includes comprehensive equations and graphs. The effects of these fuels are also examined, as are the major figures in each industry. This study intends to promote a knowledgeable conversation about the future of energy and the potential contribution of synthetic fuels to lessening our dependency on fossil fuels by highlighting the advantages and disadvantages of these fuels.

I. INTRODUCTION

People and ecosystems are impacted by climate change in a variety of ways, making it a complicated and multifaceted problem [1-3]. The necessity to promote the idea of climate change is no longer present. Even if it's a tired subject these days, it's still urgently needed. The overwhelming opinion among scientists is that human activity is the primary driver of climate change, which is occurring today and is genuine [4-6]. Global warming's effects are already being felt, and if we don't do something to solve the issue, they will probably get worse and spread faster [7-9]. Frequent heat waves [10,11], extreme weather events [12,13], rising sea levels [14], altered precipitation patterns [15], loss of biodiversity due to animals urging to withstand the rising temperatures [15], effects on human health, the economy, and so forth are some of its obvious main effects. Many people continue to see climate change as a distant or abstract threat, even in light of how urgent the issue is, and they might not even be aware of how it is already impacting their lives [16].This is partially because of the manner that political and media circles frequently address climate change. It is portrayed as a remote, technical problem that has nothing to do with people's daily lives [17, 18].In actuality, climate change poses a serious and immediate threat. The repercussions on people and ecosystems worldwide are likely to be more severe and the problem will be more difficult and expensive to solve the longer we ignore it.

Thankfully, there are a lot of climate change solutions that can be implemented right now give the resources, knowledge, and technology at our disposal. Many international climate change movements have emerged in recent decades, uniting people, groups, and governments in an effort to increase public awareness and create a roadmap for the shift to a more sustainable future. A broad spectrum of actors are also involved in the movement, from community organizers and grassroots groups to decision-makers in industry, science, and politics. There are numerous approaches to combating climate change, and the most successful one will probably include several distinct tactics. Among the most important countermeasures against climate change are:

Renewable energy: Switching to renewable energy sources like wind, solar, and hydropower is one of the most significant ways to combat climate change. Clean, plentiful, and sustainable, renewable energy can lessen greenhouse gas emissions and lessen the effects of climate change. Solar photovoltaic, wind turbine, hydroelectric power plants, geothermal energy, and tidal energy technologies are a few examples of renewable energy technology.

Energy efficiency: Reducing energy use to maintain the same level of service is a key component of energy efficiency, which is another significant response to climate change. Numerous strategies, including improved insulation, more energy-efficient appliances, and intelligent transportation networks, can help achieve this.

Carbon capture and storage (CCS): This technology stores carbon dioxide emissions underground, keeping them out of the environment by capturing emissions from power- plants and other sources. Climate change effects can be lessened and greenhouse gas emissions can be decreased with the use of CCS [19].

Synthetic fuels: Also referred to as e-fuels or artificial fuels, synthetic fuels are made from renewable or non-renewable resources and have properties similar to those of fuels obtained from fossil fuels. They can be utilized in place of conventional fossil fuels for a number of purposes, including power generation, heating, and transportation.

Carbon pricing: A strategy that uses taxes or cap-and-trade programs to set a price on carbon dioxide emissions is known as carbon pricing. As a result, companies and individuals have financial motivation to cut emissions and switch to greener technology [20].

This paper is devoted solely to the topic of synthetic fuels; it provides a quick overview of their necessity as well as an explanation of the categories and procedures involved in the creation of each main kind of synthetic fuel. The fact that synthetic fuels can replace current fuels and contribute to the reduction of greenhouse gas emissions is one of the main reasons they are being considered here and why they will be necessary in the future [21]. Fossil fuels are extensively relied upon for many critical modern activities, including transportation and electricity generation, which release copious amounts of greenhouse gases, including carbon dioxide, into the environment. This fuels climate change and other environmental issues.In contrast to fossil fuels, synthetic fuels may be created with renewable electricity, which lowers greenhouse gas emissions [22]. Porsche, a German car manufacturer, successfully tested the concept of using 100% synthetic fuel instead of fossil fuel in 2022 [23]. This fuel is made from water and carbon dioxide that is taken from the air. Further sections cover a detailed discussion of the methods required in bringing this notion to reality.Synthetic fuels are also more portable and easily stored than some other renewable energy sources, like solar and wind power [24]. This makes them a more flexible and dependable energy source. The fact that synthetic fuels can contribute to increased energy security is another reason why they will be necessary in the future [25]. Due to their heavy reliance on imported fossil fuels, many nations are susceptible to changes in price and disruptions in supply [26].

II. SYNTHETIC FUELS AND THEIR CLASSIFICATIONS

Fuels that have been chemically synthesized to imitate the physical and chemical characteristics of fossil fuels are known as synthetic fuels [27–29]. They are usually produced by chemical processes that transform non-fossil or renewable feedstock's into fuel, such as carbon dioxide, water, and biomass. They can be utilized in place of fossil fuels for a number of purposes, such as heating, power generating, and transportation [30, 31]. Given that they can be produced from carbon-neutral feedstock's like biomass or carbon dioxide that has been collected, they may be able to lower greenhouse gas emissions. Because of this, greenhouse gas can be used as a raw material to create renewable energy-based substitutes for natural gas, diesel, and petrol [32]. This indicates that the carbon dioxide extracted from the atmosphere during their creation balances the carbon dioxide emissions linked to their use and manufacturing. On the other hand, burning fossil fuels releases a significant amount of carbon dioxide, which contributes to climate change. In addition, they may be able to supply a more consistent and dependable energy source for transportation than electric batteries [31]. Electric batteries are an effective and clean energy source, but they are dependent on the grid for electricity, which can be interrupted by power outages or natural disasters. Contrarily, synthetic fuels are more resilient to disturbances because they can be transported and stored like conventional fossil fuels [33].

The development and application of new technology, as well as the enactment of laws that encourage their usage, will determine the synthetic fuel industry's future, which makes predictions difficult. However, in order to lower greenhouse gas emissions and increase energy security, synthetic fuels will probably become more prevalent in the energy mix in the future.

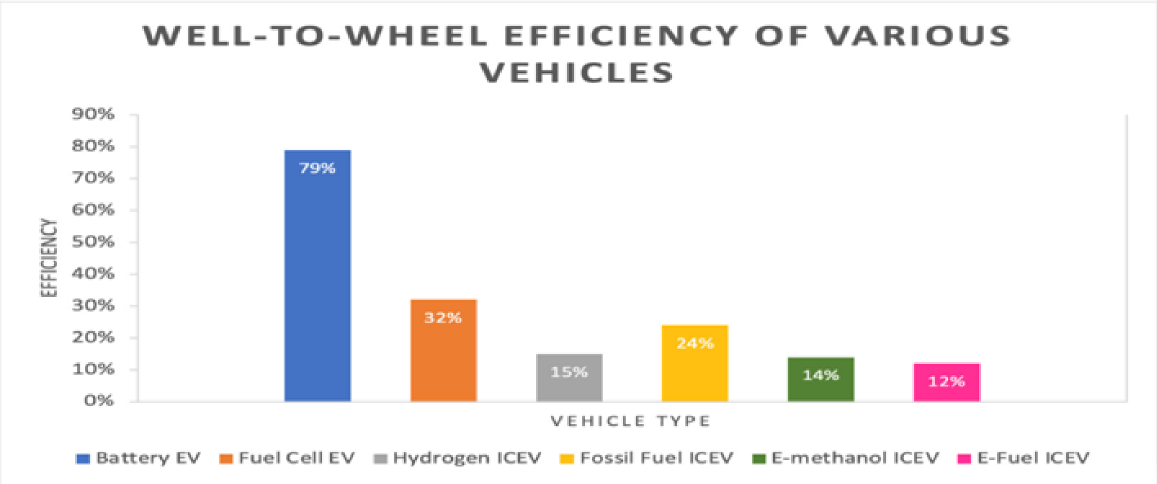

Fig 1. Chart comparison of well wheel efficiency between various fueled vehicles.

It is difficult and contextual to classify synthetic fuels into wide, mutually exclusive groupings since it depends on many of the discussed characteristics, including chemical composition, application, sustainability, feedstock, and production process. Because it makes it possible to create thicker groupings of related fuels, this study has chosen to categories synthetic fuels according to their feedstock in order to keep things simple. A deeper comprehension of the many important synthetic fuels covered in the paper can be achieved with the help of this classification scheme. The classifications depending on feedstock are-

1. Biofuels: These are artificial fuels made from biological materials, like waste materials, animal fats, or vegetable oils. Biodiesel, bioethanol, and biogas are a few types of biofuels.
2. Hydrogen fuels: These artificial fuels are created when hydrogen reacts with other molecules, most frequently carbon dioxide. Methanol, DME, and synthetic natural gas are a few fuels that fall within this category.
3. Power-to-liquid (PtL) fuels: These are synthetic fuels made by converting carbon dioxide and water into liquid fuel using electricity derived from renewable sources. Synthetic diesel, synthetic petrol and synthetic aviation fuel are a few types of PtL fuels.

III.BIOFUELS

Synthetic fuels made from animal fats, vegetable oils, and other biomass are known as biofuels [44, 45]. Feedstock, which is defined as the raw material used as input for fuel production, includes recently decomposed or live plant material as well as animal wastes used in the manufacturing of biofuels. Non-edible seeds are the source of the vegetable oil that is extracted and utilized as feedstock. For example, in India, the oil required to produce biodiesel is extracted from non-edible seeds like Neem, Mahua, Jatropha, and Karanja [46]. Other biomass feedstock's include sugarcane bagasse, rapeseed harvest, olive, agricultural residue, and waste cooking oil [47]. The feedstock for animal fat is obtained from slaughterhouses, while the feedstock for fish oil is obtained from fish processing companies.

Fuels classified as "gas-to-liquids" (GtL) are synthetic fuels made from natural gas or other gases used as feedstock's. Synthetic diesel, synthetic petrol and synthetic aviation fuel are a few types of GtL fuels. In contrast, fossil fuels are non-renewable and are derived from the remains of long-dead vegetation and fauna. In contrast, biofuels are thought to be a renewable energy source because their feedstock can be grown again endlessly. The concept of carbon neutrality states that when they are used, or burned, carbon dioxide (CO_2) levels do not increase because the majority of their ingredients are obtained from plants [48]. However, because of their similarities to fossil fuels, they are a desirable alternative fuel that can be employed in locations where fossil fuels are currently used, such as internal combustion engines.

Four "generations" of biofuels have been identified based on the kind of feedstock that is utilized [49]. The feedstock for first-generation biofuels comes exclusively from sources that are related to food. When we talk about food-based, we're talking about plants and animals that humans eat. These consist of sugarcane, vegetable oils, carbohydrates, cereal crops, and animal fats from meat. Microorganisms that ferment the feedstock and then process it to produce the necessary biofuel are primarily responsible for this generation's production [50]. After harvesting crops and removing all of their edible portions, non-food sources including wood, straw, and other leftover materials are used to produce the second generation [50]. They are also known as cellulosic biofuels because of their high cellulose component. Animal fats and oils that are not edible are also a part of the second generation. Because they are also known as algal biofuels, certain species of oil-producing algae create the third generation. Since there is a limited supply of this type of biofuel for production, large-scale production using these methods is currently being developed [51]. The fourth generation, the last and most recent sector, is created in state-of-the-art labs using cutting-edge biochemistry procedures. But before this generation is commercially used, it must first undergo experimentation [52].

Figure 2 depicts the generational groupings. Among the notable biofuels are biodiesel, bio-ethanol, bio-methanol, biogas, bio hydrogen, bio ethyl tertiary-butyl ether (ETBE), and bio MTBE.

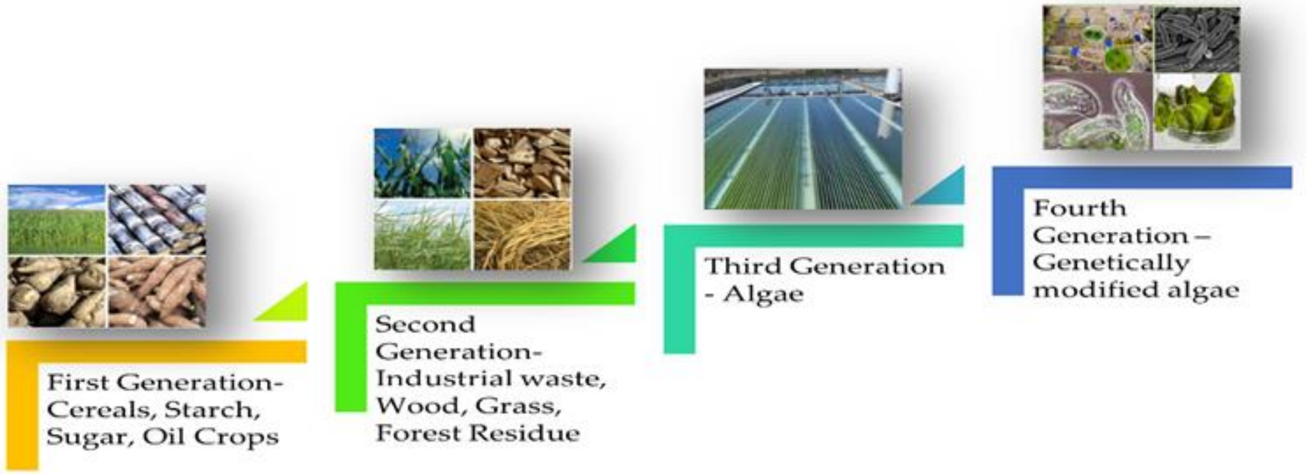

Fig 2 – Generations of Bio-Fuels

Biodegradability, non-flammability, low toxicity, safety, high combustion efficiency, abundance, lubricating nature, high cetane number, reduced emission, and renewability are some of the benefits of biofuels. Low calorific value, nitrous oxide emissions, short shelf life, and a propensity to induce engine wear are some of its drawbacks [53, 54]. Because of their miscibility, they can be combined with fossil fuels or used in their pure form [55]. Blends of biodiesel are referred to by the notation Bxx, where xx denotes the percentage of biofuel in the mix. B40, for instance, denotes a blend of 40% biofuel and 60% fossil gasoline. Existing internal combustion engines can use a blend up to B20 without requiring modifications to their structural design [56].In the subsections that follow, the commonly manufactured and consumed biofuels are covered in more detail, along with details about their production methods and pertinent graphics. The European Union is the biggest producer of biofuels as of 2022. Its most recent, ambitious policies are to blame for this [57].

3.1 Bio Diesel

Fatty acid alkyl esters, or FAAEs, are the building blocks of biodiesel, which is regarded as a competitive low-carbon diesel substitute, especially for the transportation industry [58,59]. Four basic processes can be used to make biodiesel: pyrolysis, trans esterification, micro-emulsion, and oil blends. Because of the high quality of gasoline generated, the trans esterification route is the most chosen one [60]. The fatty acids in vegetable oil or animal fat are transformed into esters by the environmentally benign chemical process of trans esterification [55]. Usually, an alcohol, like methanol or ethanol, and a catalyst, such potassium hydroxide or sodium hydroxide, are used in this reaction [61,62]. Temperature is the characteristic that affects yield the most, followed by reaction time and pressure. The trans esterification reaction's overall response is-

Triglyceride + ROH + NaOH   Biodiesel + Glycerol (1)

Glycerol is a byproduct of this process that is usually extracted and used in other applications, including soap or animal feed. The fatty acids in the vegetable oil or animal fat combine with the alcohol in this reaction to form biodiesel and glycerol [63, 64]. The process of producing biodiesel is comparatively easy to understand and may be done on a small or large scale with a range of different feedstock's. In comparison to diesel derived from petroleum, biodiesel is a flexible fuel with many uses that provides a number of benefits, such as better air quality, lower greenhouse gas emissions, and increased energy security [65–67]. It is noteworthy that while FT-diesel (examined in subsequent parts) is often frequently referred to as biodiesel, it is distinct from the FAME biodiesel that is the subject of this section [68]. The high cost and low efficiency of biodiesel are major barriers to its widespread commercialization [69]. The availability of this fuel is further limited by the high cost of feedstock and the absence of infrastructure necessary to transport substantial volumes of biodiesel from refineries to densely populated areas. Several businesses and groups are actively engaged in the creation, testing, and production of biodiesel as of 2022. Neste, a Finnish enterprise, is a prominent manufacturer of sustainable diesel fuel. The company makes sustainable diesel and other synthetic fuels from a variety of feedstock's using a patented process called "NexBTL" that was first introduced in 1997 [70]. As of 2022, World Energy, a US-based business with a network of production sites throughout the country, is a top producer of renewable diesel and biodiesel.

3.2 Hydrogenated Vegetable Oil (HVO)

Triglycerides and fatty acids are found in a range of vegetable oils and fats that are used to make HVO, an alternative fuel. Hydro-processed esters and fatty acids, or HEFA, are sometimes known as HVO [71]. Green diesel or renewable diesel are some names for it. It is produced by hydrocracking and hydrogenating paraffinic hydrocarbon lipid forms, with vegetable oil, tallow, and animal fat serving as its feedstock [72]. Out of all the feedstock's, rapeseed has the greatest product yield of HVO [73]. While biodiesel is manufactured through trans esterification, HVO is made through a hydro treated technique, despite both products being derived from similar feedstock's [74]. This distinction aids in enhancing HVO's oxidative stability. This makes it more resistant to bacterial development than biodiesel, which makes it a superior option for intermittent and long-term uses [75]. Although it has a lower density and energy content than fossil diesel, its chemical properties are similar to those of diesel [76]. In addition, it lacks oxygen, sulphur, aromatic hydrocarbons and has a high cetane number [77]. Currently ranked as the second most popular renewable diesel substitute, it is combined with fossil diesel blends that are sold at gas stations [78–80]. Figure 3 displays the HVO manufacturing flow diagram. Equation (2) shows the general reaction for the formation of HVO.

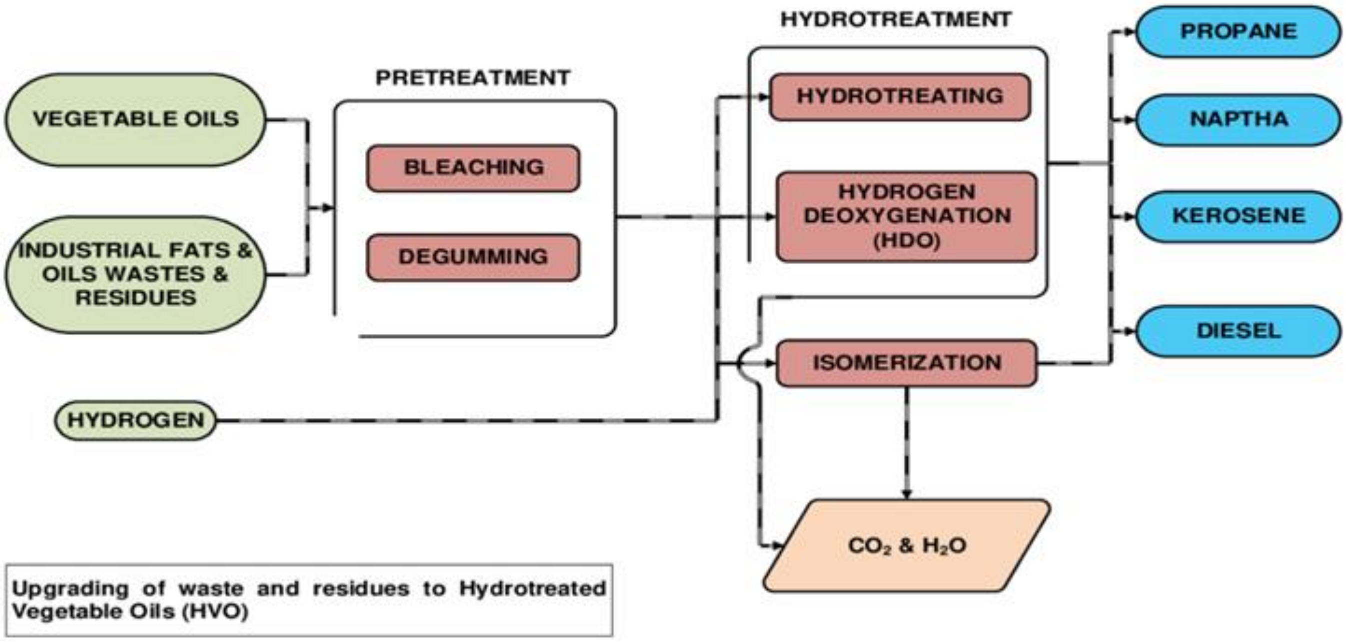

Fig 3 HVO Production Process

HVO manufacture is a multi-step, intricate process that calls for specific tools and knowledge [81]. The fatty acids in the vegetable oil or animal fat are first transformed into paraffin, olefins, and naphthene by a sequence of chemical processes, as illustrated in the equation. These chemicals are then combined to generate the HVO fuel [82, 83]. Compared to biodiesel, the resultant fuel has several benefits, such as increased stability, increased energy density, and enhanced handling qualities. Because of this, HVO is being utilized more frequently in place of diesel derived from petroleum in a number of applications.HVO has higher capital requirements for manufacturing than synthetic and biodiesel, even if it is comparable to them in terms of cetane number and other fluid qualities [84]. As of 2022, major participants in the large-scale production of HVO include Total, Emerald Biofuels, World Energy, Neste, Preem, Petrobras, Nippon Oil, and ENI. Major producers of gensets, marine engines, and aircraft engines, including Rolls-Royce, started making investments in its increased use in 2022 [85].

3.3 Bio-Methanol and Bioethanol

One kind of biofuel is bioethanol, which is made when yeast is used to ferment biomass, like corn or sugarcane [86]. The resultant liquid can be utilized in traditional petrol engines and combined with petrol to make fuel [87,88]. E10, which is frequently available at gas stations, is a mixture of 10% bioethanol and 90% unleaded petrol. There is also another blend called E85, which has 85% ethanol by volume. On traditional engines, this mixture cannot be used consistently because it will eventually wear down the engine [89, 90]. However, a specifically engineered E85 engine shows promise and allows for engine operation at lower temperatures [91,92]. Compared to petrol, bioethanol offers a number of benefits, such as lower greenhouse gas emissions and better air quality [93]. It is important to remember that ethanol and bioethanol are identical chemically. The nomenclature distinction suggests that bioethanol is ethanol made by fermentation, a biochemical process that primarily uses organic matter as feedstock. Harvesting the biomass, processing it into a fine powder, and combining it with yeast and water to make a mash are the stages involved in producing bioethanol. Next, the mash is fermented, usually with Saccharomyces cerevisiae [94], a species of yeast that produces alcohol from the sugars in the biomass.

To create bioethanol, the alcohol is then extracted from the mash and refined. The aforementioned procedures have been given different names, including scarification, fermentation, distillation, and ethanol dehydration. The overall biofuel feedstock categorization depicted in Figure 2 is the same as the feedstock classification of bio-methanol. The majority of biomass generated today is first generation, with sugarcane extract and starch being the most often used first-generation feedstock's for the production of methanol and ethanol [95,96]. Equation (3) shows the overall response of bioethanol production, while Figure 4 shows the process of producing bioethanol.

$$C_6H_{12}O_6\text{(biomass containing glucose)} + \text{yeast} \rightarrow C_2H_5OH\text{(ethanol)} + CO_2 \qquad (3)$$

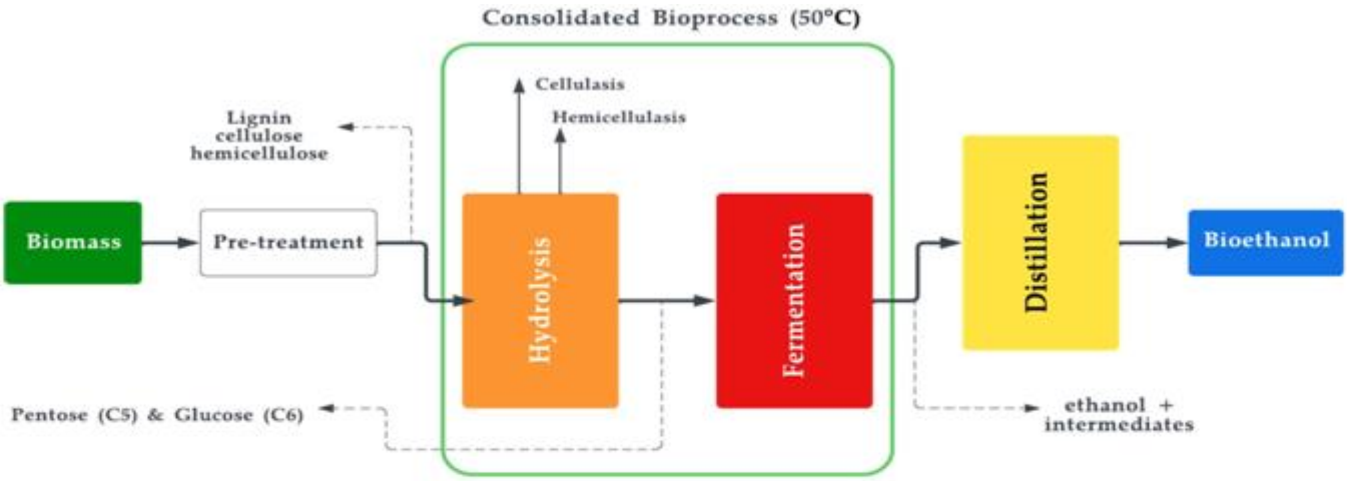

Fig 4. Bioethanol production process.

The processes used to produce bioethanol and bio-methanol are identical. It is created by employing microorganisms that can make methanol to ferment biomass, such as wood or agricultural waste [97]. The type of microbe used differs slightly from the procedure used in the manufacturing of bioethanol. The yield of ethanol/methanol varies depending on a number of factors. Temperature, pH, fermentation duration, and carbon source concentration are a few of the variables [95]. Equation (4) describes the general reaction for the generation of bio-methanol using this approach. It is noteworthy that syngas, a mixture of carbon monoxide and hydrogen produced from the gasification of biomass, is also frequently converted into methanol by catalysis around the world [98]. Methanol and ethanol production is sustainable because the majority of the processes involve the use of carbon capture technologies, biomass, and solid waste. Equation (5) shows the reverse water-gas shift reaction, which is the first step in the reaction that produces bio-methanol from syngas. Equation (6) shows the reaction that occurs when CO reacts with H2.

$$\text{Biomass} + \text{Microorganism} \rightarrow CH_3OH\text{(methanol)} \quad (4)$$

$$CO_2 + H_2 \rightarrow CO + H_2O \quad (5)$$

$$CO + 2H_2 \rightarrow CH_3OH \text{ (methanol)} \quad (6)$$

Each has advantages and disadvantages of its own; a comparison of some of these are because there is just one carbon atom in methanol, it can react with steam at lower temperatures and has the benefit of a simpler reforming process [99]. Unlike methanol, which is harmful in nature, ethanol is non-toxic [99]. When combined with petrol, ethanol performs better during combustion and exhibits less corrosion than methanol [100]. Compared to methanol, ethanol has a higher specific energy. Producing methanol is less expensive than ethanol [101]. Because of its higher equilibrium conversion and reactivity, methanol is the preferred fuel for transesterification, which produces other synthetic fuels like biodiesel [102]. While the lack of infrastructure, feedstock availability, and R&D investment risk have hindered the global development of these fuels' use, nations with cheap energy costs, like Iceland, have produced methanol at a level that is competitive with petrol [104]. Large-scale bio-methanol production has been accomplished by a number of industries, with Methanox standing as the global leader as of 2022 [105]. Other global producers of bioethanol and bio-methanol include Green Biologics Inc., LanzaTech, DuPont Industrial Biosciences, POET LLC, and GranBio. Around 2010, the Swedish Energy Board approved Chemrec, a Swedish company, to produce bio-methanol on a large scale using a unique process. Since then, other inventions have been made in this area [106].

3.4 Hydrogen Fuels

The creation of energy in the future could be significantly influenced by hydrogen energy, which is a clean, sustainable energy source. The most common element in the universe is hydrogen, which when burned merely yields heat and water as byproducts. As a result, it burns cleanly and doesn't release any damaging greenhouse gases or other pollutants. The three main methods for creating hydrogen are electrolysis, biological processes, and steam reforming. Whereas electrolysis uses electricity to divide water into hydrogen and oxygen, steam reforming uses methane and steam to make hydrogen gas. In contrast, biological processes entail the utilization of microorganisms to synthesize hydrogen from organic stuff.

At the moment, fossil fuels are the main source of hydrogen production, making it carbon-intensive. However, it is expected that hydrogen generation will become more economical and sustainable as renewable energy sources become more widely available and cost-effective. The absence of infrastructure for hydrogen transport and storage represents a significant additional obstacle [108]. The majority of hydrogen is currently transported and kept in a gaseous state, which is dangerous and necessitates costly specialized equipment. To overcome these obstacles and increase the practicality and accessibility of hydrogen energy, new technologies are being developed. Making synthetic hydrogen fuels is one of the main applications for hydrogen. Hydrogen is combined with other elements, such as carbon, oxygen, or nitrogen, to create these fuels [109]. This process yields hydrogen, which is known as "Blue Hydrogen" [121–124]. The full industrial cycle of absorbing CO2, generating H2, and creating synthetic fuels is depicted in Figure.

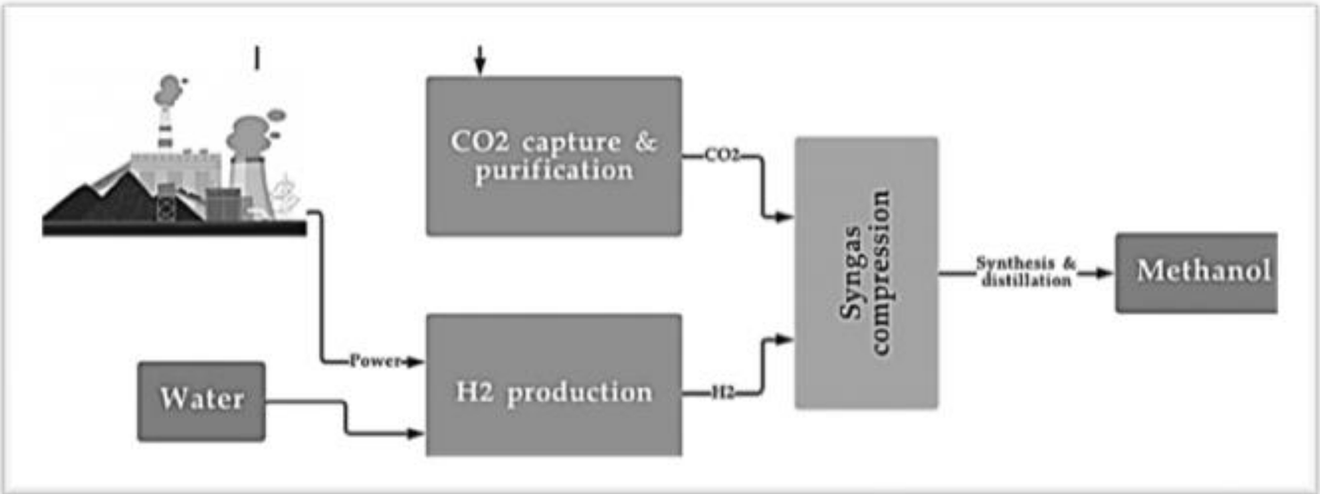

Fig 5. Synthetic fuels Production process from CO2 capture and H2 production.

Synthetic fuels based on hydrogen have their own advantages and disadvantages. Among the benefits are the fact that its feedstock (H2 and CO2) is plentiful and renewable, and that it may be generated locally, reducing the need for long-distance transportation and enhancing energy security [125–127]. The primary drawback of this product is its expensive production costs, since it necessitates sophisticated and specialised infrastructure [128,129].

3.5 Hydrogen

One clean, sustainable energy source that is useful for many different things is hydrogen. It is created by the electrolysis process, which divides water into hydrogen and oxygen with the assistance of electricity. Grey, blue, and green hydrogen are the three primary forms of hydrogen energy. Grey hydrogen is the most prevalent form of hydrogen energy and is generated from fossil fuels like natural gas. Although it has a high energy density, the process of producing it contributes to climate change by releasing carbon dioxide into the atmosphere [130]. On the other hand, green hydrogen is created using sustainable energy sources like wind and solar energy, and it is currently being pushed for widespread use in a range of applications. In Figure, all three of the major hydrogen colour codes are displayed.

Hydrogen energy is generally useful in a variety of applications. Among them are:

1. As a vehicle fuel: Cars, buses, and other vehicles can run on it. It could replace petrol and other fossil fuels because of its high energy density and capacity for energy storage and transportation.
2. In order to generate electricity, hydrogen can be consumed in a fuel cell, producing only water as a byproduct. Homes, companies, and other buildings can be powered by fuel cells because of their great efficiency [131].
3. For industrial processes: Chemical feedstock for the synthesis of chemicals, fertilizers, steel, and other synthetic fuels is what it can be used for [132,133].
4. Hydrogen can be utilized as a fuel for heating and cooling systems, offering a substitute for fossil fuels like natural gas. Because hydrogen is very reactive, electrolysis is the process that yields the cleanest form of hydrogen.
5. In order to split water into hydrogen and oxygen, energy is needed. It is one of the most popular techniques for creating hydrogen energy, and depending on the electrical source utilized, it can create both grey and green hydrogen. Alkaline, solid oxide, and proton exchange membrane (PEM) electrolysers are among the various types of electrolysers that are available [107].

An alkaline solution, like potassium hydroxide, is used as the electrolyte in alkaline electrolyzes [134]. They are not as efficient as other kinds of electrolysers, but they are comparatively easy and affordable to run [135]. Proton exchange membranes are used as the electrolyte in PEM electrolysers. They are appropriate for use in many different applications because of their great efficiency and ability to function at a wide range of temperatures. A solid oxide substance serves as the electrolyte in solid oxide electrolyzes.

Although they are extremely efficient and capable of operating at high temperatures, their production and upkeep are more costly than those of other kinds of electrolysers [136]. Uses for this kind of power are extensive. Temperature, electrolyte concentration, and electrolyte flow rate are three factors that significantly affect hydrogen yield [137].

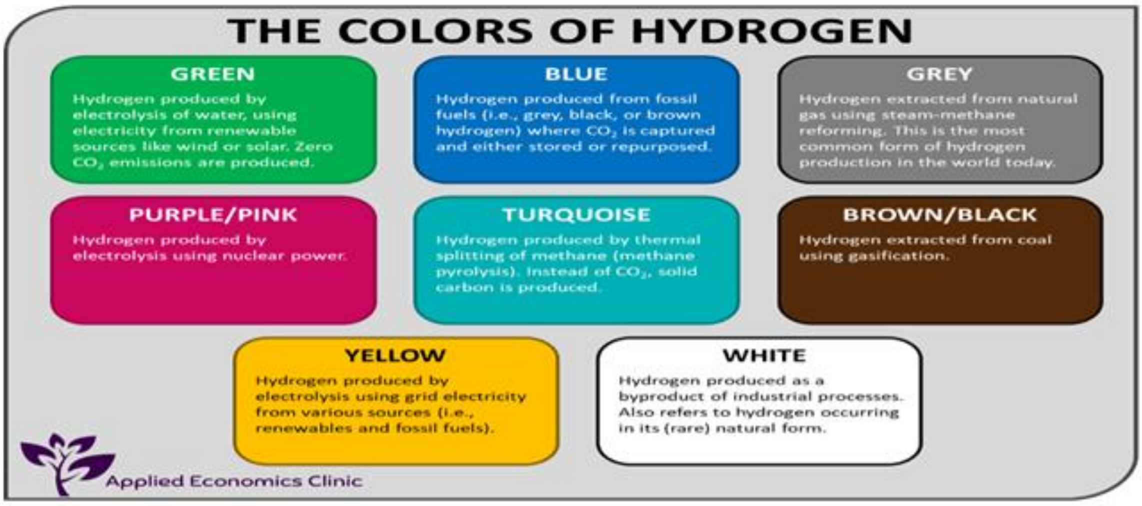

Fig 6. Popular hydrogen color codes.

Metal hydride, cryogenic, or high-pressure tanks are commonly used to store hydrogen generated through electrolysis. These days, the third kind is most commonly utilized [138]. Figure 7 shows the electrolysis procedure, and Equation (7) shows the general formula for the electrolysis of water.

$$2H_2O \rightarrow 2H_2 + O_2 \qquad (7)$$

On a worldwide basis, hydrogen energy is thought to have the potential to be very important in the shift to a cleaner and more sustainable energy system. Green hydrogen production will rise in tandem with the increased usage of renewable energy sources, thereby mitigating our dependency on fossil fuels and lowering greenhouse gas emissions. Global energy groups are currently concentrating on lowering the price of manufacturing hydrogen and increasing the effectiveness of current systems [139]. IRENA [140] is an instance of one such organization. Conversely, a number of academics and lecturers began to point out in 2021 that the hydrogen economy is a hoax orchestrated by the fossil fuel industry in an attempt to stall the present green energy transition [141–144]. Based on empirical data regarding the costs and practical efficiency of integrating hydrogen systems into the energy transition, this theory is put forth.

3.6 Syngas

Syngas, commonly referred to as synthesis gas, is a blend of gases that includes carbon monoxide (CO), hydrogen (H_2), and carbon dioxide (CO_2). It can be used as a fuel or as a feedstock to make chemicals and other synthetic fuels. Carbon-containing resources, including coal or biomass, are used as the feedstock for a multi-step process that produces syngas [145]. It is made by partially oxidising or steam reforming light hydrocarbons and gasifying heavy hydrocarbons. A carbon-containing feedstock is first gasified by heating it in the presence of partial oxygen but without air, causing the feedstock to split into its component gases. Nitrogen (N_2), which is passive and does not take part in any reactions, is typically present in the mixture together with H_2, CO_2, CO, CH_4, and CH_4 [146]. The water-gas shift reaction (WGSR) is used when the ratio needs to be lowered in order to raise the H_2 concentration and lower the CO content. This is accomplished by reforming the mixture with steam, improving its suitability for use as fuel or in the synthesis of other fuels [148]. The value of the ratio reflects the amount of air required to burn the fuel. The syngas equivalency ratio is a measure of the ratio of the actual fuel-air ratio to the stoichiometric fuel-air ratio required for full syngas combustion [153,154]. High-quality syngas can be produced at any combination of temperature and pressure by modifying the ideal ER ratio. The syngas production process is shown in Figure 8. The process and feedstock utilized in syngas generation determine its sustainability. The production of syngas from fossil fuels may have negative environmental effects. Furthermore, even with the use of renewable feedstock's, there are sustainability issues because the production process needs a large quantity of energy, which is frequently derived from fossil fuels.

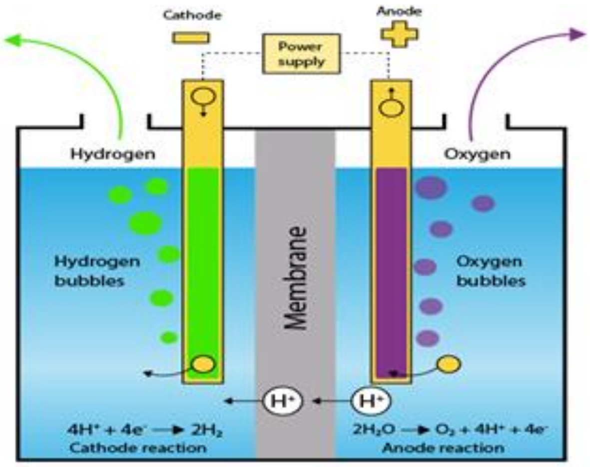

Fig 7. Electrolysis reaction

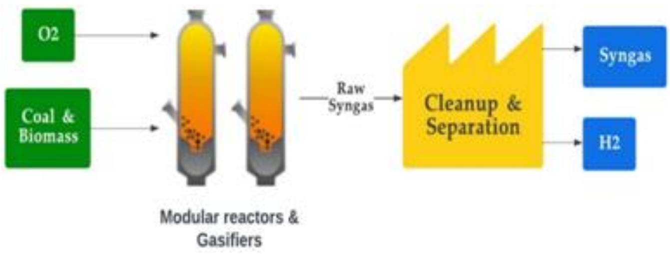

Fig 8. Production of syngas.

Syngas is widely utilised in the manufacturing of transportation fuels like jet fuel and diesel, as well as chemicals like methanol and synthetic natural gas (SNG) [155,156]. Commercial-scale production of syngas from the gasification of biomass is hampered by the lack of technology necessary for stable syngas production [157]. The different applications of syngas are shown in Figure 9 [158]. In the syngas production market, Royal Dutch Shell, Air Liquid, Linde Plc, Maire Tecnimont SpA, and Technip Energies NV are a few of the industrial businesses with a strong competitive landscape.

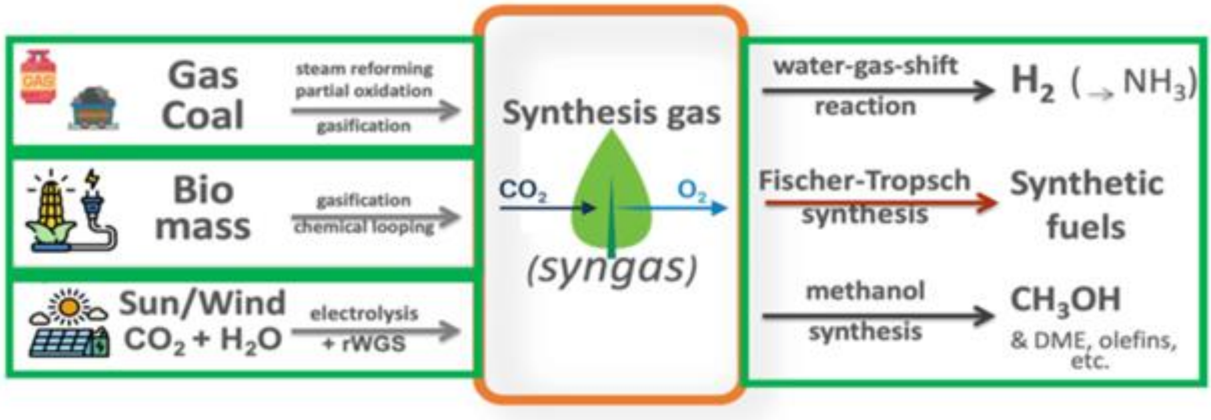

Figure 9. Production of various synthetic fuels from synthesis gas.

3.7 Methanol

Methanol is a flammable liquid that is commonly used as a solvent, a fuel, or a chemical intermediate [159–161]. It can be used in a variety of applications, including as a fuel for vehicles and as a feedstock for the production of other chemicals and materials. When used as a fuel, it produces relatively low levels of carbon monoxide and particulate matter and does not produce sulphur dioxide, which makes it a cleaner burning fuel [162,163]. One of the main advantages of methanol is that it can be produced from a variety of renewable and waste materials, such as biomass, waste gases, and waste plastics. Some of the sources of waste gases include coal oven gas, landfill gas, gas from palm kernel shell (PKS) solid waste and gas from empty fruit bunch (EFB) solid waste [164–166]. The source of plastic is majorly from the product and plastic packaging composition of municipal solid waste. This makes it a potential alternative to fossil fuels and a way to reduce greenhouse gas emissions and air pollution. There are several methods for producing methanol, the existing methods are:

Carbon monoxide hydrogenation: This process creates hydrogen and methanol by reacting carbon monoxide with water [167]. The CO needed for this process is produced industrially by reforming natural gas [98]. This section will go over this approach in more depth.

1. Biomass fermentation: This method produces methanol by fermenting biomass, such as wood or agricultural waste. In essence, it turns methane from biomaterials into methanol. This kind, which was covered in-depth in the preceding sections, is also referred to as bio-methanol. Usually applied on a small scale, this process is utilized to turn waste products or other low-value feedstock's into methanol. The feedstock's for all varieties of methanol are shown in Figure 10.
2. Direct conversion of methane to methanol: The conventional (indirect) method is used in the industrial process of transforming methane to methanol, but it is expensive due to its high energy needs. To achieve cost-effectiveness and feasibility, direct conversion routes for methane to methanol, including plasma, photocatalytic, supercritical water, and biological routes, have been established [98]. These technologies are still in the early phases of development, and it will take five to twenty years for them to become industrially viable.

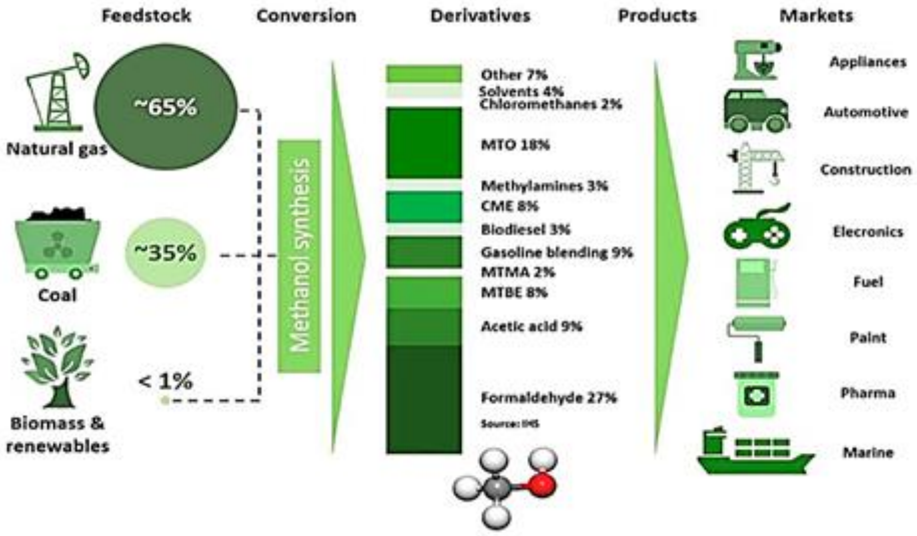

Fig 10. Various Feedstock's of methanol

Traditionally, natural gas is used to generate methanol on a big scale. Since the natural gas (methane) is first reformed to make CO and then hydrogenated in the presence of a catalyst (such as ZnO2 or copper chromite) to produce methanol, this process is regarded as indirect. High temperatures and pressures are usually used during the process, which aids in accelerating the reaction and increasing the methanol output. Since the reaction is exothermic—that is, it emits heat—cooling devices are usually used to remove the heat before the reaction gets out of hand. This technology has the benefit of being able to be produced on a small scale, and it can be used to manufacture methanol from feedstock's high in carbon or waste gases. This makes it a potentially cost-effective and environmentally friendly process for making methanol, as well as a means of lowering air pollution and greenhouse gas emissions. The process of hydration of carbon monoxide to produce methanol does have several drawbacks, though. High-quality catalyst and specialist equipment are needed for the process, both of which might raise costs. Figure 11 provides a visual representation of the method described above.

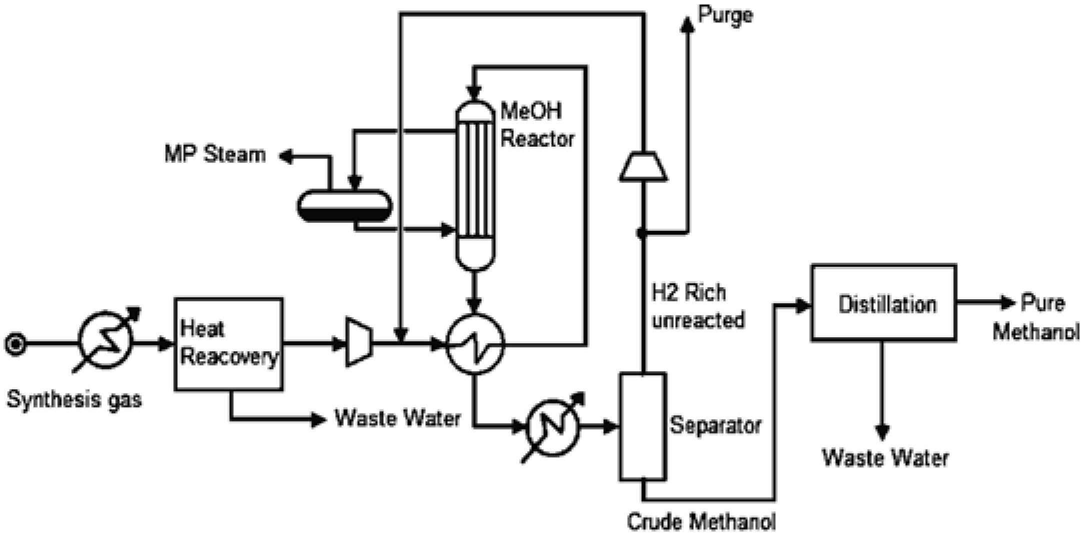

Fig 11. Methanol synthesis

3.8 Synthetic Diesel

Production of synthetic diesel can be divided into PtL and GtL categories. The PtL diesel synthetic fuel, which is created by transforming H2 and CO2 into liquid hydrocarbons, is the subject of discussion in this section. It's also critical to remember that biodiesel is an ester, whereas this is a hydrocarbon. This suggests that it is basically the same as HVO, with the exception that synthetic diesel is produced by a distinct chemical process. It is made using a procedure called the Fischer-Tropsch process, which, as Figure 9 [191] illustrates, combines hydrogen and carbon monoxide to create a range of liquid hydrocarbons, including jet fuel, diesel, and petrol.Typically, PtL diesel is made by electrolyzing water to produce hydrogen, which is then mixed with carbon dioxide to create syngas and ultimately this synthetic fuel. There are other ways to obtain carbon dioxide, such as through industrial emissions and biogas. PtL diesel can be used in many different applications because of its high energy density and ease of storage and transportation [192]. It may be used as jet fuel for airplanes and is currently used to replace conventional diesel fuel in cars, trucks, and other vehicles. Chemicals and other industrial items are also produced using it.

Fig 12. FT diesel production from syngas - Typical Fischer–Tropsch process

The aforementioned method finds use in many other applications, such as the manufacturing of chemicals and other industrial products, as well as the creation of synthetic fuels like naphtha, synthetic diesel, and jet fuel for aviation [196–198]. When compared to the manufacturing of synthetic fuels using other technologies, the technology can be used to produce synthetic fuels at a reasonable cost. But depending on where the feedstocks come from, the energy-intensive process can be expensive in some situations and have a major negative influence on the environment [198, 199]. Following Fischer–Tropsch fuel extraction, the leftover byproducts are treated using the water–gas shift (WGS) reaction [200]. This chemical process converts CO and water into H2 and CO2, which can then be utilised as feedstock to produce more synthetic fuels [201]. If the energy needed to synthesise the fuel comes from renewable sources, then synthetic diesel is regarded as sustainable. The expansion of FT diesel is restricted by the technological limitations of biomass gasification on a commercial scale, as previously described in the sections. In 2022, Neste, a Finnish firm, LanzaTech, an Indian company called Carbon Clean Solutions, and Audi will be some of the major manufacturers of synthetic diesel with significant investments made in its continued advancement.

3.9 Ammonia

Chemically, ammonia is utilised extensively in many different applications, including the production of fertilizer, refrigerants, and various other compounds [209]. Ammonia can be produced by a variety of methods, such as electrochemical, thermochemical, and electrolytic processes. The Haber-Bosch process, which entails the reaction of nitrogen and hydrogen at high temperatures and pressures, is the conventional method used to create it [210]. Although the electrochemical method is much less developed than the Haber-Bosch process, it may use less energy to create ammonia [210].Because it may be made by combining nitrogen (taken from the air) with H2 (generated through electrolysis), ammonia is referred to as a "electro-fuel." The electricity required for electrolysis is generated utilising renewable energy sources, just like with any other PtL fuel. Because of its high energy density, ammonia is becoming more and more popular as a synthetic fuel. Research is being done on it as a synthetic fuel, mainly for use in boats but also in automobiles and buses [211,212]. It can also be burned in a fuel cell to generate energy, or it can be used as a chemical feedstock in a variety of industrial processes, including the manufacture of chemicals, fertilizers, and steel. Its low-cetane value, low flame speed, and poor calorific value, among other drawbacks, make it difficult to utilize in combustion engines [213]. It is necessary to use them carefully because they are also poisonous and can quickly contaminate their surroundings [214].

Ammonia also has the benefit of cracking. By applying pressure and heat, ammonia is broken down into smaller molecules like nitrogen and hydrogen. This is a particular kind of pyrolysis. Ammonia cracking is normally done in a reactor or furnace, where it is heated to high pressures (usually between 30 and 100 atm) and temperatures (usually between 400 and 600 C) [215]. Under these circumstances, the ammonia molecule's atomic bonds weaken and are susceptible to breaking, which causes smaller molecules to form. Hydrogen, a crucial fuel for fuel cells and a lucrative chemical feedstock, is frequently produced via this procedure. In Figure 16, the uses of ammonia are depicted visually. Ammonia's primary drawback is that it is poisonous and can have negative environmental effects [216]. As of 2022, CF Industries Holdings Inc., Yara, Nutrien Ltd., OCI Nitrogen, and OSTCHEM are the leading producers of ammonia worldwide.

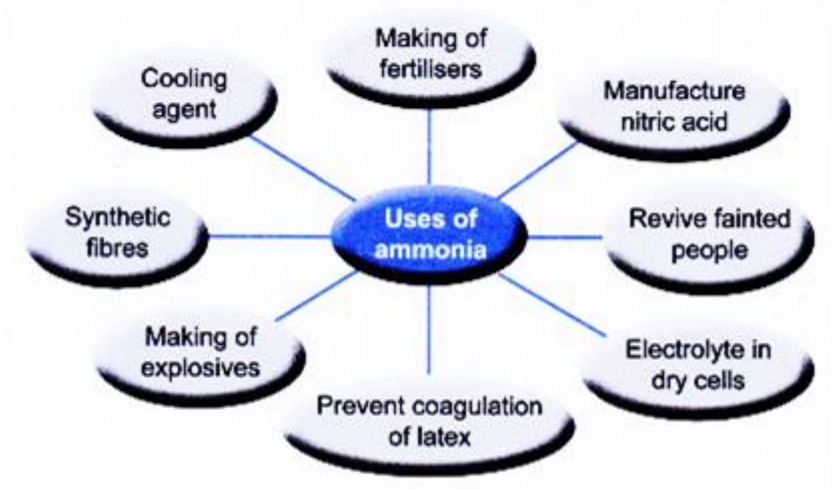

Fig 13. Uses of ammonia.

3.10 Naphtha

In the petrochemical industry, naphtha is a kind of liquid hydrocarbon that is created as a byproduct of refining crude oil [223]. It is a complex combination of hydrocarbons that can be utilized as a feedstock for the synthesis of different chemicals and fuels. It is a colorless or light yellow liquid with an aroma similar to petrol. Since naphtha may be manufactured using the FT process covered in previous sections, it is regarded as a GtL fuel [224]. Distillation is a common refinement method used to make it on an industrial basis [225]. In order to separate crude oil or coal tar into different components depending on their respective boiling points, it must first be heated and distilled [226]. After that, the mixture is put through a succession of distillation columns to remove the naphtha and other ingredients like kerosene and petrol. Usually, it is made from crude oil's middle distillates, which are the parts with a boiling point of between 200 and 300 °C. After that, hydrogen is added to the naphtha, and it is run over a catalyst—a metal or metal oxide, for example—to get rid of impurities and enhance its quality. Following purification, the naphtha is chilled and kept for later use or transfer to other facilities for additional processing. Hydrocarbons with carbon numbers between five and twelve usually make up naphtha [227]. It is composed of both olefins and n-paraffin; the olefin composition varies on the reaction pathway, where a stronger olefin composition indicates a higher octane number and, consequently, better fuel quality [228,229]. The paraffin yield quality favors high temperature and low pressure. The fractional distillation of crude oil for the manufacture of naphtha is shown in Figure 17. Crude oil is heated and distilled to separate it into different hydrocarbon components according to their boiling points during the petroleum refining process. Furthermore, a form of naphtha known as bio-naphtha is made from biomass feedstock's as opposed to fossil fuels like coal or petroleum. Bio-naphtha can be made using a biomass-to-liquid Fischer–Tropsch (BTL FT) process, which is comparable to the standard FT process [230]. The cycle of naphtha's usage is shown in Figure.

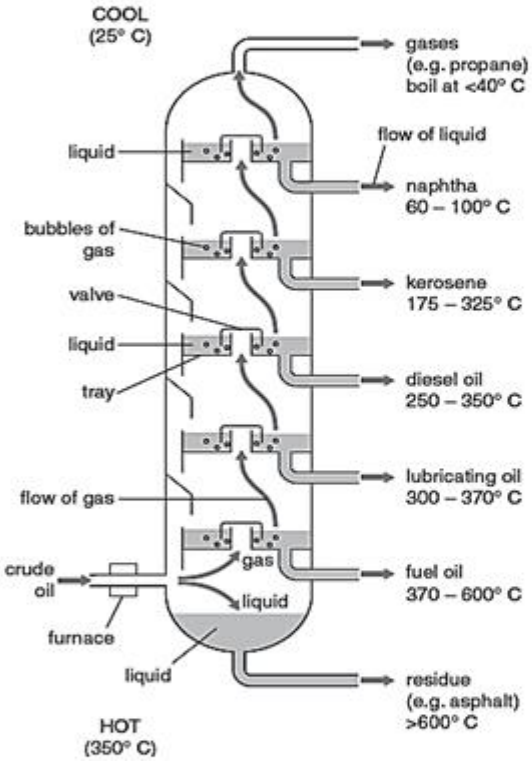

Fig 14- The fractional distillation of crude oil for the manufacture of naphtha

Uses of Naphtha:

- Feedstock for producing high octane gasoline.
- Industrial solvents and cleaning fluids
- In the home cleaning fluid
- An oil painting medium
- An ingredient in shoe polish
- An ingredient in some lighter fluids
- A fuel for portable stoves and lanterns
- As a coating for elemental lithium metal, to prevent oxidation
- As a fuel in gas turbine unit
- As the working fluid in the naphtha engine.

Fig 15 - Uses of Naphtha

Naphtha finds extensive application in the fuel and chemical sectors. It is frequently utilized as a feedstock for the synthesis of many compounds, including petrochemicals, solvents, polymers, and resins, in addition to petrol [231]. In addition, naphtha is utilized as fuel for various heating and culinary appliances, such as portable stoves. Naphtha's high energy density is one of its main characteristics, which draws interest in it as a fuel for transportation purposes [232, 233].

3.11 Liquefied Petroleum Gas (LPG)

Natural gas is extracted or petroleum is refined to create LPG, which is a mixture of propane and butane [234]. It is a GtL fuel that is made by converting natural gas or other gases into liquid form over a number of stages. In order to eliminate contaminants like water and sulphur, natural gas or other gases must first be cleaned and purified. The method of steam methane reforming is subsequently used to transform the purified gases into synthesis gas, or syngas. In this process, hydrogen and carbon monoxide are produced when the gas reacts with steam and a catalyst. Following that, the syngas is passed over a catalyst—a metal or metal oxide, for example—to transform it into a variety of hydrocarbons, including LPG [235]. As previously mentioned, LPG is also created by fractional distillation, and Figure illustrates this process' upper layer. Lower temperature, the ideal steam to feed ratio, and more trays in the furnace are the factors that encourage a high LPG yield [236].

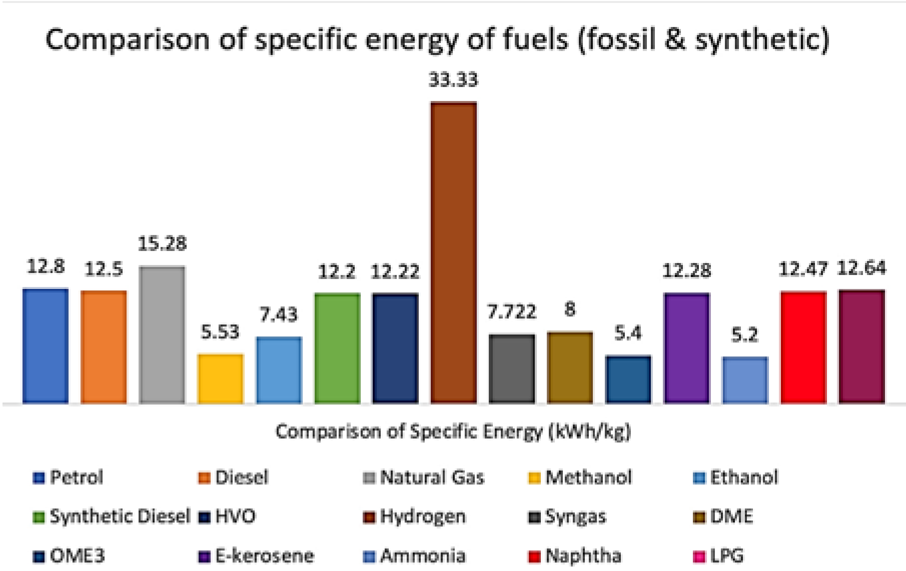

Fig 16. Comparison of specific energy of fuels

Due to its clean burning characteristics, which produce fewer pollutants than other fossil fuels, LPG is a popular choice for cooking and heating in both home and commercial settings, among its many other uses [237]. Additionally, it serves as fuel for trucks, buses, and automobiles. In addition, it serves as a solvent for a range of goods and as feedstock for the synthesis of chemicals and polymers. Propylene, which is used to make polymers, resins, and other items, is frequently produced using it [238]. Using LPG as fuel for recreational vehicles, such as boats and RVs, is a rare application of the fuel.

Many customers find it to be an appealing alternative because it is also a reasonably priced fuel [239]. Although it is widely available throughout the world, its gaseous state makes transportation challenging [240]. Its main disadvantages are its non-sustainable nature, greater engine burning temperatures, higher consumption, NOx emissions, difficulty in transportation, and high equipment costs [241]. Compared to other fossil fuels, LPG has a far smaller environmental impact even though it is not sustainable. China and India are the two countries that consume LPG at the moment (2022); the main producers of LPG in India are Indian Oil Corporation Ltd., Bharat Petroleum Corporation Limited, Hindustan Petroleum Corporation Limited, and Reliance Petroleum Ltd.

IV. CONCLUSION

To address the effects of climate change and lessen the likelihood of its unfavorable effects, governments everywhere have set goals and roadmaps for reaching net zero carbon emissions. Organizations like the Intergovernmental Panel on Climate Change (IPCC), the International Energy Agency (IEA), and the United Nations Framework Convention on Climate Change (UNFCCC) are keeping an eye on these activities. Annual conferences such as the United Nations Climate Change Conference (COP), the Global Summit on Climate Action (GSCA), and the Carbon Pricing Leadership Coalition (CPLC) Annual Conference are held to discuss progress towards these aims and to exchange ideas and best practices. While growing nations like China and India have set their targets at 2060 and 2070, respectively, developed nations like the US, the EU, the UK, Japan, Australia, and so forth have set their net zero targets at 2050. These initiatives show a dedication to making the shift to a low-carbon, more sustainable future.

The following are the main obstacles that prevent nations from achieving their net-zero emissions targets:

Cost: Making the switch to emissions-free or low-carbon technologies can be costly. Fossil fuels are a major source of energy for many nations, and moving away from them would necessitate large expenditures in new infrastructure.

Technical difficulties: Making the switch to low-carbon or zero-emission technologies may present certain technical difficulties, such as the requirement to create new technologies or alter current ones.

Political obstacles: Since the shift to net zero emissions may call for major policy adjustments and the enactment of new rules, political obstacles could arise. This can be challenging to do, especially if some societal groups or sectors are resistant to change. Changes in behavior are also necessary to reach net zero emissions; for example, people and companies must use energy-efficient practices and low-carbon modes of transportation. It can be challenging to get someone to change their behavior, especially if they are resistant to it.

International cooperation: Since global emissions must be decreased to achieve net zero emissions, cooperation between nations will be necessary. This can be difficult since different nations may not agree on the best course of action and have different objectives.

In relation to this paper's specialty, the obstacles to the widespread adoption of synthetic fuels in underdeveloped nations are their high production costs, inadequate infrastructure, low consumer awareness, and funding requirements. Because they are currently far more expensive to create than fossil fuels, both producers and consumers find synthetic fuels to be less appealing. They need specific distribution and storage infrastructure, which may not exist in many places. Adoption is challenging due to a lack of consumer knowledge and comprehension. However, as part of the energy transition and decarburization initiatives, plans to offer subsidies for synthetic fuels have been planned. These subsidies include grants for pilot projects, tax breaks, and financing for research and development in order to encourage the creation and use of synthetic fuels. Generally speaking, their goals are to lower the price of creating synthetic fuels, particularly hydrogen, and to promote the advancement and application of these technologies. The most heavily supported synthetic fuel is hydrogen in particular, as it has the potential to be a major player in the shift to a low-carbon energy system. Numerous feedstock's can be used to make hydrogen, which is also used as a feedstock for other synthetic fuels. Because of its high specific energy, hydrogen has much more potential than any other fuel now in use, both synthetic and fossil.

Figure 19 shows a comparison of particular energies in Lower Heating Value (LHV) [76,178,242–245]. Synthetic fuels can be made in a variety of ways, and the methods used to generate them can also range greatly. However, a lot of the procedures involved in producing synthetic fuels are related to one another because they frequently use comparable catalysts or other chemical processes, share similar raw materials, and go through similar beginning phases of synthesis. Furthermore, certain fuels are made using feedstock that is another fuel. The majority of the processes that are discussed in the study are related to one another, and Figure 20 provides an overview of all the manufacturing processes that are presented.

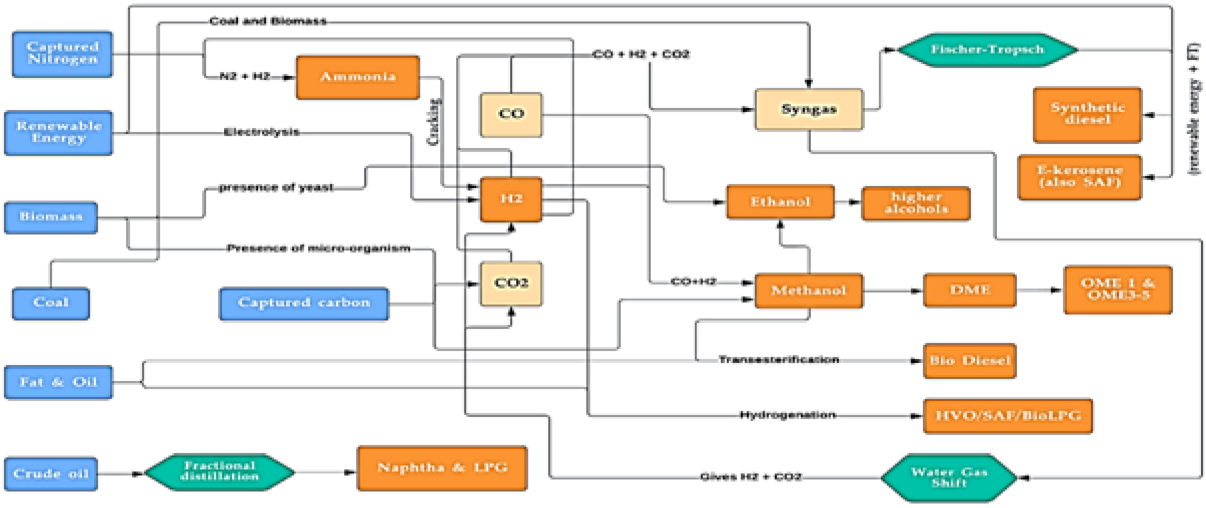

Fig 17 overview of all the manufacturing processes

It is challenging to forecast with precision how much energy hydrogen and e-fuels will provide to a net zero global economy, though, as this will rely on a number of variables, such as policy choices, raw material availability, economic conditions, and technology advancements. One of the main forces behind this expansion is the rising need for decarbonized and sustainable energy sources, and it is crucial to take into account every possible route towards sustainability. The main reason for the need is because synthetic fuels can be produced from waste, which means that in the future, they may be a more cost-effective option than traditional fossil fuels.

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