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Review Article

Synthetic Fuels as a Cornerstone of Net-Zero Emissions: A Review of Production Methods and Future Prospects

Net Sıfır Emisyonun Temel Taşı Olarak Sentetik Yakıtlar: Üretim Yöntemleri ve Gelecek Perspektiflerinin İncelenmesi

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Öz

Yenilenebilir enerji ve karbondioksitin (CO_2) dönüştürülmesiyle üretilen sentetik yakıtlar, elektrifikasyonun zor olduğu havacılık, deniz taşımacılığı ve ağır sanayi gibi sektörlerin karbonsuzlaştırılması için umut verici bir çözüm olarak öne çıkmaktadır. Bu derleme makalesi, beş temel sentetik yakıt türünü—sentetik hidrokarbonlar, metanol, amonyak, sentetik doğal gaz (SNG) ve hidrojen/yeşil hidrojen—kapsamlı bir şekilde analiz etmektedir. Her bir yakıt türü, üretim süreçleri, kullanım alanları, avantajları ve karşılaşılan zorluklar açısından değerlendirilmektedir. Sentetik hidrokarbonlar ve SNG, mevcut altyapı ile uyumluluk sağlarken; metanol ve amonyak, ulaşım ve sanayi uygulamaları için çok yönlü çözümler sunmaktadır. Yenilenebilir enerji kullanılarak su elektrolizi yoluyla üretilen yeşil hidrojen, karbon salımı içermeyen bir yakıt olarak, karbonsuzlaştırılması zor sektörler için önemli bir potansiyel taşımaktadır. Ancak, yüksek üretim maliyetleri, enerji yoğun süreçler ve altyapı gereksinimleri, bu yakıtların yaygın benimsenmesinin önündeki temel engeller arasında yer almaktadır. Teknolojik ilerlemeler, ölçek ekonomileri ve destekleyici politikalar, bu zorlukların aşılmasında kritik rol oynamaktadır. Bu makale, sentetik yakıtların sürdürülebilir ve düşük karbonlu bir enerji geleceği sağlama potansiyelini vurgulamakta ve bu yakıtların yaygınlaştırılmasını hızlandırmak için sürekli yenilik ve küresel iş birliğinin gerekliliğine dikkat çekmektedir. Sentetik yakıtların küresel enerji sistemine entegrasyonu, iklim değişikliğiyle mücadele edilmesine, enerji güvenliğinin artırılmasına ve net sıfır emisyon hedeflerine ulaşılmasına katkı sağlayacaktır.

Anahtar Kelimeler: Sentetik yakıtlar, amonyak, sentetik gaz, metanol, hidrojen

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Abstract

Synthetic fuels, produced through the conversion of renewable energy and carbon dioxide (CO_2), have emerged as a promising solution to decarbonize sectors that are difficult to electrify, such as aviation, shipping, and heavy industry. This review article provides a comprehensive analysis of five key synthetic fuel types: synthetic hydrocarbons, methanol, ammonia, synthetic natural gas (SNG), and hydrogen/green hydrogen. Each fuel is evaluated based on its production processes, applications, advantages, and challenges. Synthetic hydrocarbons and SNG offer compatibility with existing infrastructure, while methanol and ammonia provide versatile solutions for transportation and industrial use. Green hydrogen, produced via water electrolysis using renewable energy, stands out as a zero-emission fuel with the potential to decarbonize hard-to-abate sectors. However, high production costs, energy-intensive processes, and infrastructure requirements remain significant barriers to widespread adoption. Technological advancements, economies of scale, and supportive policies are critical to overcoming these challenges. This article highlights the transformative potential of synthetic fuels in achieving a sustainable, low-carbon energy future, emphasizing the need for continued innovation and global collaboration to accelerate their deployment. By integrating synthetic fuels into the global energy system, we can address climate change, enhance energy security, and pave the way for a net-zero emissions future.

Key Words: Synthetic fuels, ammonia, syngas, methanol, hydrogen

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1. Introduction

The global energy landscape is undergoing a profound transformation as societies strive to address the dual challenges of climate change and energy security [1]. Fossil fuels, which have been the cornerstone of industrialization and economic growth for over a century, are increasingly scrutinized for their environmental impact, particularly their contribution to greenhouse gas emissions [2,3]. In this context, synthetic fuels also known as electro-fuels or e-fuels have emerged as a promising alternative that could bridge the gap between traditional energy systems and a sustainable, low-carbon future. Synthetic fuels are liquid or gaseous fuels produced from renewable energy sources, such as solar, wind, or hydropower, through processes like electrolysis and chemical synthesis. Unlike conventional fossil fuels, they offer the potential for carbon-neutral or even carbon-negative energy cycles, making them a critical component of decarbonization strategies worldwide [4,5].

The concept of synthetic origins can be traced back to the early 20th century, when scientists first explored methods to convert coal and natural gas into liquid fuels. The Fischer-Tropsch process, developed in the 1920s, was a groundbreaking innovation that enabled the production of synthetic liquid hydrocarbons from coal-derived syngas. This technology played a pivotal role during World War II, particularly in Germany, where it was used to produce fuel for military vehicles and aircraft [6]. However, the post-war era saw a decline in interest in synthetic fuels as abundant and inexpensive petroleum became the dominant energy source. It was not until the oil crisis of the 1970s that synthetic fuels regained attention as a potential solution to energy security concerns. Despite significant investments in research and development during this period, the subsequent drop in oil prices and the lack of stringent environmental regulations led to a waning of interest in synthetic fuels [7].

In recent years, however, synthetic fuels have experienced a resurgence in interest, driven by the urgent need to mitigate climate change and transition to renewable energy systems. Advances in renewable energy technologies, such as wind turbines and solar panels, have dramatically reduced the cost of electricity generation, making it economically feasible to produce hydrogen through water electrolysis. This "green hydrogen" can serve as a feedstock for the production of synthetic fuels, such as methanol, ammonia, and synthetic hydrocarbons, using carbon dioxide captured from the atmosphere or industrial processes [8]. These fuels are particularly attractive because they can be used in existing infrastructure, such as internal combustion engines, aircraft, and shipping vessels, without requiring significant modifications. This compatibility makes synthetic fuels a viable option for decarbonizing sectors that are difficult to electrify, such as aviation, maritime transport, and heavy industry [9].

The potential of synthetic fuels extends beyond their environmental benefits. They also offer a pathway to energy independence and resilience, reducing reliance on fossil fuel imports and enhancing energy security [10]. Moreover, synthetic fuels can serve as a means of storing and transporting renewable energy, addressing the intermittency of solar and wind power. By converting excess renewable electricity into synthetic fuels, energy can be stored for long periods and transported to regions with high demand, effectively creating a global renewable energy market [11].

Despite their promise, synthetic fuels face significant challenges that must be addressed to realize their full potential. The production of synthetic fuels is currently energy-intensive and costly, requiring substantial investments in infrastructure and technology. Additionally, the scalability of synthetic fuel production depends on the availability of low-cost renewable electricity and efficient carbon capture technologies [12]. Policymakers, industry leaders, and researchers must work collaboratively to overcome these barriers and create an enabling environment for the widespread adoption of synthetic fuels [13].

Synthetic fuels encompass a diverse range of liquid and gaseous fuels produced through chemical processes that convert renewable energy sources, such as solar, wind, or hydropower, into energy-dense fuels suitable for transportation, industrial, and storage applications. One of the most prominent types of synthetic fuels is synthetic hydrocarbons, which include synthetic diesel, gasoline, and jet fuel [14]. These fuels are typically produced through the Fischer-Tropsch process, a catalytic chemical reaction that converts syngas—a mixture of hydrogen and carbon monoxide—into liquid hydrocarbons. Syngas can be derived from various feedstocks, including biomass (in which case the fuel is often referred to as biomass-to-liquid, or BTL), natural gas (gas-to-liquid, or GTL), or even carbon dioxide captured from the atmosphere or industrial emissions[15]. Synthetic hydrocarbons are particularly valuable because they are chemically similar to conventional fossil fuels, making them compatible with existing engines, aircraft, and infrastructure without requiring significant modifications. Another important category of synthetic fuels is methanol, a simple alcohol that can be produced by combining hydrogen (obtained through water electrolysis) with carbon dioxide. Methanol is a versatile fuel that can be used directly in internal combustion engines, blended with gasoline, or further processed into other chemicals and fuels, such as dimethyl ether (DME) or olefins. Ammonia is another synthetic fuel gaining attention, particularly for maritime shipping and as a hydrogen carrier. Produced by combining hydrogen with nitrogen (via the Haber-Bosch process), ammonia is carbon-free and can be burned directly in specialized engines or used in fuel cells to generate electricity. Additionally, synthetic natural gas (SNG) [16], also known as e-methane, is produced by combining hydrogen with carbon dioxide through a process called methanation. SNG can be injected into existing natural gas pipelines and used for heating, electricity generation, or as a feedstock for industrial processes[17]. Finally, hydrogen itself is often considered a synthetic fuel when produced via electrolysis using renewable electricity, earning it the designation of green hydrogen[18]. While hydrogen is primarily used in fuel cells for zero-emission vehicles and industrial applications, it can also serve as a precursor for other synthetic fuels. Each of these synthetic fuel types offers unique advantages and challenges, but collectively, they represent a suite of solutions capable of addressing the decarbonization needs of various sectors, from transportation to heavy industry, while leveraging renewable energy sources and reducing reliance on fossil fuels [19].

This review article aims to provide a comprehensive overview of synthetic fuels, from their historical development to their future prospects. It will explore the technological advancements that have shaped the field, the current state of synthetic fuel production, and the challenges and opportunities that lie ahead. By examining the role of synthetic fuels in the global energy transition, this article seeks to contribute to the ongoing discourse on sustainable energy solutions and inform policymakers, industry stakeholders, and researchers about the potential of synthetic fuels to shape a cleaner, more resilient energy future.

2. Synthetic Hydrocarbons: A Deep Dive

Synthetic hydrocarbons are liquid fuels chemically similar to conventional fossil fuels like diesel, gasoline, and jet fuel, but they are produced through artificial processes rather than being extracted from crude oil. These fuels are created by combining hydrogen (H_2) and carbon monoxide (CO) or carbon dioxide (CO_2) in a series of chemical reactions, often catalyzed by metals such as iron, cobalt, or ruthenium [20]. The most well-known process for producing synthetic hydrocarbons is the Fischer-Tropsch (FT) synthesis, which has been in use since the early 20th century. Synthetic hydrocarbons are particularly valuable because they can be used in existing internal combustion engines, aircraft, and infrastructure without requiring significant modifications, making them a practical solution for decarbonizing hard-to-abate sectors such as aviation, shipping, and heavy-duty transportation [21].

The production of synthetic hydrocarbons typically involves three main steps: syngas production, Fischer-Tropsch synthesis, and refining. Syngas, a mixture of hydrogen (H_2) and carbon monoxide (CO), is the primary feedstock for synthetic hydrocarbon production. Syngas can be generated from various sources, such as biomass, natural gas, carbondioxide. Through gasification, organic materials such as agricultural waste, wood, or algae are heated in a low-oxygen environment to produce syngas. This process is often referred to as biomass-to-liquid (BTL) [6]. Methane (CH_4) from natural gas can be reformed with steam or oxygen to produce syngas in a process called gas-to-liquid (GTL)[15]. CO_2 captured from the atmosphere or industrial emissions can be combined with hydrogen (produced via water electrolysis) to form syngas. This method is often referred to as power-to-liquid (PtL) and relies on renewable electricity to make the process sustainable [22].

The syngas is then fed into a Fischer-Tropsch reactor, where it undergoes a catalytic chemical reaction to form long-chain hydrocarbons. The process involves the following key reactions such as chain growth and water formation. In Chain Growth CO and H_2 molecules are polymerized into hydrocarbon chains of varying lengths [23]. The water formation (H_2O) is produced as a byproduct. The resulting product is a mixture of hydrocarbons, including paraffins, olefins, and waxes, which can be further refined into specific fuels. The raw hydrocarbons produced by the Fischer-Tropsch process are refined to create usable fuels such as synthetic diesel, gasoline, or jet fuel. This refining process involves distillation, cracking, and other chemical treatments to tailor the hydrocarbons to meet specific fuel standards [24].

Synthetic hydrocarbons have a wide range of applications, particularly in sectors where electrification is challenging or impractical such as aviation, shipping, transportation and industrial applications. Synthetic jet fuel (often referred to as sustainable aviation fuel, or SAF) is one of the most promising applications in aviation[25]. It can be blended with conventional jet fuel or used as a drop-in replacement, significantly reducing the carbon footprint of air travel. Synthetic diesel can be used in maritime vessels, offering a cleaner alternative to heavy fuel oil in shipping. In Ground Transportation, Synthetic gasoline and diesel can power cars, trucks, and buses, especially in regions where electric vehicles are not yet viable. Lastly synthetic hydrocarbons can serve as feedstocks for the chemical industry, replacing petroleum-derived products in the production of plastics, lubricants, and other materials [26].

2.1. Advantages and Challenges

Synthetic hydrocarbons are chemically identical to their fossil fuel counterparts, meaning they can be used in existing engines, pipelines, and storage systems without requiring costly modifications. When produced using renewable energy and CO_2 captured from the atmosphere, synthetic hydrocarbons can achieve carbon neutrality [27]. The CO_2 emitted during combustion is offset by the CO_2 captured during production, creating a closed carbon cycle. Synthetic hydrocarbons have a high energy density, making them suitable for applications that require long-range and high-energy output, such as aviation and shipping. The Fischer-Tropsch process can produce a wide range of hydrocarbon products, from light gases to heavy waxes, allowing for flexibility in meeting diverse fuel and chemical needs. Besides these advantages, the Fischer-Tropsch method also comes with some disadvantages. For instance, the production of synthetic hydrocarbons is currently more expensive than extracting and refining crude oil. The cost is driven by the need for large amounts of renewable energy, efficient carbon capture technologies, and expensive catalysts [28]. In addition, the process of producing syngas and converting it into hydrocarbons is energy-intensive, requiring significant inputs of electricity and heat. This makes the scalability of synthetic hydrocarbons dependent on the availability of low-cost renewable energy. While capturing CO_2 from the atmosphere or industrial sources is technically feasible, it remains costly and energy-intensive. Improving the efficiency and affordability of carbon capture technologies is critical for the widespread adoption of synthetic hydrocarbons. On the other hand, scaling up synthetic hydrocarbon production would require significant investments in new infrastructure, including electrolyzers, Fischer-Tropsch reactors, and carbon capture facilities [29].

2.2. Future Prospects

Despite these challenges, synthetic hydrocarbons are poised to play a critical role in the global energy transition. Advances in renewable energy, carbon capture, and catalysis are driving down costs and improving efficiency. Governments and private sector players are increasingly investing in synthetic fuel projects, recognizing their potential to decarbonize hard-to-abate sectors. For example, the has identified synthetic fuels as a key component of its Green Deal, while companies like Porsche and Siemens Energy are actively developing pilot plants for synthetic fuel production [30].

In conclusion, synthetic hydrocarbons represent a bridge between the fossil fuel-dependent present and a sustainable, low-carbon future. By leveraging renewable energy and innovative chemical processes, they offer a viable pathway to reducing greenhouse gas emissions while maintaining the energy density and versatility that modern societies rely on. However, realizing their full potential will require continued technological innovation, supportive policies, and global collaboration [2].

3. Methanol: A Versatile Synthetic Fuel

Methanol (CH_3OH), also known as wood alcohol, is one of the simplest alcohols and a versatile synthetic fuel with a wide range of applications. It is a liquid at room temperature, making it easy to store, transport, and use in existing infrastructure. Methanol can be produced from a variety of feedstocks, including fossil fuels, biomass, and carbon dioxide, but when synthesized using renewable energy and captured CO_2, it becomes a sustainable and carbon-neutral fuel [31]. Methanol is increasingly recognized as a key component of the global energy transition, particularly for its potential to decarbonize transportation, industrial processes, and chemical production. Methanol is primarily produced through the catalytic reaction of hydrogen (H_2) and carbon monoxide (CO) or carbon dioxide (CO_2). The process can be broken down into the following steps: The production of methanol begins with the preparation of syngas, a mixture of hydrogen (H_2) and carbon monoxide (CO), or the direct use of carbon dioxide (CO_2) [32]. The feedstock sources include fossil fuels, biomass, and carbon dioxide. Methanol has traditionally been produced from natural gas or coal through steam methane reforming (SMR) or coal gasification. However, this method is not sustainable due to its reliance on fossil fuels. Biomass, such as agricultural waste, wood, or algae, can be gasified to produce syngas, making the process more sustainable. CO_2 captured from the atmosphere or industrial emissions can be combined with hydrogen (produced via water electrolysis using renewable energy) to produce methanol. This method, often referred to as power-to-methanol (PtM), is the most sustainable and aligns with carbon-neutral goals. The syngas or CO_2 is then fed into a reactor, where it undergoes a catalytic reaction to produce methanol [33] The key reactions are from syngas [34]:

$$CO+2H_2 \rightarrow CH_3OHCO+2H_2 \rightarrow CH_3OH \qquad (1)$$

and from CO_2:

$$CO_2+3H_2 \rightarrow CH_3OH+H_2OCO_2+3H_2 \rightarrow CH_3OH+H_2O \qquad (2)$$

These reactions are typically catalyzed by copper-zinc-alumina ($Cu/ZnO/Al_2O_3$) catalysts, which operate at temperatures of 200–300°C and pressures of 50–100 bar. The crude methanol produced in the reactor contains water and other byproducts, which are removed through distillation to produce high-purity methanol suitable for fuel and industrial applications[35].

Methanol is a highly versatile synthetic fuel with a wide range of applications across multiple sectors. For instance, transportation is one of the possible main sectors for methanol usage due to the existence of internal combustion engines. Methanol can be used directly as a fuel in modified internal combustion engines or blended with gasoline (e.g., M85, a blend of 85% methanol and 15% gasoline) [36]. In the shipping industry methanol is gaining traction as a cleaner alternative to heavy fuel oil. It produces fewer emissions of sulfur oxides (SO_x), nitrogen oxides (NO_x), and particulate matter. On the other hand, methanol can be used in direct methanol fuel cells (DMFCs) to generate electricity, particularly for portable and off-grid applications[37]. For the chemical industry, methanol is a key feedstock for the production of numerous chemicals, including formaldehyde, acetic acid, and olefins. It is also a precursor for synthetic hydrocarbons and plastics, making it a critical component of the chemical supply chain. Methanol can serve as a medium for storing and transporting renewable energy. Excess electricity from wind or solar power can be used to produce hydrogen, which is then converted into methanol for long-term storage or transport to regions with high energy demand. In some regions, methanol is used as a clean-burning fuel for cooking and heating, replacing traditional biomass fuels that contribute to indoor air pollution [17].

3.1. Advantages and challenges

When produced using renewable energy and captured CO_2, methanol can be carbon-neutral. The CO_2 emitted during its combustion is offset by the CO_2 captured during its production, creating a closed carbon cycle. The storage and the transport of the methanol is easier compared to the other gas forms and hydrogen because it is a liquid at ambient temperatures. Methanol's wide range of applications—from fuel to chemical feedstock—makes it a highly versatile synthetic fuel [38]. In addition, the burn products are cleaner than conventional fossil fuels, producing fewer pollutants such as SO_x, NO_x, and particulate matter. It also has a higher octane rating than gasoline, enabling more efficient combustion. Methanol can be blended with gasoline and used in existing engines with minor modifications, reducing the need for new infrastructure. Although these advantages, the production of renewable methanol is currently more expensive than conventional methanol derived from fossil fuels. The high cost is driven by the need for renewable electricity, efficient electrolyzers, and carbon capture technologies. The production of methanol, particularly from CO_2, is energy-intensive, requiring significant inputs of electricity and heat[39]. This makes the scalability of renewable methanol dependent on the availability of low-cost renewable energy. Methanol is toxic if ingested or inhaled, and it poses safety risks due to its flammability. Proper handling, storage, and transportation protocols are essential to mitigate these risks. Methanol faces competition from other synthetic fuels, such as hydrogen and ammonia, as well as from electrification in certain sectors like transportation [21].

3.2. Future Prospects

Methanol is increasingly seen as a key player in the global energy transition. Advances in renewable energy, electrolysis, and carbon capture technologies are driving down costs and improving the sustainability of methanol production. Several pilot projects and commercial plants are already underway, particularly in Europe and China, to produce renewable methanol at scale. For example, the European Union's Green Deal includes methanol as part of its strategy to achieve carbon neutrality by 2050 [8]. In conclusion, methanol is a versatile and promising synthetic fuel with the potential to decarbonize multiple sectors, from transportation to industry. Its compatibility with existing infrastructure, combined with its ability to store and transport renewable energy, makes it a valuable component of a sustainable energy system. However, realizing its full potential will require continued innovation, supportive policies, and investments in renewable energy and carbon capture technologies[40].

4. Ammonia: A Carbon-Free Synthetic Fuel

Ammonia (NH_3) is a compound of nitrogen and hydrogen that has long been used as a fertilizer and industrial chemical. However, in recent years, ammonia has gained significant attention as a carbon-free synthetic fuel and energy carrier, particularly for its potential to decarbonize hard-to-abate sectors such as shipping, heavy industry, and power generation. Unlike other synthetic fuels, ammonia contains no carbon, meaning its combustion does not produce carbon dioxide (CO_2). When produced using renewable energy, ammonia becomes a truly sustainable and zero-emission fuel, making it a key player in the global energy transition[41].

Ammonia is primarily produced through the Haber-Bosch process, which was developed in the early 20th century. The process involves four main steps: Hydrogen Production, Nitrogen Production, Haber-Bosch Synthesis, Purification and storage. The first step in ammonia production is the generation of hydrogen (H_2). Traditionally, hydrogen has been produced from natural gas through steam methane reforming (SMR), a process that emits significant amounts of CO_2. However, for sustainable ammonia production, hydrogen is increasingly being produced via water electrolysis using renewable electricity[42]. This method, known as green hydrogen, is carbon-free and aligns with decarbonization goals. After, Nitrogen (N_2) is obtained from the air through a process called air separation. Air is compressed and cooled to liquefy it, and then nitrogen is separated from oxygen and other gases using fractional distillation. Lastly, the hydrogen and nitrogen are then fed into a Haber-

Bosch reactor, where they react under high pressure (150–300 bar) and temperature (400–500°C) in the presence of an iron-based catalyst to produce ammonia. The process is highly energy-intensive, requiring significant inputs of heat and pressure. The reaction is as follows[43]:

$$N_2+3H_2\rightarrow 2NH_3 N_2+3H_2\rightarrow 2NH_3 \quad (3)$$

The ammonia synthesized within the reactor undergoes purification and liquefaction processes to facilitate its storage and transportation. Typically, ammonia is stored in a liquid state, either under moderate pressure or at cryogenic temperatures. In recent years, ammonia has garnered significant attention as a potential zero-carbon fuel within the shipping industry. It can be utilized as a combustible fuel in internal combustion engines or employed in fuel cells to propel ships, presenting a more environmentally sustainable alternative to conventional heavy fuel oil. Prominent shipping entities and international organizations, including the International Maritime Organization (IMO), are actively investigating ammonia as a pivotal solution for decarbonizing maritime transportation [44].

Furthermore, ammonia demonstrates versatility as a fuel source in gas turbines and power plants for electricity generation [45]. It can also be co-fired with coal or natural gas in existing power plants to mitigate carbon dioxide (CO_2) emissions. Owing to its high hydrogen content (17.6% by weight) and favorable liquefaction properties, ammonia serves as an efficient hydrogen carrier. It can be transported over extensive distances and subsequently decomposed, or "cracked," into hydrogen and nitrogen for utilization in fuel cells or various industrial processes [42].

Ammonia remains an indispensable feedstock for the production of nitrogen-based fertilizers, which are critical to global agricultural practices. However, there is a growing emphasis on producing ammonia through renewable energy sources to minimize the carbon footprint associated with fertilizer manufacturing. Beyond its agricultural applications, ammonia is integral to the synthesis of various chemicals, including nitric acid, explosives, and synthetic fibers. Additionally, it is employed in refrigeration systems and as a cleaning agent in industrial and domestic contexts [46].

4.1. Advantages and Challenges

Ammonia is inherently carbon-free, meaning its combustion does not emit carbon dioxide (CO_2). This characteristic positions it as a promising fuel for decarbonizing sectors that are challenging to electrify, such as shipping and heavy industry. With its high energy density, ammonia is particularly well-suited for applications demanding long-range and high-energy output, including maritime transport. Additionally, the global infrastructure for ammonia production and distribution is already well-established, primarily due to its extensive use in fertilizer manufacturing [46].This existing infrastructure can be strategically repurposed and expanded to support its adoption as a fuel. Ammonia also serves as an efficient and cost-effective medium for hydrogen storage and transportation, addressing key challenges associated with hydrogen’s low energy density and high storage costs. Its versatility extends to a wide range of applications, from fuel to chemical production, underscoring its potential as a synthetic fuel with multifaceted utility[47].

However, the utilization of ammonia across various industries is not without challenges. These include high energy consumption, toxicity, stringent safety requirements, flammability risks, and the generation of nitrogen oxides (NO_x) during combustion. The production of green ammonia, which relies on renewable energy sources, is currently more costly compared to conventional ammonia derived from fossil fuels[48]. This cost disparity is driven by the need for renewable electricity, advanced electrolyzers, and the energy-intensive Haber-Bosch process. The Haber-Bosch process, in particular, demands substantial heat and pressure inputs, making the scalability of green ammonia contingent on the availability of affordable renewable energy. Furthermore, ammonia’s toxic and corrosive nature necessitates rigorous safety protocols and infrastructure modifications to mitigate risks during storage, transportation, and handling [49].

From a combustion perspective, ammonia exhibits a narrower flammability range and a slower combustion rate relative to conventional fuels, posing challenges for its use in internal combustion engines and gas turbines. Ongoing research is focused on developing advanced combustion technologies and catalysts to enhance its performance. Additionally, while ammonia itself is carbon-free, its combustion can produce nitrogen oxides (NO_x), which are harmful pollutants. To address this, advanced combustion techniques and exhaust treatment systems are being explored to minimize NO_x emissions and ensure environmentally sustainable utilization [50].

4.2. Future Prospects

Ammonia is increasingly recognized as a pivotal element in the global energy transition, particularly due to its potential to decarbonize hard-to-abate sectors such as shipping, power generation, and heavy industry. Numerous pilot projects and commercial initiatives are currently underway to scale up green ammonia production and explore its viability as a fuel. For instance, Japan's Green Ammonia Consortium is actively developing technologies for ammonia-based power generation and marine fuel applications. Similarly, the European Union's Green Deal has incorporated ammonia into its broader strategy to achieve carbon neutrality by 2050 [51]. Major companies like Yara and CF Industries are also making significant investments in green ammonia production facilities powered by renewable energy, further underscoring its growing importance in the global energy landscape.

In summary, ammonia emerges as a promising carbon-free synthetic fuel with the potential to play a critical role in decarbonizing key sectors. Its versatility, high energy density, and well-established infrastructure position it as a valuable component of a sustainable energy system. However, fully realizing its potential will require sustained innovation, supportive policy frameworks, and substantial investments in renewable energy and advanced combustion technologies to address existing challenges and optimize its applications [52,53].

5. Synthetic Natural Gas (SNG): A Renewable Alternative to Fossil Gas

Synthetic natural gas (SNG) is a methane-based fuel that is chemically identical to conventional natural gas but is produced artificially through processes that utilize renewable energy and carbon dioxide (CO_2). SNG is often referred to as e-methane when produced using renewable electricity or renewable natural gas (RNG) when derived from biomass. It is a versatile and sustainable fuel that can be used for heating, electricity generation, and transportation, making it a key component of the global energy transition [54]. By leveraging renewable energy and carbon capture technologies, SNG offers a pathway to decarbonize sectors that rely heavily on natural gas while utilizing existing infrastructure. The production of synthetic natural gas typically involves the following steps: Hydrogen Production, Carbon Dioxide Capture, Methanation, Purification and Compression. The first step in SNG production is the generation of hydrogen (H_2). This is usually done through water electrolysis, a process that splits water into hydrogen and oxygen using electricity [55]. When the electricity comes from renewable sources such as wind, solar, or hydropower, the hydrogen produced is referred to as green hydrogen. The next step is the capture of carbon dioxide (CO_2). CO_2 can be sourced from various places, including industrial emissions: Capturing CO_2 from factories, power plants, or other industrial processes, Direct Air Capture (DAC): Extracting CO_2 directly from the atmosphere using specialized technologies, Biomass: Using CO_2 produced during the fermentation or gasification of biomass[56]. In the methanation stage, the hydrogen and CO_2 are then fed into a methanation reactor, where they undergo a catalytic reaction to produce methane (CH_4) and water (H_2O) according to the following reactions[29,57,58].

$$CO_2+4H_2 \rightarrow CH_4+2H_2OCO_2+4H_2 \rightarrow CH_4+2H_2O \tag{4}$$

This process, known as the Sabatier reaction, is typically catalyzed by nickel-based catalysts and operates at temperatures of 300–400°C and pressures of 10–30 bar. Lastly, the synthetic methane produced in the reactor is purified to remove any impurities and then compressed for storage and transport. It can be injected directly into existing natural gas pipelines or stored in tanks for later use[59].

Synthetic natural gas (SNG) exhibits a broad spectrum of applications, particularly in sectors that are heavily dependent on natural gas, including heating, electricity generation, transportation, industrial processes, and grid balancing and energy storage. SNG can be utilized for residential, commercial, and industrial heating, serving as a substitute for conventional natural gas in boilers and furnaces. This application is especially significant for decarbonizing heating systems in regions where electrification remains impractical or unfeasible. In the realm of electricity generation, SNG can be combusted in gas turbines or combined-cycle power plants to produce electricity [58]. Additionally, it plays a critical role in power-to-gas systems, where surplus renewable electricity is converted into SNG for storage and subsequently reconverted into electricity during periods of peak demand. Within the transportation sector, SNG can be employed as a fuel for natural gas vehicles (NGVs), including cars, buses, and trucks. It can also be liquefied to produce liquefied synthetic natural gas (LNG), which is particularly suited for heavy-duty transportation and maritime shipping [48].

In industrial contexts, SNG serves as a vital feedstock for processes that traditionally rely on natural gas, such as the production of chemicals, fertilizers, and steel. Furthermore, SNG can be integrated into existing natural gas infrastructure by being injected into pipelines and stored in underground gas storage facilities. This capability makes SNG a valuable asset for grid balancing and the long-term storage of renewable energy, thereby enhancing the stability and flexibility of energy systems [60].

5.1. Advantages and Challenges

When produced using renewable energy and captured carbon dioxide (CO_2), synthetic natural gas (SNG) achieves carbon neutrality. The CO_2 emitted during its combustion is counterbalanced by the CO_2 captured during its production, establishing a closed carbon cycle. SNG is chemically identical to conventional natural gas, enabling its seamless integration into existing natural gas infrastructure, including pipelines, storage facilities, and end-use appliances, without necessitating significant modifications. This compatibility enhances its practicality and reduces implementation barriers [61]. SNG offers a viable solution for the storage and long-distance transportation of renewable energy, addressing the intermittency challenges associated with solar and wind power. Its versatility is evident in its wide range of applications, spanning heating, electricity generation, transportation, and industrial processes, making it a highly adaptable synthetic fuel. Furthermore, SNG burns cleaner than coal or oil, emitting fewer pollutants such as sulfur oxides (SO_x), nitrogen oxides (NO_x), and particulate matter, thereby contributing to improved air quality. However, the production of SNG currently incurs higher costs compared to the extraction and processing of conventional natural gas. These elevated costs are driven by the need for renewable electricity, efficient electrolyzers, and carbon capture technologies [62]. The production process, particularly the methanation stage, is energy-intensive, requiring substantial inputs of electricity and heat. As a result, the scalability of SNG is contingent upon the availability of low-cost renewable energy. Additionally, while capturing CO_2 from industrial emissions or the atmosphere is technically feasible, it remains both costly and energy-intensive. Enhancing the efficiency and affordability of carbon capture technologies is critical for the widespread adoption of SNG. Another challenge lies in the potential for methane leakage during the production, storage, or transport of SNG. Methane is a potent greenhouse gas, and any leakage could significantly undermine the climate benefits of SNG. Therefore, rigorous monitoring and maintenance of infrastructure are essential to minimize methane emissions. Finally, SNG faces competition from alternative synthetic fuels, such as hydrogen and ammonia, as well as from electrification in sectors like heating and transportation, which could influence its adoption trajectory.

5.2. Future Prospects

Synthetic natural gas is increasingly seen as a key component of the global energy transition, particularly for its ability to decarbonize sectors that rely heavily on natural gas. Several pilot projects and commercial initiatives are underway to scale up SNG production and explore its use in various applications. The European Union's Green Deal includes SNG as part of its strategy to achieve carbon neutrality by 2050 [63].

In conclusion, synthetic natural gas is a promising renewable fuel with the potential to decarbonize heating, electricity generation, and transportation while leveraging existing natural gas infrastructure. Its compatibility with current systems, combined with its ability to store and transport renewable energy, makes it a valuable component of a sustainable energy system. However, realizing its full potential will require continued innovation, supportive policies, and investments in renewable energy and carbon capture technologies.

6. Hydrogen and Green Hydrogen: The Fuel of the Future

Hydrogen (H_2) is the simplest and most abundant element in the universe, and it has long been recognized as a potential clean energy carrier. When used as a fuel, hydrogen produces only water (H_2O) as a byproduct, making it a zero-emission energy source. However, not all hydrogen is created equal. The environmental impact of hydrogen depends on how it is produced. Green hydrogen, produced using renewable energy, is the most sustainable form of hydrogen and is increasingly seen as a cornerstone of the global energy transition. Hydrogen, particularly green hydrogen, has the potential to decarbonize a wide range of sectors, including transportation, industry, and power generation. Hydrogen is often categorized by color based on its production method and associated carbon emissions[64]:

1. Grey Hydrogen: Produced from natural gas through steam methane reforming (SMR), a process that emits significant amounts of CO_2. This is the most common form of hydrogen today.
2. Blue Hydrogen: Produced from natural gas like grey hydrogen, but with the addition of carbon capture and storage (CCS) to reduce CO_2 emissions.
3. Green Hydrogen: Produced through water electrolysis using renewable electricity, resulting in zero carbon emissions. This is the most sustainable form of hydrogen.
4. Other Colors: Hydrogen can also be produced from coal (brown or black hydrogen) or nuclear energy (pink or purple hydrogen), but these methods are less common.

The production of green hydrogen involves Water Electrolysis, Renewable electricity and Purification and Compression. Green hydrogen is produced by splitting water (H_2O) into hydrogen (H_2) and oxygen (O_2) using an electric current. This process, known as water electrolysis, takes place in an electrolyzer. There are three main types of electrolyzers. Alkaline electrolysers use an alkaline solution as the electrolyte and are the most mature and cost-effective technology[65]. Proton exchange membrane uses a solid polymer electrolyte and are more efficient and compact, making them suitable for variable renewable energy sources. Solid oxide electrolyzers [66], operate at high temperatures and are highly efficient but less commercially mature. For hydrogen to be considered "green," the electricity used in the electrolysis process must come from renewable sources such as wind, solar, or hydropower. This ensures that the entire production process is carbon-free. The hydrogen produced in the electrolyzer is purified to remove any impurities and then compressed for storage and transport. Hydrogen can be stored as a gas at high pressure or as a liquid at very low temperatures [67].

Hydrogen, particularly green hydrogen, has a wide range of applications across multiple sectors. Hydrogen has emerged as a versatile and sustainable energy carrier with applications across multiple sectors. In transportation, hydrogen is utilized in fuel cell vehicles (FCVs), including cars, buses, trucks, and trains, offering longer ranges and faster refueling times compared to battery-electric vehicles. Additionally, hydrogen is being explored as a fuel for aviation and shipping, particularly in the form of liquid hydrogen or ammonia, which serves as a hydrogen carrier [48]. In the industrial sector, hydrogen plays a critical role as a feedstock for chemical production, including the synthesis of ammonia for fertilizers and methanol for chemicals and fuels. It also holds transformative potential in steelmaking, where it can replace coal in the reduction process, significantly reducing CO_2 emissions and enabling the production of green steel [68]. Furthermore, hydrogen is widely used in oil refineries to remove sulfur and other impurities from crude oil. In power generation, hydrogen can be employed in stationary fuel cells to produce electricity for buildings, data centers, and remote locations. It also serves as a means of grid balancing, where excess renewable energy is stored as hydrogen and later converted back to electricity during periods of high demand, facilitating the integration of renewable energy into the grid. Hydrogen can serve as a medium for storing and transporting renewable energy. Excess electricity from wind or solar power can be used to produce hydrogen, which can then be stored or transported to regions with high energy demand [69].

6.1. Advantages and Challenges

Hydrogen, particularly green hydrogen produced via water electrolysis using renewable energy, offers numerous advantages as a sustainable energy carrier. One of its most significant benefits is its zero-emission potential, as its only byproduct is water, making it one of the cleanest energy sources available. Hydrogen is also highly versatile, with applications spanning transportation, industry, power generation, and energy storage, enabling its integration into diverse sectors of the economy. Its high energy density by weight makes it particularly suitable for applications requiring long-range and high-energy output, such as aviation and shipping. Additionally, hydrogen serves as an effective medium for energy storage and transport, addressing the intermittency of renewable energy sources like solar and wind by enabling long-term storage and global distribution. Perhaps most importantly, hydrogen is one of the few solutions capable of decarbonizing hard-to-abate sectors, including heavy industry, aviation, and shipping, where electrification is often impractical [70].

However, the widespread adoption of hydrogen faces several challenges. The high production costs of green hydrogen, driven by the expense of electrolyzers and renewable electricity, remain a significant barrier, although costs are expected to decline with technological advancements and economies of scale. The energy-intensive nature of electrolysis further complicates scalability, as it requires substantial inputs of low-cost renewable energy to be economically viable. Storage and transport present additional challenges due to hydrogen's low energy density by volume, necessitating compression or liquefaction, which increases energy requirements and infrastructure costs. The development of a robust hydrogen economy will also require significant investments in infrastructure, including electrolyzers, storage facilities, pipelines, and refueling stations. Finally, safety concerns related to hydrogen's high flammability necessitate stringent handling, storage, and transport protocols, while public perception and regulatory frameworks will play a critical role in its adoption [71].

6.2. Future Prospects

Hydrogen, particularly green hydrogen, is increasingly seen as a key component of the global energy transition. Governments, industries, and investors are ramping up efforts to scale up hydrogen production and develop the necessary infrastructure. For example, the European Union's Hydrogen Strategy aims to install 40 GW of electrolyzers by 2030. Countries like Japan, South Korea, and Australia are investing heavily in hydrogen technologies and infrastructure. Companies like Siemens, ITM Power, and Plug Power are developing advanced electrolyzers and fuel cells to drive down costs and improve efficiency [72].

In conclusion, hydrogen, especially green hydrogen, represents a transformative opportunity to decarbonize the global economy. Its versatility, zero-emission potential, and ability to store and transport renewable energy make it a critical component of a sustainable energy system. However, realizing its full potential will require continued innovation, supportive policies, and global collaboration to overcome the challenges of cost, infrastructure, and scalability [73].

7. Final Findings: Synthetic Fuels Overview

Synthetic fuels represent a diverse and innovative suite of energy solutions designed to address the dual challenges of climate change and energy security. Each type of synthetic fuel, synthetic hydrocarbons, methanol, ammonia, synthetic natural gas (SNG), and hydrogen/green hydrogen offers unique advantages and faces distinct challenges. Below is a comprehensive analysis of their potential, limitations, and economic considerations[74].

Synthetic hydrocarbons, such as synthetic diesel, gasoline, and jet fuel, are chemically similar to conventional fossil fuels but are produced artificially using renewable energy and captured carbon dioxide (CO_2). Their primary advantage lies in their compatibility with existing infrastructure, including engines, aircraft, and pipelines, making them a practical solution for decarbonizing hard-to-abate sectors like aviation and shipping [17]. Additionally, when produced using renewable energy and CO_2 capture, synthetic hydrocarbons can achieve carbon neutrality. However, their production is energy-intensive and costly, relying on processes like the Fischer-Tropsch synthesis, which requires significant inputs of renewable energy and carbon capture infrastructure. The unit production cost of synthetic hydrocarbons ranges from $3–6 per gallon, with market selling costs between $4–8 per gallon, making them more expensive than conventional fuels [75].

Methanol is a versatile synthetic fuel that can be used directly as a fuel, blended with gasoline, or as a feedstock for chemical production. Its liquid form at room temperature makes it easy to store and transport, and it is compatible with existing engines with minor modifications. When produced using renewable energy and captured CO_2, methanol is carbon-neutral [76]. However, its production costs are high, particularly for green methanol, which relies on electrolysis and CO_2 capture. Methanol also has a lower energy density compared to hydrocarbons and poses toxicity and safety risks. The unit production cost of green methanol is approximately $800–1200 per ton, with market selling costs ranging from $1000–1500 per ton[77].

Ammonia is a carbon-free synthetic fuel with high energy density, making it particularly suitable for applications like maritime shipping and as a hydrogen carrier. It benefits from an existing global infrastructure due to its widespread use in the fertilizer industry. However, the production of green ammonia, which involves electrolysis and the Haber-Bosch process, is energy-intensive and costly. Ammonia also poses toxicity and safety risks, and its combustion can produce nitrogen oxides (NO_x), which are harmful pollutants. The unit production cost of green ammonia ranges from $500–800 per ton, with market selling costs between $600–1000 per ton[78].

Synthetic natural gas (SNG), or e-methane, is chemically identical to conventional natural gas and can be injected directly into existing gas pipelines and infrastructure. It is produced through the methanation of hydrogen and CO_2, making it carbon-neutral when renewable energy is used. SNG is highly versatile, with applications in heating, power generation, and transportation. However, its production is energy-intensive and costly, and there are risks of methane leakage, which could undermine its climate benefits. The unit production cost of green SNG is approximately $20–30 per MMBtu, with market selling costs ranging from $25–35 per MMBtu [79].

Hydrogen, particularly green hydrogen produced through water electrolysis using renewable energy, is a zero-emission fuel with immense potential to decarbonize hard-to-abate sectors like heavy industry, aviation, and shipping. It has a high energy density by weight and can be used in fuel cells, as a chemical feedstock, or as an energy carrier [30]. However, hydrogen faces significant challenges, including high production costs, low energy density by volume, and the need for expensive storage and transport infrastructure. Safety concerns related to its flammability also pose barriers to widespread adoption. The unit production cost of green hydrogen ranges from $3–6 per kg, with market selling costs between $4–8 per kg [80].

While all synthetic fuels offer promising pathways to decarbonization, they differ significantly in terms of compatibility with existing infrastructure, energy density, and production costs. Synthetic hydrocarbons and SNG have the advantage of being fully compatible with current infrastructure, making them easier to integrate into existing energy systems. Methanol and ammonia also offer some compatibility but require modifications and face challenges related to toxicity and emissions. Hydrogen, while highly versatile and zero-emission, faces the biggest infrastructure and cost challenges. In terms of costs, all synthetic fuels are currently more expensive to produce and sell than their fossil fuel counterparts. However, these costs are expected to decline with technological advancements, economies of scale, and increased availability of low-cost renewable energy. Government policies, such as carbon pricing, subsidies, and renewable energy mandates, will play a critical role in accelerating the adoption of synthetic fuels.

Table 1. Comparative Analysis: Advantages and Disadvantages [75,77–80].

Synthetic Fuel	Advantages	Disadvantages	Unit Production Cost ($)	Market Selling Cost ($)
Synthetic Hydrocarbons	Compatible with existing infrastructure; high energy density; carbon-neutral.	High production costs; energy-intensive; requires renewable energy and CO_2.	3–6 per gallon	4–8 per gallon
Methanol	Easy storage/transport; versatile; carbon-neutral; compatible with engines.	High production costs; toxicity; lower energy density.	800–1200 per ton	1000–1500 per ton
Ammonia	Carbon-free; high energy density; existing infrastructure; hydrogen carrier.	High production costs; toxicity; NO_x emissions; advanced combustion required.	500–800 per ton	600–1000 per ton
Synthetic Natural Gas	Fully compatible with gas infrastructure; carbon-neutral; versatile.	High production costs; energy-intensive; methane leakage risks.	220–30 per MMBtu	25–35 per MMBtu
Hydrogen/Green Hydrogen	Zero emissions; high energy density; versatile; decarbonizes hard-to-abate sectors.	High production costs; expensive storage/transport; safety concerns.	3–6 per kg	4–8 per kg

Synthetic fuels hold significant promise in the global effort to decarbonize energy systems, particularly in sectors that are difficult to electrify, such as aviation, shipping, and heavy industry. Among these, green hydrogen and ammonia are particularly promising due to their zero-emission potential and versatility. A key advantage of synthetic hydrocarbons and synthetic natural gas (SNG) lies in their compatibility with existing infrastructure, enabling seamless integration into current energy systems. In contrast, hydrogen faces substantial infrastructure challenges, requiring significant investments in production, storage, and distribution networks. While high production and selling costs currently pose a barrier to the widespread adoption of synthetic fuels, ongoing technological advancements and supportive policies are expected to drive cost reductions over time. Additionally, hydrogen and ammonia excel as energy carriers, facilitating the long-term storage and global transport of renewable energy, while SNG offers valuable grid-balancing capabilities. However, the deployment of synthetic fuels is not without challenges. Environmental and safety concerns, such as the toxicity of methanol and ammonia, the flammability of hydrogen and SNG, and emissions of nitrogen oxides (NO_x) from ammonia combustion or methane leakage from SNG, must be carefully addressed to ensure safe and sustainable implementation.

8. Conclusion

Synthetic fuels represent a transformative opportunity to address the pressing challenges of climate change, energy security, and the decarbonization of hard-to-abate sectors. By leveraging renewable energy and innovative chemical processes, synthetic fuels such as synthetic hydrocarbons, methanol, ammonia, synthetic natural gas (SNG), and hydrogen/green hydrogen offer a pathway to reduce greenhouse gas emissions while maintaining the energy density and versatility that modern societies rely on. Each type of synthetic fuel has its unique advantages, from compatibility with existing infrastructure to carbon neutrality and the ability to store and transport renewable energy. However, they also face significant challenges, including high production costs, energy-intensive processes, and the need for new infrastructure and safety measures.

The production of synthetic fuels is currently more expensive than traditional fossil fuels, but ongoing technological advancements, economies of scale, and supportive policies are expected to drive down costs over time. Governments, industries, and researchers must work collaboratively to overcome these barriers, investing in renewable energy, carbon capture technologies, and infrastructure development. Policies such as carbon pricing, subsidies, and renewable energy mandates will play a critical role in accelerating the adoption of synthetic fuels and creating a level playing field with fossil fuels.

Synthetic fuels are not a one-size-fits-all solution but rather a complementary set of tools that can be tailored to specific applications and sectors. For example, synthetic hydrocarbons and SNG are well-suited for sectors like aviation and heating, where electrification is challenging. Methanol and ammonia offer versatile solutions for transportation and industrial processes, while green hydrogen holds immense potential for decarbonizing heavy industry and serving as a global energy carrier.

In conclusion, synthetic fuels are a vital component of the global energy transition, offering a bridge between the fossil fuel-dependent present and a sustainable, low-carbon future. While challenges remain, the potential benefits—reduced emissions, energy security, and the decarbonization of hard-to-abate sectors—make synthetic fuels a cornerstone of efforts to combat climate change and achieve net-zero emissions. With continued innovation, investment, and collaboration, synthetic fuels can help pave the way for a cleaner, more resilient, and sustainable energy system for generations to come. The future of synthetic fuels depends on continued innovation, supportive policies, and global collaboration. Advances in electrolysis, carbon capture, and catalysis are expected to drive down costs, while government incentives and international partnerships will help scale up production and build the necessary infrastructure. With these efforts, synthetic fuels can play a transformative role in achieving a sustainable and low-carbon energy future.

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