

The Clean Energy Transition: Analyzing the Role and status of Hydrogen blending in Sustainable Energy Solutions

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ABSTRACT

The global energy landscape is undergoing a transformative shift, driven by the urgent need to mitigate climate change impacts and reduce reliance on fossil fuels. Conventional hydrocarbon-based energy systems are primary sources of greenhouse gas emissions, prompting an intensified search for cleaner, more sustainable alternatives. Hydrogen blending has emerged as a promising avenue within sustainable energy strategies, offering applications across energy conversion, storage, and production technologies. This paper provides a comprehensive review of hydrogen blending, focusing on its integration in fuel cells, oxy-fuel combustion, and renewable hydrogen production via water electrolysis. Recent advancements in these areas illustrate hydrogen's potential to enhance efficiency and decrease emissions across sectors, from transportation to grid-scale power. By analyzing trends in global hydrogen demand, the technological status of hydrogen blending, and identifying existing research gaps, this study presents a roadmap for future exploration and innovation in hydrogen-based energy solutions. The findings underscore hydrogen's role in accelerating the clean energy transition, serving as a critical pathway toward achieving a sustainable, low-carbon energy infrastructure.

Keywords - Fuel cells, greenhouse gas emissions, hydrogen blending, renewable hydrogen production, sustainable energy.

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I. INTRODUCTION

The global energy sector is experiencing a significant transformation, driven by the pressing need to address climate change and lessen dependency on fossil fuels. Conventional energy sources, especially hydrocarbons, are major contributors to greenhouse gas emissions, resulting in serious environmental impacts. Consequently, there is an increasing demand for sustainable energy alternatives that are reliable, clean, and efficient. In this context, hydrogen blending has begun to play a crucial role as essential elements in various energy conversion and storage technologies. Their applications in fuel cells, oxy-fuel combustion, and hydrogen production from renewable resources present exciting opportunities for innovation and research in the pursuit of sustainable energy solutions. [1] Numerous studies have explored the potential of hydrogen blending in the context of energy production. For instance, hydrogen fuel cells have been recognized for their high efficiency and low emissions, making them suitable for a range of

applications from transportation to stationary power generation. [2]

Previous work has also highlighted advancements in water electrolysis, a method that utilizes renewable energy to produce green hydrogen, thereby reducing carbon footprints. [1]

The primary contribution of this paper is its comprehensive review of the various blended forms of hydrogen and their applications in sustainable energy production. By analyzing the recent trends of global hydrogen demands, status of hydrogen blending technology, identifying gaps, and suggesting avenues for future research, this paper offers a roadmap for advancing hydrogen-based clean energy solutions. The insights gathered will be valuable to researchers, policymakers, and industry stakeholders, highlighting how hydrogen in various blended forms could drive the transition toward a sustainable, low-carbon energy future.

II. GLOBAL HYDROGEN OVERVIEW

2.1 GLOBAL HYDROGEN DEMANDS

The demand for hydrogen globally has steadily increased from 2021 to 2024, reaching nearly 100 million tonnes (Mt) by 2024. This growth has largely been driven by established uses in refining and industrial applications, which still account for most of the demand. The International Energy Agency (IEA) has documented that new, low-emission applications in sectors like heavy industry, long-distance transport, and energy storage, while growing, still constitute less than 1% of total demand. However, demand in these sectors has increased by around 40% compared to 2022, reflecting significant interest and ongoing expansion

2.2 GLOBAL HYDROGEN PRODUCTION

In terms of production, global low-emissions hydrogen output is expected to reach 49 Mt per year by 2030, based on project announcements. By 2023, low-emissions hydrogen remained below 1 Mt, but initiatives in countries such as China, which accounts for a significant share of the global electrolyzer capacity, are expected to drive rapid scaling. As of 2023, water electrolysis capacity reached 1.4 GW, with a projected increase to 5 GW by the end of 2024, driven largely by Chinese and European projects.

The IEA has highlighted that this shift towards low-emission hydrogen production and expanded applications in renewable energy storage, heavy transport, and green industrial processes will play a key role in meeting the global climate targets outlined in the Net Zero Emissions by 2050 Scenario. Key government policies, including tax incentives and emissions mandates, have also begun creating demand through mechanisms like Germany's Carbon Contracts for Difference and EU mandates for low-emission aviation and shipping fuels. [3, 4, 5, 6] Trends in global hydrogen demand, production, and electrolyzer capacity from 2021 to 2024 are represented in the following table.

Table 1. Global Hydrogen Demand, Production, and Electrolyzer Capacity Trends (2021–2024) [3, 4, 5, 6]

Metric	2021	2022	2023	2024 (Projected)
Total Hydrogen	~94 Mt	~96 Mt	97 Mt	~100 Mt
Low-Emissions Hydrogen	~0.5 Mt	~0.7 Mt	<1 Mt	Projected to grow by 10%

Demand				
Low-emissions H2	~0.5 Mt	~0.7 Mt	<1 Mt	Projected to grow by 10%
Demand				
Water Electrolyzer Capacity	~0.8 GW	~1 GW	1.4 GW	5 GW
Projected Low-Emissions H2 Supply by 2030	-	38 Mt (2023 projection)	49 Mt (2024 projection)	49 Mt

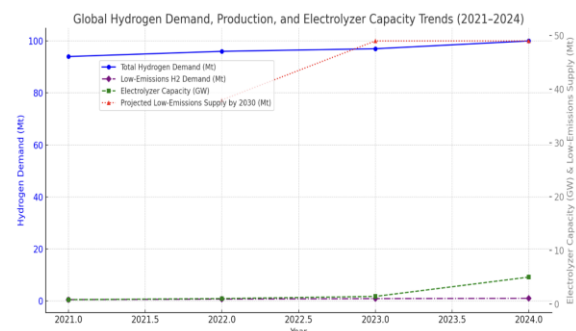


Fig 1. Graphical Representation of the global trends (2021–2024) [3, 4, 5, 6]

Hydrogen Blending

Hydrogen blending is the process of introducing hydrogen gas into natural gas pipelines to produce a composite fuel mixture. This blend allows for the use of existing infrastructure while decreasing carbon emissions, as hydrogen's combustion emits only water vapor rather than carbon dioxide.

To analyse the efficiency of using natural gas alone versus natural gas blended with hydrogen, it's essential to consider differences in energy density, combustion characteristics, emissions, and system modifications, as shown in several recent studies.

2.3 ENERGY DENSITY AND FUEL EFFICIENCY

2.3.1 Natural Gas:

Methane has an energy density of approximately 50 MJ/kg, which makes it highly efficient for combustion-based applications. A study by Li et al. (2022) published in Fuel confirms that natural gas provides substantial energy output per unit volume due to its high energy density, making it ideal for power generation applications.

2.3.2 Hydrogen Blending:

Hydrogen has a lower volumetric energy density (about 10.8 MJ/m³), which, when blended, reduces the overall energy density of the gas mixture. Research by Guandalini and Campanari (2017) in *Applied Energy* indicates that blending hydrogen with natural gas at low concentrations (up to 20% by volume) only slightly reduces the energy density and does not significantly affect system efficiency, assuming optimized combustion control.

2.4 ON EFFICIENCY AND OTHER THERMAL PROPERTIES

Hydrogen has a higher flame speed and a wider flammability range than methane, which facilitates complete combustion at low concentrations. Studies by Parra et al. (2019) in *International Journal of Hydrogen Energy* show that up to 10% hydrogen blending can enhance the thermal efficiency of natural gas systems by supporting more complete combustion and reducing unburned hydrocarbons . [9]

However, for 20%, combustion temperatures increase due to hydrogen's high flame temperature, requiring modifications to prevent issues like flashback and to maintain efficiency in gas turbines and engines. This was confirmed in research by Florisson et al. (2020), which outlines the adaptation needed in infrastructure for higher hydrogen concentrations . [9]

2.5 CARBON EMISSIONS MENTAL EFFICIENCY

2.5.1 Emission Reductions:

Studies, such as those by Pellegrino et al. (2022) in *Energy Conversion and Management*, indicate that blending hydrogen into natural gas reduces carbon emissions by lowering the carbon content per unit of energy produced. For instance, blending 10% hydrogen by volume can reduce CO₂ emissions by approximately 8% without major changes in energy output . [9]

2.5.2 System Efficiency:

Blending shown to improve environmental efficiency through emissions reductions but requires fine-tuning of distribution and combustion systems to manage the potential for higher leakage rates. Studies by Melaina et al. (2021) in *Renewable and Sustainable Energy Reviews* emphasize that blending ratios above 15% may necessitate

infrastructure improvements to ensure efficiency and safety due to hydrogen's higher propensity for leakage . [9]

2.5.3 Infrastructure and Efficiency Losses:

Hydrogen blends can lead to material embrittlement and increased leak rates in existing natural gas pipelines, which may reduce system efficiency. A study by Reuß et al. (2020) in *Journal of Natural Gas Science and Engineering* highlights that beyond 20% hydrogen blending, infrastructure modifications are critical to prevent energy losses and maintain system reliability . [9]

Table 2. Comparison of Efficiency and Infrastructure Requirements for Natural Gas vs. Hydrogen-Natural Gas Blends

Parameter	Natural Gas Alone	Natural Gas with Hydrogen Blending
Energy Density	~50 MJ/kg	~47 MJ/kg for 10% hydrogen blend by volume; reduces as hydrogen increases
Carbon Emissions	~0.2 kg CO ₂ per kWh	~0.18 kg CO ₂ per kWh for 10% hydrogen blend (10% reduction)
Thermal Efficiency	35-40% in combined-cycle systems	Can increase to 42% for up to 15% hydrogen blend
Infrastructure Modifications	No additional modifications required for pipelines or appliances	Minimal for blends below 10%; major modifications required above 20%
Combustion Properties	Stable flame speed and combustion characteristics	Higher flame speed; increased combustion efficiency at low blends

III. HYDROGEN BLENDING PROJECTS IN INDIA

3.1 GAIL – (HYDROGEN BLENDING PROJECT)

Gas Authority of India Limited (GAIL) has launched India's first project to blend hydrogen with natural gas in Indore, Madhya Pradesh, supplying the hydrogen-blended gas to Avantika Gas Limited, a joint venture with HPCL. This pilot project aligns with the National Hydrogen Mission and aims to assess the feasibility of integrating hydrogen into the City Gas Distribution (CGD) network, marking a significant step towards a carbon-neutral future. [10]

Beginning with the injection of grey hydrogen at the City Gate Station (CGS), the project will transition to green hydrogen. GAIL has secured the necessary regulatory approvals and consulted experts to evaluate the blending's impact. This

initiative reflects GAIL's commitment to a gas-based economy and is expected to help establish a regulatory framework for hydrogen injection into natural gas, enabling similar projects across India. [10] In a significant move toward exploring new and alternative energy sources in alignment with the National Green Hydrogen Mission, GAIL (India) Limited has inaugurated its first Green Hydrogen Plant at GAIL Vijaipur in Madhya Pradesh. [11]

The green hydrogen plant is a step toward GAIL's goal of supplementing its natural gas business with carbon-free hydrogen. The plant is also in line with the National Green Hydrogen mission, which aims to increase India's green hydrogen production capacity to 5 million tons per year by 2030. GAIL is also a member of the National Gas Hydrate Programme (NGHP), which explores and develops gas hydrate resources. Gas hydrates are ice-like crystalline compounds that contain natural gas and water. [11]

This Green Hydrogen plant has a production capacity of 4.3 TPD of hydrogen, generated through 10 MW PEM (Proton Exchange Membrane) electrolyzer units by using electrolysis of water powered by renewable energy. The hydrogen produced will have a purity of 99.999% (by volume) and will be generated at a pressure of 30 Kg/cm². [11]

Initially, the hydrogen produced from this facility will be utilized as a fuel in conjunction with natural gas for various processes and equipment operating within the existing plant at Vijaipur. There are plans to eventually dispense this hydrogen to retail customers in nearby areas, transported through high-pressure cascades. [11]

In addition to sourcing renewable power through open access, GAIL is also establishing approximately 20 MW of solar power plants at Vijaipur, including both ground-mounted and floating systems, to fulfill the green power requirements for the 10 MW PEM electrolyzer. [11]

The 10 MW Proton Exchange Membrane (PEM) electrolyzer is a key technology in GAIL's Green Hydrogen Plant, enabling the production of green hydrogen through the electrolysis of water

using renewable energy sources. This electrolyzer operates by applying electricity to water, which splits it into hydrogen and oxygen. The PEM membrane facilitates the movement of protons from the anode to the cathode, allowing for efficient hydrogen generation with a high purity level of 99.999%. The design of the PEM electrolyzer allows for rapid response to fluctuations in energy supply, making it suitable for integration with variable renewable energy sources like solar and wind [12]

In addition to its technical capabilities, the construction of the PEM electrolyzer involves sophisticated components such as the membrane electrode assembly and bipolar plates, which ensure effective gas distribution and heat management. The facility at Vijaipur not only supports hydrogen production but also aligns with India's broader goals of increasing the share of natural gas in the energy mix and achieving net-zero emissions by 2070 [12]

As GAIL continues to innovate in hydrogen technologies, this project serves as a critical step toward establishing a sustainable hydrogen economy in India. [12]

IV. HYDROGEN BLENDING PROJECTS IN EUROPE

4.1 HYDROGEN PROJECT IN FRANCE – (GRHYD)

The GRHYD project, launched in 2014, is France's first Power-to-Gas demonstrator, involving 11 leading partners dedicated to zero-carbon energy. This innovative initiative, coordinated by ENGIE in collaboration with 10 other partners and supported by the government through ADEME's Future Investment Program and the Tenerrdis competitiveness cluster, aims to evaluate the technical and economic viability of incorporating hydrogen into natural gas networks for residential energy needs. [13]

Located in the new neighborhood of Cappelle-la-Grande, GRHYD supplies approximately 100 homes and a health center boiler with a blend of hydrogen and natural gas, with hydrogen content up to 20% by volume. Over five

years of study, authorization, and demonstration, this project is testing the potential of mixed hydrogen-natural gas solutions to power heating, hot water, and cooking systems. McPhy, one of the project's partners, provided its McStore solid hydrogen storage technology for safe and efficient storage. GRHYD marks a significant milestone as a large-scale demonstration, paving the way for future industrialization of Power-to-Gas technology in France. [13] The French government is backing the GRHYD hydrogen energy storage project, led by ENGIE and a consortium of industrial partners. France aims to achieve 23% renewable energy consumption by 2020, and this project is designed to convert excess renewable energy into hydrogen. This hydrogen is blended with natural gas for applications like space heating, water heating, and fueling. By offering a way to store surplus power from variable renewable sources like wind and solar, GRHYD not only helps manage renewable electricity supply but also lowers greenhouse gas emissions. [14]

Initiated in 2014, GRHYD began with two years of technical and social studies, followed by a five-year demonstration phase targeting transport and residential energy use. This approach addresses key environmental and energy challenges, such as reducing greenhouse gas emissions, supporting local industry and resources, stimulating economic growth, and advancing hydrogen-fueled transportation. [14]

The project includes two major demonstration areas within the Dunkerque Urban Community:

i. Transportation Demonstrator:

The Hythane® fuel project adapts a natural gas fueling station to deliver a blend of hydrogen and natural gas, starting at 6% hydrogen and gradually increasing to 20%. About 50 buses will operate on this blended fuel. [14]

ii. Residential Demonstrator:

In the Cappelle-la-Grande neighborhood, around 200 homes will be supplied with a hydrogen-natural gas mix (up to 20% hydrogen) generated from renewable wind energy. Excess power is converted into hydrogen for storage and later distribution. [14]

At the core of GRHYD's Power-to-Gas system is a proton exchange membrane (PEM) electrolyzer, capable of producing up to 10 cubic meters of hydrogen per hour, alongside a metal hydride storage module with a 5 kg capacity. This setup enables efficient hydrogen production, storage, and injection into the natural gas network. The demonstration phase includes real-world testing, with the hydrogen content adjusted based on green electricity availability, capped below 20% by volume for safety compliance. [14]

4.2 HYDROGEN BLENDING PROJECT IN GERMANY – (GET H₂ NUKLEUS)

By 2025, the GET H₂ consortium—including bp, Evonik, Nowega, OGE, and RWE Generation—aims to establish Germany's first open-access hydrogen infrastructure. The GET H₂ Nukleus project will link green hydrogen production with industrial consumers across Lower Saxony and North Rhine-Westphalia. Spanning approximately 130 kilometers from Lingen to Gelsenkirchen, this network will be the first regulated H₂ infrastructure offering non-discriminatory access and transparent pricing. As an Important Project of Common European Interest (IPCEI), GET H₂ Nukleus is eligible for European funding. [15, 16]

Green hydrogen will be generated in Lingen, Lower Saxony, using a wind-powered electrolyzer with a capacity exceeding 100 MW, to be installed at the RWE power plant site. Existing gas pipelines managed by transmission operators Nowega and OGE will be repurposed for 100% hydrogen transport. Nowega is also constructing a new pipeline to connect the electrolysis facility with the main line to the Ruhr region, while Evonik will build a partial pipeline from the Marl Chemical Park to bp's Ruhr Oel refinery in Gelsenkirchen. This infrastructure will enable the transport of climate-neutral hydrogen to industrial clients, allowing them to integrate green hydrogen into their production processes and significantly reduce CO₂ emissions. [15, 16]

To support hydrogen storage, Nowega and OGE are linking the RWE Gas Storage West facilities in Gronau-Epe with a new pipeline, where a cavern storage site for hydrogen will also be developed. By 2030, the GET H₂ partners plan to expand this project to connect additional industrial clients and import pathways, paving the way for an integrated hydrogen network across Germany. The GET H₂ Nukleus project could serve as a foundation for Germany's national H₂ core network, currently under development by FNB Gas e.V., with initial

pipeline conversions and new constructions already underway. [15, 16]



Fig 1. Process flow of GET H₂ Nukleus project [15]

Fig 2. illustrates the planned GET H₂ Nukleus hydrogen infrastructure network in Germany. It shows a pipeline network that will connect various facilities for hydrogen production, storage, and usage by 2025.

On the left side, there is an "Electrolysis" facility located in Lingen, Lower Saxony, where green hydrogen will be produced using renewable wind energy. The green hydrogen generated here will be transported through an approximately 130-kilometer pipeline network. The hydrogen pipeline then leads from the RWE power station in Lingen, through Lower Saxony and North Rhine-Westphalia, reaching a cavern storage facility in Gronau-Epe. This facility will store hydrogen in underground caverns.

Continuing along the pipeline, the infrastructure connects to multiple industrial sites in the Ruhr area, including Evonik's Marl Chemical Park and bp's Ruhr Oel refinery in Gelsenkirchen. The hydrogen will be used as a climate-neutral feedstock in various industrial processes at these facilities.

On the far right side, a map of Germany shows the project area with an outline of the pipeline path, focusing on the connection between Lower Saxony and North Rhine-Westphalia, marking the locations of major project facilities. Key points of the project include the green hydrogen production, pipeline transport, underground storage, and industrial usage in the Ruhr region, which aims to reduce CO₂ emissions in the industrial sector. Fig. 3

illustrates the proposed blending map of GET H₂ Nukleus project where continuous green line in the map is about conversion management of existing line and the dotted green line is about new construction line management.



Fig. 3 Proposed blending map of GET H₂ Nukleus project [16]

4.3 HYDROGEN BLENDING PROJECT IN UNITED KINGDOM – (HyDeploy)

The HyDeploy project, now in its final stages as HyDeploy2, has successfully completed a series of trials and created a comprehensive evidence base supporting hydrogen blending in the UK's gas network.

4.3.1 Project Scope and Objectives:

HyDeploy aimed to demonstrate that a 20 mol% hydrogen blend with natural gas could be safely distributed and used within the existing gas infrastructure, starting with a private network trial at Keele University and then expanding to a public network trial in Winlaton.

The project supports the UK's goal of achieving Net Zero by 2050 by proving that hydrogen blending is a viable step toward decarbonizing heat in the UK [17, 18, 19]

4.3.2 Key Achievements:

Successful Trials: The Keele University trial confirmed safety and operational feasibility in a controlled private network setting. Following this, the Winlaton trial in Gateshead demonstrated that hydrogen blending could be safely applied to a public network. Both trials achieved significant carbon reductions and validated the blend's compatibility with existing gas appliances and infrastructure. [17, 18, 19] **Regulatory Progress:** The project secured two exemptions from the Gas Safety (Management) Regulations (GSMR) for hydrogen blending. These exemptions, granted by the Health and Safety Executive (HSE), allowed for controlled blending of up to 20 mol% hydrogen in the Keele and Winlaton networks. [18, 19]

Public Engagement: HyDeploy prioritized public engagement, surveying and interviewing residents to ensure their concerns were addressed. Public response was largely positive, with a significant increase in support for hydrogen blending over the trial period. By the end of the Winlaton trial, 78% of residents favored hydrogen blending [19]

4.3.3 Safety and Evidence Base for GB-Wide Application:

The evidence generated from HyDeploy2 has been pivotal in establishing the feasibility of hydrogen blending on a national scale. This includes extensive testing on materials, appliances, and industrial applications, confirming that hydrogen blends can operate safely within the current gas network.[19] The evidence base has been submitted to the HSE and the Department for Energy Security and Net Zero (DESNZ) for a comprehensive review, with the goal of amending GSMR to allow hydrogen blending nationwide. [19]

4.3.4 Policy Support and Strategic Alignment:

The UK government's Energy White Paper and 10-Point Plan highlight hydrogen blending as a critical element in the country's Net Zero strategy. In December 2023, a strategic policy decision was made in favor of hydrogen blending, influenced by the HyDeploy project's findings. This positions hydrogen as an essential component of the UK's decarbonization efforts [18, 19]

4.3.5 Next Steps:

Review and Amendment of Regulations: The comprehensive evidence base provided by HyDeploy is under review by the HSE and DESNZ, with the aim of formalizing hydrogen blending regulations within the GB gas distribution network.

Future Implementations: A roadmap for hydrogen blending across the entire GB gas network has been proposed, with plans for widespread adoption by 2026. This involves further collaboration between government bodies, industry stakeholders, and gas distribution networks . [17]

In summary, HyDeploy has established a strong foundation for hydrogen blending, proving both the technical and regulatory feasibility of this approach to reduce carbon emissions. The project's success has positioned hydrogen blending as a feasible, scalable solution for decarbonizing the UK's gas infrastructure.

V. HYDROGEN BLENDING PROJECT IN AUSTRALIA – (ATCO)

ATCO Australia achieved a 10% hydrogen blend using a solar-powered electrolyzer, supplying 3,000 homes with hydrogen-blended natural gas.

In late 2022, ATCO took a transformative step in Western Australia by blending renewable hydrogen into the natural gas distribution network in the City of Cockburn. This project, launched in line with WA's Renewable Hydrogen Strategy, marked a significant milestone as one of Australia's largest hydrogen blending initiatives, impacting around 2,700 homes and businesses across Glen Iris, Treeby, and Calleya Estates. By gradually introducing renewable hydrogen—between 2% and 10%—into targeted sections of the natural gas grid, the project aims to explore how this sustainable energy source can integrate into existing infrastructure without disrupting appliance performance. <https://www.atco.com/en-au/projects/hydrogen-blending.html>

The initiative is designed to provide critical, real-world insights into hydrogen's role within Australia's energy mix, particularly its potential to reduce carbon emissions when paired with renewable energy for production. Hydrogen,

when generated via electrolysis powered by renewable sources, emits no carbon, making it an attractive energy solution. ATCO's Clean Energy Innovation Hub (CEIH) has been at the forefront of this innovation, producing hydrogen since 2019. To meet the project's hydrogen needs, ATCO combines solar energy from the Jandakot Operations Centre with supplemental grid electricity, certified renewable through Large-scale Generation Certificates.

This project represents a step towards a greener future, building on existing gas infrastructure that can adapt and evolve alongside hydrogen. Extensive tests have shown that current Australian appliances can safely use gas containing up to 10% hydrogen without modification, ensuring no inconvenience for customers during this initial blending phase. While future, higher hydrogen blends might require appliance adjustments, ATCO's current project remains well within safe limits, underscoring its commitment to innovation without compromising consumer safety. [20]



Fig 2. Blending Map of ATCO project. From [20]

ATCO's vision extends beyond the technical; the company's commitment to community well-being, sustainability, and collaboration is woven into the project's design. By working with local communities and adhering to core values of integrity, agility, and safety, ATCO is leading an energy transformation that considers both the technical demands of a low-carbon future and the human aspects of community partnership. This approach not only supports the environment but also fosters trust, showing how energy companies can play a pivotal role in sustainable development. [20]

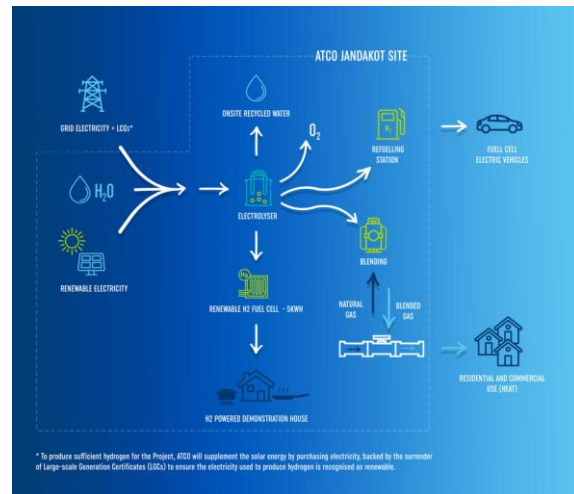


Fig 3. Process flow of ATCO project. From [20]

This diagram illustrates ATCO's hydrogen blending and renewable energy system at their Jandakot site, with the process and energy flow from renewable electricity generation to residential and commercial use. Here's a breakdown:

5.3 Renewable Electricity and Grid Electricity:

The process begins with renewable electricity generated on-site (likely from solar panels) and supplemented by grid electricity when needed. To ensure this additional electricity is renewable, ATCO uses Large-scale Generation Certificates (LGCs), which certify that the electricity is sourced from renewable origins.

5.4 Water Electrolysis:

Renewable electricity powers an electrolyzer that splits water (H_2O) into hydrogen (H_2) and oxygen (O_2). This electrolysis process is crucial for producing green hydrogen, as it only requires water and electricity, with no carbon emissions if the electricity source is renewable.

5.5 Oxygen Byproduct:

The oxygen produced during electrolysis is released or used for other purposes (e.g., in industry or medical applications).

5.6 Hydrogen Blending and Fuel Cell Applications:

5.6.4 Hydrogen Blending:

A portion of the hydrogen produced is blended with natural gas to create a blended fuel mix. This blended gas is then piped through the existing natural gas network to residential and commercial customers for heating.

5.6.5 Fuel Cell:

Another portion of the hydrogen is used to power a 5 kWh hydrogen fuel cell, which supplies energy to a demonstration house. This house is powered entirely by renewable hydrogen, showcasing hydrogen's potential as a standalone energy source. [7]

5.6.6 Refueling Station:

Some of the hydrogen is also directed to a refueling station, where it is used to fuel hydrogen-powered electric vehicles, demonstrating the use of hydrogen in transportation.

5.7 Residential and Commercial Use:

The blended hydrogen and natural gas mix is distributed to homes and businesses for heating, reducing reliance on fossil fuels and thereby lowering carbon emissions.

This project not only demonstrates the integration of hydrogen into existing energy systems but also offers insights into its potential applications, from household heating and electricity generation to sustainable transportation. The system is designed to show that hydrogen, especially when produced from renewable sources, can play a versatile role in decarbonizing various sectors.

VI. HYDROGEN BLENDING PROJECT IN USA

- (HYBLEND)

The HyBlend initiative tackles technical barriers to safely blending hydrogen into natural gas pipelines. By focusing on materials compatibility research, techno-economic analysis, and life cycle analysis, HyBlend will develop publicly accessible tools to evaluate the potential benefits, costs, and risks of hydrogen blending. This initiative aligns with the DOE's H2@Scale vision, which aims to expand clean hydrogen use across multiple sectors in the economy.

With the U.S. containing roughly three million miles of natural gas pipelines and over 1,600 miles of hydrogen pipelines, injecting clean hydrogen into natural gas lines could provide a lower-emission energy source. However, the maximum feasible blend of hydrogen depends on pipeline material integrity, system age, and blend concentration. Key outcomes of the project include tools to assess the cost-effectiveness and environmental benefits of hydrogen blending, as well as tools to evaluate the associated risks for pipeline infrastructure. [21]

The report *Hydrogen Blending into Natural Gas Pipeline Infrastructure: Review of the state of Technology* reviews literature on hydrogen blending in natural gas pipelines, examining the opportunities and challenges associated with safely integrating hydrogen, even at low concentrations (1–10% by volume). It highlights that compatibility varies based on pipeline conditions and operating pressures, and recommends a case-by-case assessment to identify necessary infrastructure upgrades. Research findings indicate that hydrogen affects both fatigue crack growth and fracture resistance in pipeline steels, especially at low hydrogen pressures. Polyethylene materials also show changes in density and crystallinity when exposed to hydrogen, though more research is needed to fully understand these effects. [22]

Several mature modeling approaches assess hydrogen's impact on pipeline operations, enabling improved techno-economic analyses. ASME B31.12 guidelines provide conservative estimates for repurposing natural gas pipelines, originally intended for new hydrogen lines. Operational studies show that hydrogen blending affects hydraulic properties, requiring higher compressor speeds and energy for consistent pressure maintenance. The report emphasizes balancing costs for pipeline upgrades, compression stations, and inspection frequency against reduced transmission capacity and compression energy needs. Future modeling and techno-economic tools will facilitate scenario-based assessments for hydrogen blending and ultimately support decarbonization goals. An upcoming open-source software tool will integrate these findings, improving hydrogen compatibility evaluations and enabling comparison across multiple energy pathways. [22]

VII. Hydrogen Blending in Natural Gas Systems: Challenges and Mitigation Strategies

7.1 Pipeline Integrity and Material Compatibility

Challenge: Hydrogen is known to cause embrittlement in some materials commonly used in pipelines, particularly certain types of steel, which increases the risk of leakage and infrastructure degradation [23]

Mitigation Strategies: To address these risks, thorough materials testing on pipeline

infrastructure is essential, particularly on high-risk segments. Replacing incompatible materials with hydrogen-compatible alternatives, such as polymers or specialized steel, is recommended. Additionally, targeted upgrades to high-risk sections can enhance system integrity. [23]

7.2 Equipment Compatibility and Blending Limits

Challenge: Most natural gas appliances and equipment are not designed to operate efficiently or safely with hydrogen concentrations above certain levels. [24] Typically, appliances can handle up to 20% hydrogen by volume without requiring major modifications.

Mitigation Strategies: Establishing regulatory blending limits (up to around 20%) can ensure appliance compatibility without significant upgrades. Developing standards for hydrogen-compatible appliances and certifying such equipment can further support safe hydrogen integration. Additionally, consumer education on hydrogen-compatible appliances is important for both safety and efficiency. [24]

7.2 Energy Density, Calorific Value, and Metering

Challenge: Hydrogen has a lower energy density than natural gas, resulting in lower energy content per unit volume, which may lead to billing inconsistencies [25]

Mitigation Strategies: Implementing smart metering systems can help account for variations in energy content based on hydrogen blend ratios, ensuring fair and accurate billing. Additionally, systems that continuously monitor calorific value differences in real time can help address these energy density challenges, particularly in regions with fluctuating hydrogen concentrations.[25]

7.3 Safety and Leak Detection

Challenge: Hydrogen leaks more easily than natural gas and burns with an invisible flame, making it challenging to detect with standard sensors

[26] Current detection systems are not fully optimized for hydrogen, posing unique safety risks.

Mitigation Strategies: Advanced leak detection technologies, such as specialized hydrogen sensors, can improve safety by identifying leaks at lower concentrations. Establishing hydrogen-specific safety protocols and providing training for pipeline operators, emergency responders, and technicians are also crucial steps. [26]

7.4 Regulatory and Permitting Challenges

Challenge: Regulatory frameworks for hydrogen blending are limited and vary across regions, creating uncertainty for stakeholders. [27] This lack of clear standards complicates permitting and compliance.

Mitigation Strategies: Developing internationally accepted regulatory standards for hydrogen blending, including safety requirements, operational guidelines, and blending thresholds, would provide greater clarity. Streamlining permitting processes and offering financial incentives for hydrogen blending projects can also encourage industry participation.[27]

7.5 Public Perception and Acceptance

Challenge: Public concerns regarding the safety and reliability of hydrogen-blended gas may lead to resistance, particularly if safety risks are not well understood. [28]

Mitigation Strategies: Public awareness campaigns can play an important role in building trust and understanding about hydrogen blending. Engaging with local communities and consumer advocacy groups can improve transparency, address concerns, and foster acceptance of hydrogen integration into natural gas systems. [28]

VIII. CONCLUSION

In conclusion, this review highlights the transformative potential of hydrogen blending as a vital component in the global shift toward sustainable energy systems. The integration of hydrogen into conventional energy processes—

whether in fuel cells, oxy-fuel combustion, or renewable hydrogen production—demonstrates its versatility and effectiveness in reducing emissions and enhancing energy efficiency. The ongoing development of hydrogen projects around the world, from large-scale blending initiatives in the UK to ambitious hydrogen infrastructure plans in countries like Australia, India, and Germany, underscores a widespread commitment to hydrogen as a clean energy vector.

The current advancements in hydrogen blending technology illustrate promising avenues for reducing reliance on fossil fuels and achieving significant decarbonization. However, further research is essential to address challenges in hydrogen production, storage, and distribution. Investment in research and infrastructure, alongside supportive policies and international collaboration, will be critical to overcoming these challenges and enabling hydrogen's full potential.

As the global demand for hydrogen grows, this analysis indicates that hydrogen blending can play a pivotal role in meeting the world's clean energy goals. By advancing innovation in hydrogen-based technologies and integrating hydrogen into diverse sectors, we can accelerate progress toward a resilient, low-carbon energy landscape, ultimately supporting the urgent global mission to combat climate change.

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