



DECARBONIZING HYDROGEN FROM PETROLEUM FEEDSTOCKS: ADVANCES IN LOW-CARBON PATHWAYS FOR EXISTING INFRASTRUCTURE

Nature's most abundant element, hydrogen, remains vital to many of the processes utilized for fuel efficiency, but it remains a major contributor to refinery CO₂ emissions. Increasing pressures on existing refineries leave researchers with the demand to find critical solutions to address the climate impact. This paper evaluates emerging low-carbon hydrogen pathways and their compatibility with existing industrial infrastructure and economic viability. Hydrogen is often characterized by “color” based on its production method. The paper focuses on two main low-carbon pathways at the forefront of research: blue hydrogen and turquoise hydrogen (methane pyrolysis). Additionally, this paper reviews the latest advances of each pathway and their promising potential as near-term decarbonization solutions and analyzes evolving government regulations. Specifically, looking into the comparison of blue hydrogen reducing lifecycle emissions by over 75% compared to traditional gray hydrogen. Additionally, turquoise hydrogen offers a near-zero emission alternative with solid carbon as a valuable byproduct. Together, these insights provide a comprehensive outlook of how these processes could lead to a more sustainable and cleaner solution for the petrochemical sector. into unified networks, ultimately leading to reductions in manual intervention [3].

Introduction

Hydrogen is the most abundant element in the universe, but crucial to many of the processes used in petroleum refineries globally. The issue faced when using hydrogen, however, is the byproduct produced when trying to improve the quality of the fuel, carbon. Contributing significantly to the global emission output, governments globally are putting pressure on refineries to look for a viable path to reduce the high carbon emissions. While some methods are still under considerable development, researchers are opting for lower-carbon pathways that are compatible with the existing infrastructure, remaining a priority. According to the International Energy Agency (IEA), prospects note that the global hydrogen demand could reach 225 million tonnes per year by 2050, compared to the estimated 100 million tonnes in 2019 [1]. As the global demand for hydrogen increases, the need to decarbonize it remains a priority as many countries are implementing measures to accelerate progress to a cleaner solution [2,3].

Hydrogen is a crucial resource in modern petroleum refinery methods. The element has a variety of purposes in enhancing the overall fuel, via methods such as hydrocracking, hydrotreating, and desulfurization; collectively, these three concepts provide benefits that help maximize fuel yields, improve the overall quality of feedstocks, and lower an important emission, sulfur [4]. In these processes, hydrogen reacts with heavy hydrocarbons and sulfur-based compounds, breaking them down to remove impurities and replace sulfur with potential environmental

implications. Forming cleaner hydrocarbons and H₂S can lead to improved fuel quality and reduced emissions. Overall, the natural element aids many methods to generate petroleum. To supply the volumes of hydrogen often required for these processes, refineries rely on a method called Steam Methane Reforming (SMR) of natural gas. Traditionally, SMR combines methane with steam at high temperatures to produce hydrogen, but with a carbon dioxide byproduct [5]. The issue arises with the carbon dioxide byproduct, as it contributes to the emissions that many refineries are under pressure to reduce. Hydrogen produced through SMR is commonly known as gray hydrogen. Although gray hydrogen is quite advantageous economically, costing approximately \$1.50 - \$2.50 per kilogram, its high carbon

footprint raises concerns regarding its contribution to greenhouse gas emissions [6,7].

As the traditional method leads to a higher carbon footprint, governments have increased pressure on refineries to find feasible methods of hydrogen production with less environmental impact. Governments have implemented stricter regulations to get refineries to comply by requiring carbon pricing, emission reporting mandates, and the Greenhouse Gas Reporting program, all aimed at reducing the carbon footprint in refineries [8, 9, 10, 11]. Attention increased on major capital investments and reevaluating refinery operations, leaving refineries with the task to find low-carbon pathways that remain compatible with the existing infrastructure [1]. Some countries, such as Japan, are already implementing alternative hydrogen production methods. The refineries there are adopting methods to expand hydrogen generation capacity through the integration of renewable energy and electrolysis-based production [11]. As more countries attempt to adopt more environmentally friendly low-carbon hydrogen solutions, the hope to find a cleaner solution for hydrogen is becoming a topic, globally needed.

Recent technical advances are offering promising results to decarbonize hydrogen production from petroleum feedstocks, while still leveraging existing infrastructure. These advances include blue hydrogen, electrified steam methane reforming, methane pyrolysis (also known as turquoise hydrogen), and other hybrid approaches, as broken down in Figure 1 below [6, 2, 7]. In parallel, increasing global research into various methods to keep up with the recent policy implementation, such as the Inflation Reduction Act in the United States, EU carbon reduction mandates, and Japan's national Hydrogen roadmap, is providing

Gray	Fossil Fuels	From fossil fuels without CCUS (Commonly through steam methane reforming)
Blue	Fossil Fuels	Natural gas with CCUS (through steam methane reforming, auto-thermal reforming, chemical looping reforming, etc.
Turquoise	Fossil Fuels	Thermal splitting of methane (pyrolysis). Release solid carbon, instead of gas
Green	Water/Biomass	Electrolysis (powered by renewable energy sources) and other technologies (using biogas, biomethane, bio-waste, etc.)

Figure 1: Summary of different hydrogen production methods based on associated color classifications.

economic incentives for low-carbon hydrogen production and encouraging investment into scalable methods to implement the new methods [9, 10, 12].

As these developments continue to improve, it provides an opportunity to explore low-carbon hydrogen production methods specifically for petroleum refineries, bringing the gap between current high-emissions and steps towards a sustainable hydrogen future. This paper focuses on the emerging pathways and compatibility with existing infrastructure to achieve a sustainable but equitable cleaner energy future.

Previous Hydrogen Pathways

Hydrogen can be produced from a variety of primary energy sources, and the differences in processes, energy-influencing cost, and associated emissions have led to the classification of hydrogen by "colors," as listed in Figure 2 [6, 7]. Historically, and in many refineries today, hydrogen is produced through natural gas, coal, or oil as a feedstock. Production is followed by methods including steam methane reforming (SMR) or coal gasification, both of which release considerable amounts of CO₂, approximately 13 CO₂ per kg, which result in the creation of gray hydrogen [13]. SMR and coal gasification are the two methods primarily producing gray hydrogen. SMR involves the process of reacting natural gas with steam in a reformer to produce syngas, followed by the water-gas shift reaction, resulting in CO₂ and H₂ [14]. Coal gasification, on the other hand, involves pulverized coal reacting at high temperatures with oxygen and steam to produce syngas, also containing CO₂ and H₂. Both methods have proven to be efficient, resulting in 60–85% efficiency for SMR and 74–85% for coal gasification [8]. Gray hydrogen remains heavily utilized in the petrochemical industry and for ammonia production. The major disadvantage of this type of hydrogen is its carbon intensity, with global emissions estimated to be approximately 830 Mt CO₂ per year [8].

However, while government regulations continue to tighten regarding global emissions issues for climate change, the high carbon footprint of gray hydrogen remains a significant challenge. The need for cleaner hydrogen is pivotal, and necessary research uncovers new pathways, hoping to remediate the effects. This paper will therefore shift focus to the lower carbon "colors" of hydrogen, examining those to be more environmentally friendly, and addressing their compatibility with existing infrastructure. In the following sections, the emerging methods will be explored to understand their potential for decarbonizing hydrogen supply for industrial and refinery applications.

Blue Hydrogen (SMR/ATR + CCS)

Blue Hydrogen is one decarbonization pathway being researched. Although its core technologies have been studied for decades, the most recent developments are showing promising signs of developing a low-carbon pathway that still leverages existing industrial infrastructure. Essentially, this type of hydrogen takes the same gray hydrogen processing method but instead couples it with carbon capture and storage (CCS) [15,16]. SMR remains strongly competitive economically for producing hydrogen from natural gas, but the issue with the method is that it reduces in efficiency by 18% with carbon capture, increasing the cost by \$1.10/kg H₂. Whereas a strong competitor in recent years developing a lot more traction is autothermal reforming (ATR), a process combining partial oxidation and steam reforming in the same reactor, eventually producing syngas, which is then coupled with CCS as well, as seen in Figure 3. As a possible alternative to SMR, efficiency only drops 2% with carbon capture, increasing cost by \$0.44/kg H₂. Although it remains favorable for carbon capture in comparison to SMR, it doesn't fully replace SMR, which remains economically competitive [16]. Comparing the two results, in a study by Oni et al. [16], ATR has the lowest life cycle greenhouse gas emissions (GHG), 3.91 kgCO₂eq/kg H₂, followed by SMR-85% (6.66 kgCO₂eq/kg H₂). Other advancements include quantifying emissions reductions, refining process integration, and aligning production with the latest policy thresholds to improve low-carbon hydrogen pathways.

One emerging area of interest involves advanced modelling

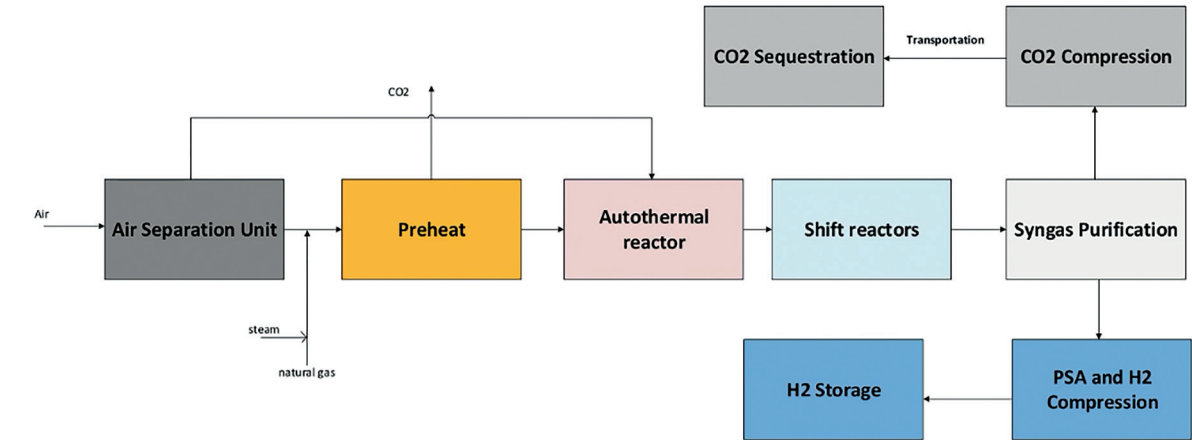


Figure 2 "Autothermal reforming process" Adapted from M. S. Kumar et al. [34].

studies that move beyond equilibrium assumptions, assuming all reactions run to thermodynamic equilibrium ignoring the heat and mass transfer limitations. This method integrates detailed reactor kinetics and CCS performance. In [17] Bayramoğlu and Bayramoğlu developed a coupled SMR with CCS model with capabilities of linking reactor operating conditions with capture system performance. This study extended traditional equilibrium-based SMR analyses by integrating a MATLAB-based plug flow reactor (PFR) model that incorporates detailed Langmuir–Hinshelwood–Hougen–Watson (LH–HW) kinetics for methane steam reforming and water-gas shift reactions. By coupling these kinetic models with an Aspen HYSYS-based CCS system, the work enabled a fully integrated assessment of hydrogen yield and CO₂ emission intensity under realistic reactor operating conditions [17]. By processing through this method in comparison to traditional SMR, which produces approximately 9-12 kg CO₂ per kg of H₂, the integrated CCS method can reduce emissions to approximately 2-3 kg CO₂ per kg H₂ [17]. In addition, leading to a >75% reduction in carbon intensity under optimized conditions.

Similarly, other research comparing ATR and SMR pathways found that CCS integration can cut well-to-gate greenhouse gas emissions by more than 60% [17]. By combining kinetics with the SMR modelling and integrated CCS system, researchers saw the same byproduct CO₂, but by incorporating the CCS unit chemically absorbed the CO₂ with a solvent. The solvent was able to reduce most of the CO₂ before it would then enter the atmosphere, resulting in a significant reduction of emissions. Additionally, leveling the cost of hydrogen (LCOH) in the range of \$0.13-\$0.52/kg-H₂ compared with gray hydrogen [18]. Previously, blue hydrogen had been considerably more costly, but by including this new methodology, it helps reduce the cost gap. More advanced SMR-CCS configurations have also been proposed in recent modeling work, introducing updated process configurations and solvents that enhance CO₂ removal efficiency and improve economic outcomes. Collectively, these modelling advancements are crucial as they also help provide quantitative data on how blue hydrogen systems could potentially meet emerging emissions criteria.

Carbon capture technology significantly shapes blue hydrogen's low-carbon promise. Several commercial and planned facilities, such as those detailed in industry partnerships like BP's H₂Teesside project, which aims to employ gas-heated reformers with advanced capture, claim potential capture rates approaching 99 % of CO₂ produced in reforming [19, 20]. While scale-up performance data remains limited, assessments of existing capture facilities signify that commercial CCS projects have struggled to achieve the high capture rates often assumed in literature. Stressing that the advances must be paired with performance monitoring and emissions accountability to validate blue hydrogen low-carbon pathways is practical and not only capable of being modelled.

Lifecycle analyses provide a more nuanced understanding of blue hydrogen's climate impacts. Although integrating CCS can significantly reduce direct CO₂ emissions from reforming processes, meaning residual emissions persist. Recent lifecycle assessments show that retrofitting existing SMR plants with CCS (SMR-CCS) can lower overall climate change compared to gray hydrogen but does not reach the stringent climate impact

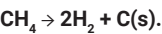
limits thresholds, as defined in European policy frameworks [20]. A potential issue that leads to this failure is possibilities of downstream hydrogen leakage. The leaked hydrogen acts as an indirect greenhouse gas, prolonging the methane atmospheric lifetime and increasing climate issues, counteracting any benefits the decarbonized hydrogen could produce.

While ATR-CCS demonstrates promising signs, the results remain sensitive to key economic and operational parameters such as natural gas prices, hydrogen storage requirements, and CO₂ transport costs. Therefore, further research and pilot-scale demonstrations are still required before large-scale deployment can be justified. Additional studies emphasize that achieving competitive carbon footprints not only depends on capture performance but also on methane leakage in upstream natural gas supply chains, which can erode lifecycle gains if not controlled. This issue also distinguishes blue hydrogen pathways from renewable pathways, where production emissions are close to zero [18].

One of blue hydrogen's core advantages compared to other low-carbon hydrogen pathways is its compatibility with existing industrial infrastructure. Many of the existing reforming units, established pipeline networks, and CO₂ storage sites can be leveraged for the recent hydrogen changes. This would enhance scalability in refineries and chemical processing plants, proving a viable low-carbon pathway. Despite the limitations of blue hydrogen, it still proves to be a technically and economically beneficial decarbonization strategy compatible with existing infrastructure, providing a potential pathway to lower-carbon emissions. As a result, blue hydrogen remains a promising strategy for lowering the carbon footprint.

Turquoise Hydrogen (Methane Pyrolysis)

Another extensively researched pathway is turquoise hydrogen. The hydrogen from this process is produced by undergoing thermal decomposition of methane (CH₄) into hydrogen and solid carbon without directly generating carbon dioxide (CO₂). In contrast to SMR-CCS, which still involves CO₂, turquoise hydrogen provides a potential pathway to avoiding CO₂ emissions by producing a solid carbon byproduct. This byproduct can then be stored and utilized for various other industrial applications [21, 22]. Methane pyrolysis is processed by breaking the strong carbon-hydrogen (C-H) bonds in methane at high temperatures (typically around >700-1200 degrees Celsius). The products resulting in hydrogen and solid carbon can be represented by the equation:



This reaction allows for nearly zero direct CO₂ while producing the hydrogen needed [22]. This approach can eliminate the need for other methods of carbon capture and storage (CCS) infrastructure typically needed when generating blue hydrogen. In comparison to conventional SMR, methane pyrolysis also proves to be substantially cleaner. A comprehensive techno-economic review on methane pyrolysis emphasizes that it can operate with near-zero CO₂ emissions and often uses less energy than water electrolysis, while producing only solid carbon byproduct, making it also a promising pathway for low-carbon hydrogen production [23].

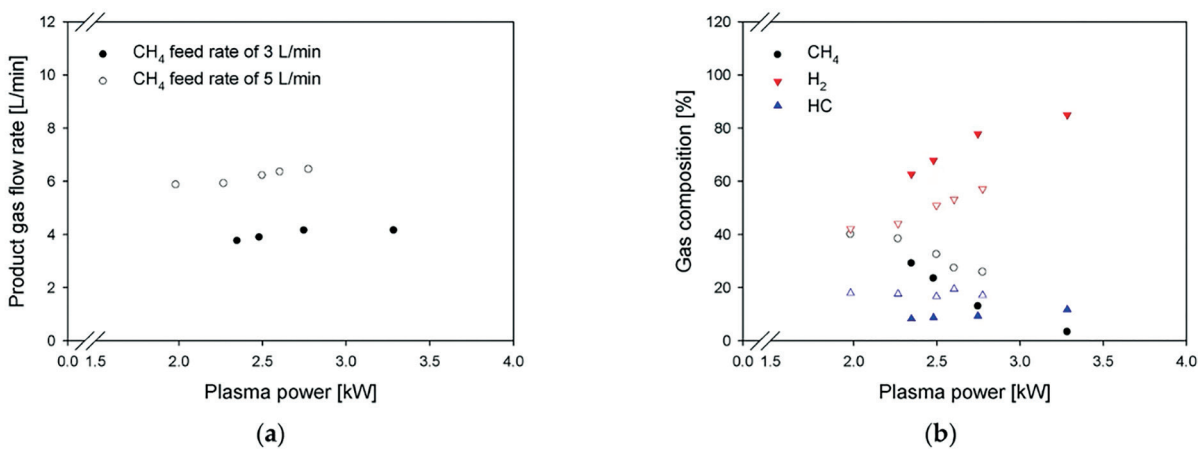


Figure 3: “Changes in (a) product gas flow rate and (b) product gas composition as a function of plasma power at a CH₄ feed rate of 3 L/min (solid symbol) and 5 L/min (open symbol).” Sourced from Park et al. [27].

One research method employs catalyst reactor configurations to enhance methane conversion and hydrogen yield. In a recent study conducted at Gifu University in Japan, researchers demonstrated that utilizing specialized catalysts, such as permalloy (Ni-Fe) plate catalysts, had the potential to achieve methane conversion rates of nearly 90% at temperatures exceeding 800 °C in medium-scale reactors [24]. The resulting products of this reaction include the hydrogen alongside solid carbon in fibrous and agglomerated morphologies, which can serve as a valuable byproduct and improve process economics. The applications include, but are not limited to, lithium-ion anodes, graphene production, and potential applications in advanced composite materials, as well [25]. Reactor-scale investigations further showed the dominant performance of temperature, indicating that the higher temperatures helped promote both catalytic and gas-phase methane decomposition [24]. While the inlet methane flow rate governed residence time and conversion efficiency, which helped determine the decarbonization effect. Beyond conventional electrically heated furnaces, alternative reactor concepts have also been explored, like microwave-heated systems [26]. These systems have been explored to improve heating uniformity and exert greater control over carbon formation and catalyst stability. Additionally, researchers found that with this method, temperatures above 800 °C result in approximately 90% methane conversion but even noted that increasing temperatures to 1000 °C saw hydrogen selectivity of approximately 90% [26]. By achieving hydrogen selectivity at that amount, it emphasizes the potential of becoming a cleaner hydrogen pathway, particularly if costs are leveled with traditional gray hydrogen SMR processing [26]. Although the results confirmed that the carbon generated was reasonably low, approximately 1-2%, the running cost due to consumption of the catalyst metal could potentially hinder its practical application [24]. Regardless, the study confirms that the catalyst exhibits strong performance and can contribute significantly to the advances of methane pyrolysis. Together, these developments underscore the flexibility of methane pyrolysis across multiple thermal environments, presenting as a potential, scalable, low-emissions hydrogen production alternative [24].

Another methane pyrolysis method being researched includes plasma-assisted methane pyrolysis. This method directly enables thermal cracking of methane into two products, hydrogen and solid carbon, without the formation of carbon oxides (CO and CO₂) [27]. Recent advancements regarding arc and non-thermal plasma systems demonstrated stable operation at atmospheric pressures, which is beneficial, especially given the natural tendency of methane pyrolysis requiring high temperatures [28]. Researchers found that with these methods, methane conversion and hydrogen yield strongly depended on the power input of plasma [27, 28]. By increasing the plasma power, it can enhance the heat and mass transfer within the reaction zone, resulting in higher methane conversion and hydrogen yield. It still increases the production of solid carbon, but this could be a valuable source for other industries. Experimental studies show that minimal formation of carbon oxides (CO and CO₂) is rarely generated under experimental conditions. Park et al. [28] investigated such an effect of plasma power on methane thermal cracking reactions under constant methane supply. With two separate methane feed streams at 3 L/min and 5 L/min (depicted in Figure 4a), as plasma power increased, hydrogen content also increased and reached

84.9% and 57.1%, respectively [28]. Furthermore, as seen in Figure 4b, the hydrocarbon byproduct content based on methane feed rate stayed low at 9% and 18%, respectively, while carbon oxides were not detected in the gas produced in either methane thermal cracking reaction stream [28]. This is significant, as it places plasma-assisted methane pyrolysis as a key method of a potential low-carbon hydrogen pathway. Although these approaches remain heavily experimental, the range of design pathways is under investigation and shows promising hopes for advancing as a low-carbon hydrogen pathway [28].

Figure 4: “Changes in (a) product gas flow rate and (b) product gas composition as a function of plasma power at a CH₄ feed rate of 3 L/min (solid symbol) and 5 L/min (open symbol).” Sourced from Park et al. [27].

Lastly, a major scientific goal with methane pyrolysis includes finding a catalyst material that can lower the high operating temperatures and make this method more economically viable. To achieve this, researchers have attempted to develop quantitative models of methane pyrolysis using density functional theory and catalyst adsorption energy correlations [29]. After incorporating various chemical models, such as Sabatier, transition-state, and microkinetic models, the resulting model has the capability of computing the reaction rate solely as a function of temperature T, partial pressures of methane (CH₄) and hydrogen (H₂), and adsorption energy, valid for any catalyst material [29]. Although these results are still being heavily developed to predict optimal catalyst materials, it lays the potential groundwork for future larger-scale reactor designs. In the future, this could aid the foundation for future large-scale studies of surfaces and alloy compositions using machine learning algorithms.

An advantage of using methane pyrolysis includes its ability to be located near existing natural gas infrastructure, including pipeline networks, storage facilities, and industrial feedstock supply chains. Like blue hydrogen, this makes it an economically valuable solution to decarbonizing the hydrogen, while still being compatible with current infrastructure [21]. This compatibility supports decentralized or modular deployment close to industrial

end-users such as refineries or ammonia synthesis plants, reducing the need for centralized greenfield hydrogen hubs [21]. In addition, the byproduct solid carbon proves to be advantageous for multiple industries, showing the benefits that generating turquoise hydrogen has over other hydrogen generation methods. Various forms of carbon — from carbon black used in polymers and coatings to graphite and carbon nanotubes for batteries and advanced materials — may offer upside revenue that improves the economics of hydrogen production [21]. This economic advantage will also help offset the production costs currently being incurred.

However, an important consideration is the potential challenges turquoise hydrogen has brought to refineries. Most of the implementations of this pathway require high temperatures for efficient methane decomposition [23]. While the concept seems to be quite beneficial, there are still major scale-up barriers taking the lab-scale demonstrations to industries that remain unknown [23]. Recent comprehensive reviews emphasize that although methane pyrolysis is technically promising, a lot of the research is still in early commercialization stages. Hence, researchers are prioritizing catalyst longevity, reactor design optimization, and integration with renewable heat sources to reduce associated emissions further [23]. Even though it is not fully developed to the same extent as SMR-based blue hydrogen, active research into catalytic media, plasma systems, and reactor design puts methane pyrolysis as a hopefully transitional hydrogen production technology, providing a pathway for decarbonization strategies.

Feasibility Comparison

Evaluating the low-carbon hydrogen pathways discussed for petroleum refineries, there are some important considerations to account for. These include carbon intensity, infrastructure compatibility, cost, and scalability, essentially the concepts that help take the ideas from research to being able to be deployed into industrial practices. Table 1 presents a comparative analysis of hydrogen production technologies of blue and turquoise hydrogen types as compared to gray hydrogen [31,35]. Beginning with gray hydrogen, produced primarily via SMR without carbon capture, is currently still the dominant pathway seen in refineries today, but it contributes heavily to a high carbon footprint. Emissions typically range from 9 to 12 kg CO₂ per kg H₂. Comparing that to Congress regulations, hoping to achieve hydrogen with lifecycle greenhouse gas emissions no greater than 4 kg CO₂ per kg H₂, gray hydrogen is significantly higher and contributes largely to greenhouse gas outputs [6, 13, 30]. Although it proves to be economically advantageous, with costs between \$1.50-\$2.50, gray hydrogen faces demanding regulatory pressures, conflicting with recent decarbonization incentives [6].

In comparison, blue hydrogen through SMR or ATR, but integrated with CCS, has the additional benefit of remaining compatible with existing refinery infrastructure. Coupling the reforming process with CCS has found to be able to reduce emissions close to approximately 2–3 kg CO₂ per kg H₂, representing over a 75% reduction compared to conventional gray hydrogen [16, 15]. Additionally, this is favorable with the targets outlined by Congress, making blue hydrogen a beneficial low-carbon

Table 1: Comparative Analysis of Hydrogen Production Technologies

Source: “Green, blue, and turquoise hydrogen: A review of production technologies and sustainability” Adapted from Dr M. S. Kumar et al. [31, 35].

Aspect	Blue Hydrogen	Turquoise Hydrogen
Feedstock	Natural gas / fossil fuels	Methane (fossil or biogas)
Main Processes	SMR, ATR, POX with CCS	Methane cracking, catalytic decomposition
Efficiency	65–85% (SMR, ATR)	~60–70% (methane cracking)
GHG Emissions	Medium (dependent on CCS performance)	Low (solid carbon byproduct)
Scalability	High	Medium (technology still maturing)
Cost (USD/kg H ₂)	~2.0–3.0	~2.0–3.5 (varies by method)
Maturity Level	High (industrial deployment)	Medium (R&D to pilot stage)
Byproducts	CO ₂ (captured), CO	Solid carbon
Key Barrier	CCS cost and infrastructure	Catalyst deactivation, high operating temperature

Table 2: Comparison of Energy Input Sources and Sustainability Considerations

Source: " Green, blue, and turquoise hydrogen: A review of production technologies and sustainability" Adapted from Dr M. S. Kumar et al. [35].

Hydrogen Type	Primary Energy Input	Production Process	Carbon Emissions	Sustainability Considerations
Gray Hydrogen	Natural gas (fossil fuel)	Steam Methane Reforming (SMR)	High (CO ₂ released directly)	Economically viable but environmentally damaging without CCS
Blue Hydrogen	Natural gas + carbon capture	SMR with carbon capture and storage (CCS)	Medium (partial CO ₂ captured and stored)	Lower emissions than grey hydrogen; CCS effectiveness varies
Turquoise Hydrogen	Methane + renewable or fossil heat	Methane pyrolysis (thermal cracking)	Low to medium (solid carbon byproduct)	Promising intermediary pathway; solid carbon requires long-term management

hydrogen pathway. Other benefits are not limited to, but also emphasize this hydrogen’s compatibility with existing infrastructure, like steam reformers, pipelines, and CO₂ storage sites. Due to the addition of CCS, economically placing blue hydrogen is a crucial spot as it has leveled the costs, ranging closer to \$2-\$3 per kilogram when optimized with CCS [31-35]. Although there are potential hazards with this pathway, blue hydrogen is a potential near-term solution for decarbonizing hydrogen, making progress towards a more sustainable energy solution.

Turquoise hydrogen, although still experimental, offers a promising near-zero emission solution. After undergoing methane pyrolysis and decomposing into the products of hydrogen and solid carbon, the method eliminates direct CO₂ emissions [23, 21]. Crucial for decarbonizing hydrogen and potentially mitigating future risks of leakage. The resulting byproduct, solid carbon, also proves to be economically advantageous for its various applications in other industries, like batteries, energy storage, or even construction [32]. In addition, methane pyrolysis reactors are compatible with existing natural gas infrastructure, including pipelines and storage facilities. This would simplify the distribution of hydrogen in the long run as well. Although challenges persist, with high operating temperatures and the demand for further ongoing research to further develop methods that could be scaled to an industrial scale, it provides the groundwork for finding those potential solutions. With further research and investment, turquoise hydrogen pathways could also be a potential low-carbon pathway, while still being compatible with existing infrastructure. Table 2 presents a side-by-side comparison of the energy input and sustainability considerations of turquoise hydrogen with both gray and blue hydrogen types [35].

Overall, while blue hydrogen offers more compatibility and advancements to date, turquoise hydrogen remains a possible solution for the future, as both methods are compliant with existing refinery infrastructure.

Conclusion and Outlook

As the search for a new low-carbon hydrogen pathway intensifies, many industries find themselves needing to find the latest innovations to combat their carbon emissions. The concept of decarbonizing hydrogen production from petroleum feedstocks, although challenging, presents a significant opportunity that could lead to a global reduction in emissions. After looking at several pathways shaping the future with a lower carbon footprint, concepts like blue and turquoise hydrogen provide possible opportunities to a cleaner solution. Each method discussed has its own unique advantages and limitations, varying in compatibility with existing infrastructure. However, further development and implementation could help trend emissions in the opposite direction.

Together, both methods offer a practical near-term solution that can leverage existing reformers, pipelines, and storage facilities, reducing carbon intensity without extensive redesign or costing the current industrial infrastructure. Although neither method is sustainable nor close to near-zero emissions, like green hydrogen, which is produced through water electrolysis powered solely by renewable electricity, they still offer opportunities for emissions reduction. Unlike green hydrogen, the other two methods have more compatibility with existing infrastructure. But as researchers advance green hydrogen methods, future applications could potentially revolutionize the

petrochemical industry, creating a more sustainable, cleaner energy solution. In the meantime, pathways like blue and turquoise hydrogen could mitigate further emission increases while that is further developed.

Looking forward, continued research and technological advancements will be essential to achieving the targets set by government regulations. Advancing current designs will not only enhance feasibility but could also lead to a more cost-effective low-carbon hydrogen. With strategic implementation and combining methodology, the hydrogen sector could advance towards a scalable and sustainable solution, positioning the abundant element as one of the vital resources of a cleaner industrial and energy future.

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Biographies

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Dr. Shah earned his doctorate in Chemical Engineering from The Pennsylvania State University and is a Fellow of The Chartered Management Institute, London. He is a Chartered Scientist (CSci) with the Science Council, a Chartered Chemist (CChem) with the Royal Society of Chemistry, a Chartered Engineer (CEng) with the Engineering Council, UK, and a Chartered Petroleum Engineer (CPEng) with the Energy Institute. He was recently granted the honorific distinction of "Eminent Engineer" by Tau Beta Pi, the oldest and largest engineering honor society in the United States, an honor reserved for engineers demonstrating exceptional professional achievement and character.

Actively engaged in academia and mentorship, Dr. Shah serves on the Advisory Boards of Farmingdale State College (Mechanical Technology and Engineering Management), Auburn University (Tribology and Lubrication Science), and the State University of New York at Stony Brook (Chemical Engineering and Materials Science & Engineering). He is

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