

The role of the industrial gas industry in mitigating air pollution through technological innovation and sustainable practices

by

Biola C. Daniel

B.E., City College of New York, 2019

A REPORT

submitted in partial fulfillment of the requirements for the degree

MASTER OF SCIENCE

Department of Chemical Engineering
Carl R. Ice College of Engineering

KANSAS STATE UNIVERSITY
Manhattan, Kansas

2026

Approved by:

Co-Major Professor
Placidus Amama

Approved by:

Co-Major Professor
Larry Erickson

Copyright

© Biola Daniel 2026.

Abstract

Air pollution remains one of the most significant environmental challenges affecting public health and global ecosystems. Industrial activities contribute substantially to atmospheric emissions, including greenhouse gases and other pollutants. However, the industrial gas sector also plays a critical role in reducing environmental impacts through technological innovation, improved efficiency, and sustainable practices. Industrial gases such as oxygen, nitrogen, hydrogen, and carbon dioxide are essential to numerous industrial applications including manufacturing, healthcare, metallurgy, and energy production.

This report examines the role of the industrial gas industry in mitigating air pollution through the implementation of advanced technologies and environmentally sustainable practices. Particular focus is placed on hydrogen production, renewable energy integration, gas recycling systems, and carbon capture and storage technologies. Emerging developments such as green hydrogen production through renewable-powered electrolysis demonstrate the potential of industrial gases to support decarbonization strategies across multiple sectors.

In addition to environmental benefits, technological innovations in the industrial gas industry offer significant economic opportunities. Investments in renewable energy systems, gas recycling infrastructure, and carbon capture technologies can reduce operational costs while generating new revenue streams through the sale of captured carbon dioxide and hydrogen fuel. By integrating advanced gas production technologies, renewable hydrogen systems, gas recycling processes, and carbon capture strategies, the industrial gas sector has the potential to significantly reduce industrial emissions while supporting the transition toward low-carbon energy systems and sustainable industrial development. In addition, this report incorporates chemical engineering principles, including reaction stoichiometry and mass balance analysis, to

quantify emissions and evaluate the effectiveness of hydrogen production pathways. A simulated case study is also presented to estimate emission reductions associated with gray, blue, and green hydrogen systems.

Table of Contents

List of Figures	vi
List of Tables	vii
Acknowledgements	viii
Introduction	1
Background	2
Technological Innovations in Industrial Gas Production.....	4
Gas Separation Technologies in Industrial Gas Production	5
Chemical Engineering Principles in Hydrogen Production	8
Conventional Hydrogen Production	10
Blue Hydrogen and Carbon Capture Integration	11
Green Hydrogen via Electrolysis	12
Quantitative Emissions Comparison of Hydrogen Production Pathways.....	14
Water Quality Considerations for Electrolysis	17
Renewable Energy Integration.....	18
Large-Scale Renewable Hydrogen Projects.....	18
Gas Recycling and Argon Recovery	19
Carbon Capture and Utilization	21
Simulated Case Study and Experimental Validation	22
Economic and Environmental Impacts	25
Future Trends and Challenges	26
Conclusion	27
References	28

List of Figures

Figure 1. Simplified industrial gas system showing separate air separation and hydrogen production units, including renewable-powered hydrogen production and carbon dioxide capture and storage processes.	3
Figure 2. Simplified cryogenic air separation process including compression, liquefaction, and cryogenic distillation for the production of industrial gases.	5
Figure 3. Grey hydrogen production via steam methane reforming with direct carbon dioxide emissions.	11
Figure 4. Blue hydrogen production using steam methane reforming with carbon capture and storage to reduce carbon dioxide emissions.	12
Figure 5. Green hydrogen production via water electrolysis powered by renewable electricity with no direct carbon dioxide emissions.	16
Figure 6. Industrial argon recycling system for gas recovery and reuse.	20
Figure 7. Overview of carbon capture and utilization pathways for captured carbon dioxide.	21

List of Tables

Table 1. Comparison of Major Hydrogen Production Pathways	13
Table 2. Quantitative Emissions Comparison.....	14
Table 3. Approximate Cost Comparison of Hydrogen Production Pathways	17
Table 4. Environmental and Economic Benefits of Industrial Gas Recycling	21
Table 5. Economic and Environmental Impacts of Clean Industrial Gas Technologies	25

Acknowledgements

The author would like to thank the Department of Chemical Engineering at Kansas State University for their academic support and guidance throughout the completion of this report.

Introduction

Air pollution represents a major global environmental and public health challenge. According to the World Health Organization (WHO), millions of premature deaths occur annually as a result of air pollution exposure, primarily from respiratory and cardiovascular diseases (World Health Organization, 2022). Industrial emissions are among the primary contributors to atmospheric pollution, releasing substances such as carbon monoxide (CO), nitrogen oxides (NO_x), sulfur dioxide (SO₂), and particulate matter into the environment.

Despite its contribution to emissions, the industrial sector also possesses significant potential to reduce environmental impacts through technological innovation. One sector with increasing relevance in environmental mitigation is the industrial gas industry. Industrial gases, including oxygen (O₂), nitrogen (N₂), hydrogen (H₂), argon (Ar), and carbon dioxide (CO₂), play a critical role in numerous industrial processes ranging from chemical production to metal fabrication and healthcare applications.

Advances in gas production, purification, and recycling technologies have enabled the industrial gas industry to reduce emissions while improving operational efficiency. Furthermore, the increasing integration of renewable energy sources into industrial gas production has accelerated the transition toward low-carbon technologies. Hydrogen production through renewable-powered electrolysis, gas recycling technologies, and carbon capture systems represent key strategies for reducing industrial emissions (International Energy Agency, 2023).

This report examines how technological innovation within the industrial gas industry contributes to mitigating air pollution and supporting sustainable industrial development.

From a chemical engineering perspective, evaluating these technologies requires the application of mass and energy balances, reaction kinetics, and thermodynamic analysis to

quantify emissions and process efficiency. This report focuses on hydrogen production as a primary case study to evaluate how industrial gas technologies can reduce air pollution through chemical engineering principles and process optimization.

Background

The industrial gas industry encompasses the production, distribution, and application of gases used across a wide range of industries including manufacturing, electronics, healthcare, food processing, and energy systems. Major industrial gas companies such as Air Liquide, Linde plc, and Air Products supply these gases globally through advanced production and distribution networks (Linde plc, 2022).

Historically, the production of industrial gases has relied heavily on energy-intensive processes such as cryogenic air separation and steam methane reforming (International Energy Agency, 2023). These processes can contribute to greenhouse gas emissions and energy consumption if not optimized for efficiency. As a result, researchers and industry leaders have increasingly focused on developing cleaner production technologies and improving operational efficiency.

Recent literature highlights several technological advancements aimed at reducing emissions associated with industrial gas production. These innovations include improved gas separation technologies, renewable energy integration, carbon capture systems, and hydrogen production through electrolysis powered by renewable electricity. Studies have demonstrated that hydrogen produced using renewable electricity can significantly reduce lifecycle greenhouse gas emissions compared to conventional hydrogen production methods (International Renewable Energy Agency, 2022).

In addition to technological advancements, regulatory frameworks and environmental policies have encouraged industries to adopt cleaner technologies. Regulations such as emission limits and environmental reporting requirements have motivated companies to implement sustainable practices and invest in low-carbon technologies (U.S. Environmental Protection Agency, 2023). The major technological pathways through which the industrial gas industry contributes to emissions reduction are illustrated in *Figure 1*.

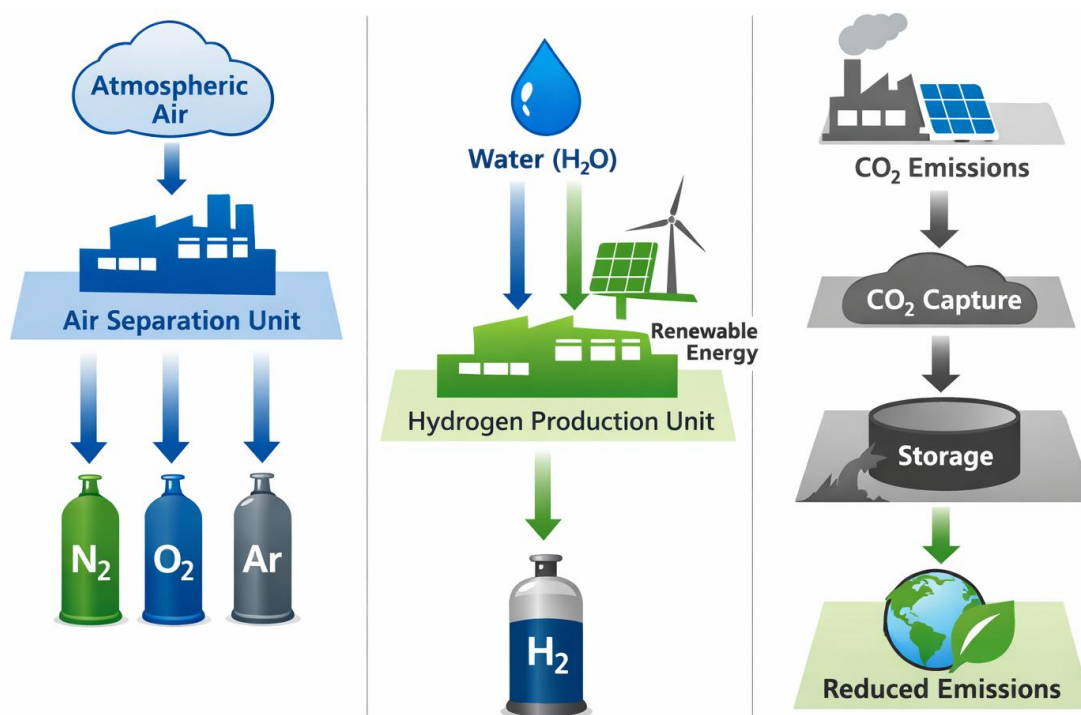


Figure 1. Simplified industrial gas system showing separate air separation and hydrogen production units, including renewable-powered hydrogen production and carbon dioxide capture and storage processes.

In addition to traditional industrial gases such as oxygen, nitrogen, and argon, both hydrogen and carbon dioxide are increasingly recognized as critical gases in modern industrial systems. Hydrogen plays a central role as both an energy carrier and a chemical feedstock, particularly in the transition toward low-carbon energy systems. At the same time, carbon dioxide, traditionally viewed as a waste product, is increasingly being captured, utilized, and

managed as part of emissions reduction strategies. Carbon dioxide is now used in applications such as chemical production, food processing, and enhanced oil recovery, while also serving as a key focus in carbon capture and storage technologies. The evolving roles of hydrogen and carbon dioxide reflect a broader shift within the industrial gas industry toward sustainability, resource efficiency, and emissions management.

Technological Innovations in Industrial Gas Production

Technological innovation has become a central strategy for reducing environmental impacts in the industrial gas sector. Advances in gas separation technologies, digital monitoring systems, and process optimization have improved efficiency while reducing emissions.

Cryogenic air separation remains one of the most widely used methods for producing industrial gases such as oxygen, nitrogen, and argon. In this process, atmospheric air is compressed, cooled, and liquefied before being separated into its primary components through cryogenic distillation. Modern facilities have implemented advanced heat integration systems, improved compressors, and energy recovery systems to reduce power consumption. A simplified overview of the cryogenic air separation process used to produce these gases is illustrated in

Figure 2.

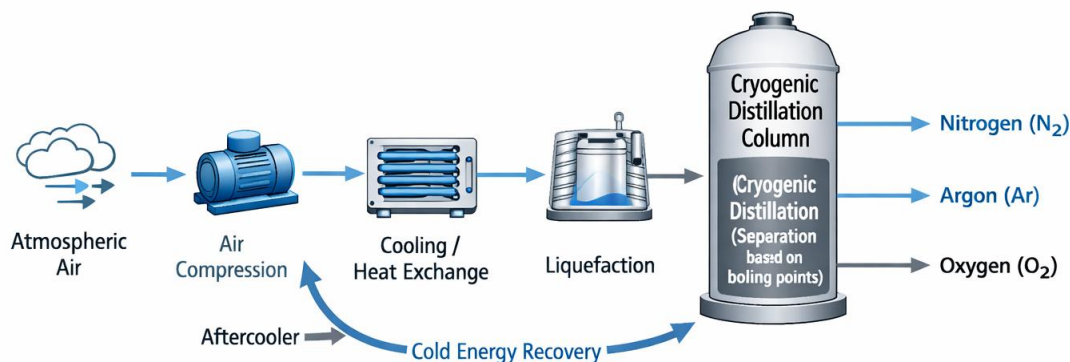


Figure 2. Simplified cryogenic air separation process including compression, liquefaction, and cryogenic distillation for the production of industrial gases.

Digital monitoring technologies also enable operators to optimize plant performance and detect inefficiencies in real time. Artificial intelligence and machine learning are increasingly used to improve industrial gas production efficiency. Predictive maintenance systems can identify potential equipment failures before they occur, minimizing downtime and reducing energy waste. Leak detection systems using advanced sensors and data analytics also help reduce fugitive emissions.

Another important innovation involves the use of renewable energy to power industrial gas production facilities. Wind and solar energy can supply electricity for air separation units and hydrogen electrolysis systems, reducing reliance on fossil fuels and contributing to more sustainable industrial gas production (International Energy Agency, 2023).

From an engineering standpoint, these technological improvements are driven by process optimization principles, including heat integration, mass transfer efficiency, and system-level energy minimization. These principles enable industrial gas systems to reduce energy consumption and associated emissions while maintaining high production efficiency.

Gas Separation Technologies in Industrial Gas Production

The separation of atmospheric air into its primary components, including nitrogen, oxygen, and argon, is a fundamental operation within the industrial gas industry. This process is typically achieved through cryogenic air separation, in which air is compressed, cooled, and liquefied before undergoing fractional distillation based on differences in boiling points.

In addition to cryogenic processes, adsorption-based separation technologies such as pressure swing adsorption (PSA) and temperature swing adsorption (TSA) are widely used for

gas purification and hydrogen recovery. These systems operate based on differences in adsorption affinity of gas species on solid adsorbents.

In PSA systems, gas mixtures are introduced at high pressure, where specific components such as carbon dioxide, carbon monoxide, or nitrogen preferentially adsorb onto the surface of materials such as activated carbon or zeolites. The desired gas, such as hydrogen, passes through as the product stream. The adsorbed species are then released by reducing the pressure, allowing regeneration of the adsorbent material.

TSA systems operate on a similar principle but utilize temperature changes rather than pressure changes to achieve desorption. Heating the adsorbent releases the captured gases, enabling cyclic operation of the system.

From a chemical engineering perspective, these processes are governed by adsorption equilibrium, mass transfer rates, and cyclic operation efficiency. The performance of PSA and TSA systems is influenced by factors such as pressure, temperature, flow rate, and adsorbent material properties.

Industrial gas companies such as Air Products, Linde plc, and Air Liquide utilize these technologies extensively in large-scale operations. PSA systems are commonly used for hydrogen purification in refineries and chemical plants, while cryogenic air separation units are used to produce high-purity oxygen, nitrogen, and argon for industrial applications.

The integration of these separation technologies enables efficient gas production, reduces waste, and supports emissions reduction strategies by improving process efficiency and enabling gas recycling.

Hydrogen Production and Renewable Energy Integration

Hydrogen plays an increasingly important role in global decarbonization strategies because it can serve as both an energy carrier and an industrial feedstock. However, the environmental benefits of hydrogen depend largely on how it is produced. According to the International Energy Agency (IEA), global hydrogen demand reached approximately 97 million tonnes (Mt) in 2023, with most hydrogen currently used in refining and chemical production. Despite growing interest in low-emissions hydrogen, less than 1% of global hydrogen production currently comes from low-carbon sources (International Energy Agency, 2023).

Green hydrogen is increasingly recognized as an emerging industrial gas with significant strategic importance in modern energy and industrial systems. While traditional industrial gases such as oxygen, nitrogen, and argon have long-established roles in manufacturing and chemical processing, hydrogen is rapidly gaining importance due to its potential to support decarbonization efforts. In particular, green hydrogen is being adopted as both a clean energy carrier and a chemical feedstock in industries such as ammonia production, petroleum refining, and steel manufacturing. Although green hydrogen currently represents a small fraction of total hydrogen production, its role is expected to expand significantly as industries transition toward lower-emission technologies and sustainable energy systems.

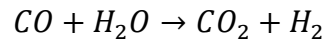
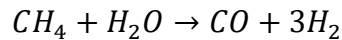
From an emissions perspective, hydrogen production represents a significant opportunity for industrial decarbonization. The IEA estimates that global hydrogen production resulted in approximately 920 Mt of CO₂ emissions in 2023, largely due to the continued reliance on fossil-based production pathways (International Energy Agency, 2023). As a result, reducing emissions associated with hydrogen production is considered a high-impact strategy for mitigating industrial greenhouse gas emissions.

Hydrogen is typically prioritized for sectors that are difficult to decarbonize through direct electrification. These sectors include heavy industry, steel manufacturing, long-distance transportation, and chemical production. Because hydrogen can store and transport energy in molecular form, it provides an alternative pathway for reducing emissions in applications where electricity alone may not be sufficient.

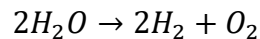
Chemical Engineering Principles in Hydrogen Production

Hydrogen production processes can be analyzed using fundamental chemical engineering principles, including reaction stoichiometry, thermodynamics, reaction kinetics, and transport phenomena. These principles provide a quantitative framework for understanding both process efficiency and associated emissions.

Steam methane reforming (SMR) and the water-gas shift reaction can be represented by the following chemical equations:



For green hydrogen production via electrolysis, the overall reaction is:



From a mass balance perspective, the relationship between reactants and products directly determines emissions. At steady-state, the system can be described by the general balance:

$$Input = Output$$

For SMR, the carbon entering the system as methane is conserved and ultimately exits as carbon dioxide, making emissions proportional to feed composition. This direct relationship allows emissions to be quantified on a per-unit production basis.

Reaction kinetics further influence hydrogen production efficiency. The rate of SMR reactions increases with temperature and is strongly dependent on catalyst activity, typically involving nickel-based catalysts. Higher reaction rates improve methane conversion but require greater energy input, creating a trade-off between efficiency and emissions. Inadequate reaction conditions or catalyst deactivation can result in incomplete conversion, leading to increased emissions and reduced hydrogen yield.

These reactions highlight the fundamental difference between hydrogen production pathways. In SMR, carbon-containing feedstocks inherently generate carbon dioxide as a byproduct, whereas electrolysis eliminates carbon from the reaction pathway entirely.

In conventional hydrogen production, steam methane reforming (SMR) is the dominant process. The primary reaction involves methane reacting with steam to form carbon monoxide and hydrogen, followed by the water-gas shift reaction, which converts carbon monoxide into carbon dioxide and additional hydrogen. From a stoichiometric perspective, the carbon contained in methane is ultimately converted into carbon dioxide, making emissions an inherent outcome of the reaction pathway.

From a thermodynamic standpoint, SMR is a highly endothermic process, requiring significant heat input at temperatures typically ranging from 700 to 1000°C. According to Le Chatelier's principle, higher temperatures favor hydrogen production, while lower pressures promote the formation of products due to an increase in the number of moles. However, the high energy demand of the process contributes to indirect emissions through fuel combustion required to sustain operating conditions.

Reaction kinetics also play a critical role in hydrogen production efficiency. SMR reactions are typically catalyzed using nickel-based catalysts, and reaction rates increase with

temperature. Catalyst performance, including surface area and resistance to deactivation, directly influences conversion efficiency. Catalyst fouling or deactivation can lead to incomplete methane conversion, resulting in increased emissions and reduced hydrogen yield.

Transport phenomena, including heat transfer, mass transfer, and fluid flow, further influence reactor performance. Efficient heat transfer is necessary to maintain reaction temperatures, while mass transfer governs the diffusion of reactants to catalyst surfaces. Limitations in these processes can reduce reaction efficiency and increase the formation of unwanted byproducts.

In contrast, green hydrogen production through water electrolysis follows a different reaction pathway, where water is split into hydrogen and oxygen using electrical energy. Because this process does not involve carbon-containing reactants, direct carbon dioxide emissions are eliminated. However, the overall environmental impact depends on the energy source used to power the electrolysis system.

Mass and energy balances are essential tools for quantifying emissions across hydrogen production pathways. By applying steady-state mass balance principles, the relationship between feed composition and emission output can be determined, enabling comparison of gray, blue, and green hydrogen systems on a consistent basis.

Conventional Hydrogen Production

The dominant conventional method for hydrogen production is steam methane reforming (SMR) (International Energy Agency, 2023). In this process, methane from natural gas reacts with steam at high temperature to produce synthesis gas (syngas), which contains hydrogen and carbon monoxide. The carbon monoxide then undergoes the water-gas shift reaction, producing

additional hydrogen and carbon dioxide. Although SMR is widely used due to its technical maturity and relatively low cost, it is associated with significant carbon emissions. The conventional hydrogen production pathway using steam methane reforming is illustrated in *Figure 3*.

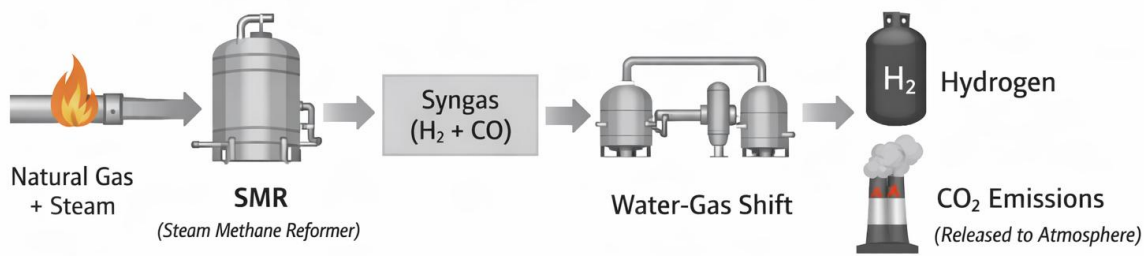


Figure 3. Grey hydrogen production via steam methane reforming with direct carbon dioxide emissions.

From a stoichiometric perspective, each mole of methane converted in steam methane reforming ultimately produces carbon dioxide through the water-gas shift reaction. This direct relationship between feed composition and emissions highlights the importance of mass balance analysis in quantifying environmental impact.

Hydrogen produced through conventional natural gas pathways typically emits approximately 10–12 kg CO₂-equivalent per kilogram of hydrogen, while hydrogen produced from coal gasification can emit 22–26 kg CO₂-equivalent per kilogram of hydrogen (International Energy Agency, 2023). Because the majority of these emissions occur during the production stage, hydrogen production facilities represent key targets for emission reduction technologies.

Blue Hydrogen and Carbon Capture Integration

One approach for reducing emissions from fossil-based hydrogen production is the use of carbon capture, utilization, and storage (CCUS). Hydrogen produced from fossil fuels with

carbon capture is commonly referred to as blue hydrogen. In blue hydrogen systems, carbon dioxide generated during SMR or autothermal reforming is captured before it is released into the atmosphere. The integration of carbon capture technologies in hydrogen production is illustrated in *Figure 4*.

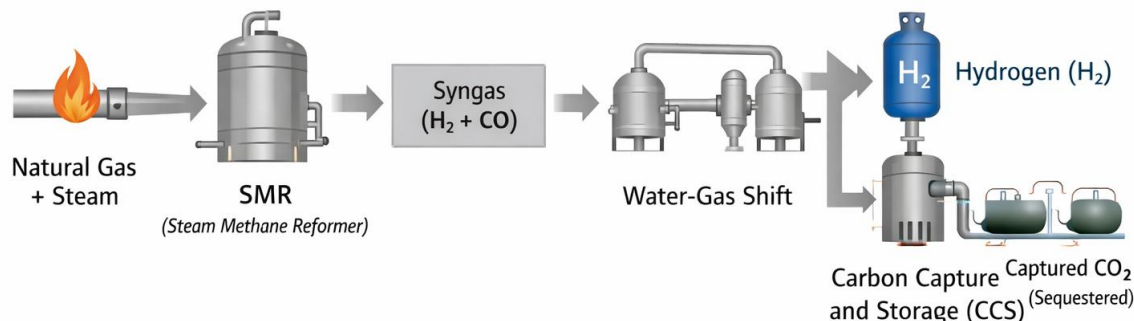


Figure 4. Blue hydrogen production using steam methane reforming with carbon capture and storage to reduce carbon dioxide emissions.

Typical carbon capture systems can achieve efficiencies between 70–90%, resulting in significant reductions in carbon dioxide emissions. When applied to conventional hydrogen production, this corresponds to an estimated reduction of approximately 60–80% in CO₂ emissions compared to gray hydrogen, depending on system design and operating conditions.

The effectiveness of blue hydrogen as a decarbonization strategy depends on several factors, including capture efficiency, energy requirements for compression and transport, and upstream methane leakage in natural gas supply chains. Studies have shown that life-cycle emissions from blue hydrogen can vary significantly depending on natural gas sourcing and methane leakage rates, highlighting the importance of supply-chain emissions management.

Green Hydrogen via Electrolysis

An alternative low-carbon pathway is green hydrogen, which is produced through water electrolysis powered by renewable electricity. Electrolysis splits water into hydrogen and oxygen

without generating direct carbon emissions during the production process. Recent advancements in electrolysis technology have focused on improving both membrane materials and electrocatalysts to enhance efficiency, durability, and overall system performance. For example, proton exchange membrane (PEM) systems utilizing composite materials have demonstrated improved proton conductivity and stability, contributing to more efficient and scalable electrolysis processes (Turan et al., 2026). In addition, transition metal-based electrocatalysts, such as cobalt phosphide systems, have shown enhanced hydrogen evolution and oxygen evolution reaction performance, supporting more efficient and economically viable hydrogen production (Huang, et al., 2026). As a result, the overall environmental impact of green hydrogen depends primarily on the carbon intensity of the electricity used. Several studies have also evaluated the environmental impacts and supply chain considerations associated with renewable hydrogen production and industrial deployment (Sola et al., 2024) (Röper et al., 2024). A comparison of the major hydrogen production pathways, including their primary production methods and associated emissions, is summarized in *Table 1*. The green hydrogen production process using renewable-powered electrolysis is illustrated in *Figure 5*.

Table 1. Comparison of Major Hydrogen Production Pathways

<i>Hydrogen Type</i>	<i>Primary Production Method</i>	<i>Energy Source</i>	<i>Typical CO₂ Emissions</i>	<i>Key Characteristics</i>
<i>Grey Hydrogen</i>	Steam Methane Reforming (SMR)	Natural Gas	~10–12 kg CO ₂ /kg H ₂	Most common production method; high emissions
<i>Blue Hydrogen</i>	SMR or ATR with Carbon Capture	Natural Gas + CCUS	Lower than grey hydrogen depending on capture rate	Reduces emissions using carbon capture technologies
<i>Green Hydrogen</i>	Water Electrolysis	Renewable Electricity (Solar/Wind)	Near-zero direct emissions	Sustainable long-term hydrogen production pathway

While Table 1 provides a general comparison of hydrogen production pathways, a more detailed quantitative assessment of emissions is necessary to evaluate their impact on air pollution.

Quantitative Emissions Comparison of Hydrogen Production Pathways

A quantitative comparison of emissions associated with gray, blue, and green hydrogen production pathways is presented to evaluate their relative impact on air pollution.

Table 2. Quantitative Emissions Comparison

<i>Hydrogen Type</i>	<i>CO₂ (kg/kg H₂)</i>	<i>Reduction vs Gray</i>
<i>Gray</i>	10–12	—
<i>Blue</i>	2–4	60–80% ↓
<i>Green</i>	~0–1	90–100% ↓

These values are based on reaction stoichiometry, carbon capture efficiency, and process energy requirements. From a chemical engineering perspective, these emission values can be justified using mass balance and reaction stoichiometry. At steady-state, the system follows:

$$\text{Input} = \text{Output}$$

For example, if gray hydrogen production results in 10 kg of CO₂ per kilogram of hydrogen, an 80% carbon capture efficiency in a blue hydrogen system would reduce emissions to approximately 2 kg CO₂ per kilogram of hydrogen produced. This simple calculation illustrates how carbon capture efficiency directly determines the percentage reduction in emissions observed in blue hydrogen systems.

In steam methane reforming, the carbon entering the system as methane is conserved and ultimately converted into carbon dioxide through the reforming and water-gas shift reactions.

This relationship establishes a direct proportionality between hydrogen production and CO₂ emissions.

For blue hydrogen systems, the effective emissions can be approximated by incorporating carbon capture efficiency:

$$\text{CO}_2^{\text{emitted}} = \text{CO}_2^{\text{produced}} \times (1 - \eta_{\text{capture}})$$

where η_{capture} represents the carbon capture efficiency. This relationship explains the observed 60–80% reduction in emissions. For example, at a capture efficiency of 80%, only 20% of the produced CO₂ is released, corresponding directly to an 80% reduction in emissions. In contrast, green hydrogen production eliminates carbon from the reaction pathway entirely, resulting in near-zero direct CO₂ emissions. The reduction trends are consistent with the elimination or capture of carbon dioxide generated during hydrogen production reactions.

Because electrolysis does not involve carbon-containing reactants, direct carbon dioxide emissions are effectively eliminated. When powered by renewable energy sources, green hydrogen systems can achieve up to 90–100% reductions in CO₂ emissions relative to conventional hydrogen production. In addition, reductions in nitrogen oxides (NO_x) and particulate matter emissions can exceed 80–90% due to the absence of combustion processes.

In comparison, blue hydrogen systems achieve moderate reductions in air pollutants due to the continued use of high-temperature reforming processes. While carbon capture technologies significantly reduce CO₂ emissions, reductions in NO_x and particulate matter are typically more limited, generally ranging between 20–40% and 10–25%, respectively.

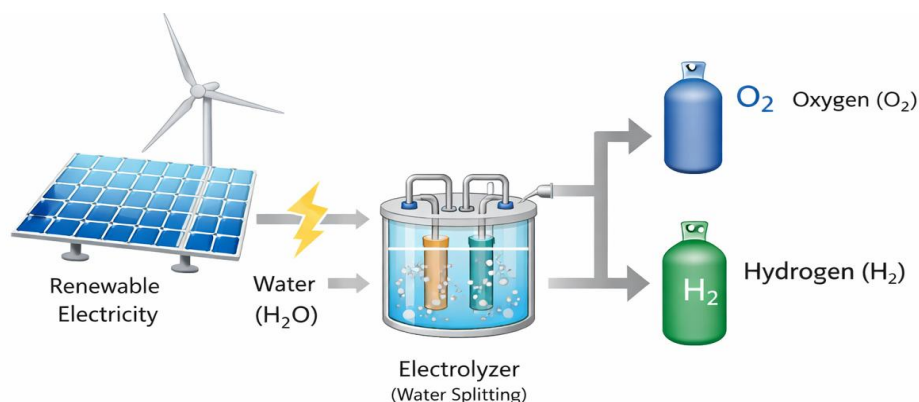


Figure 5. Green hydrogen production via water electrolysis powered by renewable electricity with no direct carbon dioxide emissions.

Recent studies have also explored the integration of hydrogen energy storage systems with renewable power grids to improve system stability and energy reliability. Hydrogen can be produced using excess renewable energy and stored for later use, helping to balance fluctuations in power generation and demand. This approach enables hydrogen to function not only as an industrial gas but also as a key energy storage medium within integrated energy systems (Umansky et al., in press). In addition, recent studies have demonstrated the feasibility of hydrogen supply chains using advanced storage technologies such as metal hydride systems, which enable efficient hydrogen transport and storage under controlled pressure and temperature conditions (Yamaguchi et al., 2026).

Electrolysis is an electricity-intensive process, with typical electricity requirements on the order of 50–55 kWh per kilogram of hydrogen, depending on electrolyzer technology and operating conditions (U.S. Department of Energy, 2023). In addition to electricity requirements, electrolysis systems require water resources, with approximately 9 kg of water required to produce 1 kg of hydrogen under ideal stoichiometric conditions. Because electricity consumption is the primary cost driver for electrolysis-based hydrogen production, the cost of hydrogen can vary significantly depending on the production pathway and energy source. Green hydrogen is

widely considered a key long-term solution for decarbonizing industrial and energy systems. The approximate production costs associated with the major hydrogen production pathways are summarized in *Table 3*. The major hydrogen production pathways, including grey, blue, and green hydrogen, are illustrated in *Figures 3–5*, highlighting differences in production methods and associated emissions. From a chemical engineering perspective, these emission reductions are directly explained by differences in reaction pathways and mass balance of carbon within each system. These results demonstrate that hydrogen production pathway selection is one of the most impactful levers for reducing industrial air pollution.

Table 3. Approximate Cost Comparison of Hydrogen Production Pathways

<i>Hydrogen Type</i>	<i>Production Method</i>	<i>Estimated Cost Range</i>	<i>Key Cost Drivers</i>
<i>Grey Hydrogen</i>	Steam Methane Reforming (SMR)	\$1 – \$2 per kg H ₂	Natural gas price, plant efficiency
<i>Blue Hydrogen</i>	SMR with Carbon Capture	\$1.5 – \$3 per kg H ₂	Carbon capture cost, natural gas supply
<i>Green Hydrogen</i>	Renewable Electrolysis	\$4 – \$6 per kg H ₂	Electricity price, electrolyzer cost

Water Quality Considerations for Electrolysis

Water quality is a critical factor in hydrogen production through electrolysis. Electrolyzers require high-purity water to operate efficiently and to prevent degradation of key components such as membranes, catalysts, and electrodes. Impurities including dissolved salts, minerals, organic compounds, and particulates can lead to scaling, fouling, corrosion, and reduced system performance. As a result, most industrial electrolysis systems rely on deionized or distilled water to ensure consistent operation and maintain hydrogen purity.

The use of untreated water sources, such as seawater, presents significant technical challenges. Seawater contains high concentrations of dissolved salts, particularly sodium chloride, which can promote corrosion and lead to undesirable side reactions during electrolysis,

including chlorine gas formation. These reactions can reduce hydrogen production efficiency and damage system components. Therefore, direct seawater electrolysis is not widely implemented at industrial scale. Instead, seawater is typically treated through desalination processes, such as reverse osmosis, before being used in electrolysis systems.

Water consumption is also an important consideration in large-scale hydrogen production. Approximately 9 kilograms of water are required to produce 1 kilogram of hydrogen under ideal stoichiometric conditions. In regions with limited freshwater availability, integrating desalination systems with renewable-powered electrolysis offers a potential pathway for sustainable hydrogen production. Ensuring proper water treatment and management is essential for the long-term viability and scalability of green hydrogen technologies (U.S. Department of Energy, 2023; International Energy Agency, 2023). Ongoing research is focused on developing direct seawater electrolysis technologies to reduce reliance on energy-intensive desalination processes.

Renewable Energy Integration

The integration of renewable electricity sources such as solar and wind energy is essential for reducing emissions associated with hydrogen production. Because electrolyzers can operate flexibly, they can also help balance renewable electricity systems by consuming excess electricity during periods of high renewable generation. This flexibility allows hydrogen production facilities to act as both energy storage systems and industrial production facilities.

Large-Scale Renewable Hydrogen Projects

Large-scale renewable hydrogen projects are being developed globally to support decarbonization efforts. One of the most prominent examples is the NEOM Green Hydrogen Project in Saudi Arabia, a large-scale renewable hydrogen facility that integrates approximately

4 GW of wind and solar power to produce hydrogen for conversion into ammonia for export (NEOM Green Hydrogen Company, 2023). The facility is expected to produce up to 600 tonnes of hydrogen per day once operational, making it one of the largest renewable hydrogen projects currently under development. Projects such as NEOM demonstrate the potential for renewable energy and industrial gas technologies to enable large-scale hydrogen production and support global decarbonization strategies.

Projects such as NEOM demonstrate the potential for renewable energy and industrial gas technologies to enable large-scale hydrogen production and accelerate global decarbonization strategies.

Gas Recycling and Argon Recovery

Industrial gas recycling has become an important strategy for reducing environmental impacts and improving resource efficiency. Gases such as argon and nitrogen are widely used in manufacturing processes including welding, semiconductor fabrication, and metal processing. Rather than releasing these gases into the atmosphere after use, companies increasingly implement recycling systems to capture and reuse them.

Argon recycling systems typically involve several stages including gas collection, purification, and compression. Waste argon generated during industrial processes is first captured through specialized gas recovery systems. The recovered gas stream may contain contaminants such as particulate matter, oxygen, nitrogen, and moisture depending on the industrial process in which the gas was used. The gas is therefore passed through filtration and drying systems to remove particulate contaminants and water vapor before further purification.

After preliminary treatment, the gas undergoes purification using separation technologies such as cryogenic distillation or pressure swing adsorption (PSA) to restore the required purity

level for industrial reuse. A simplified representation of the argon recycling process is illustrated in *Figure 6*.

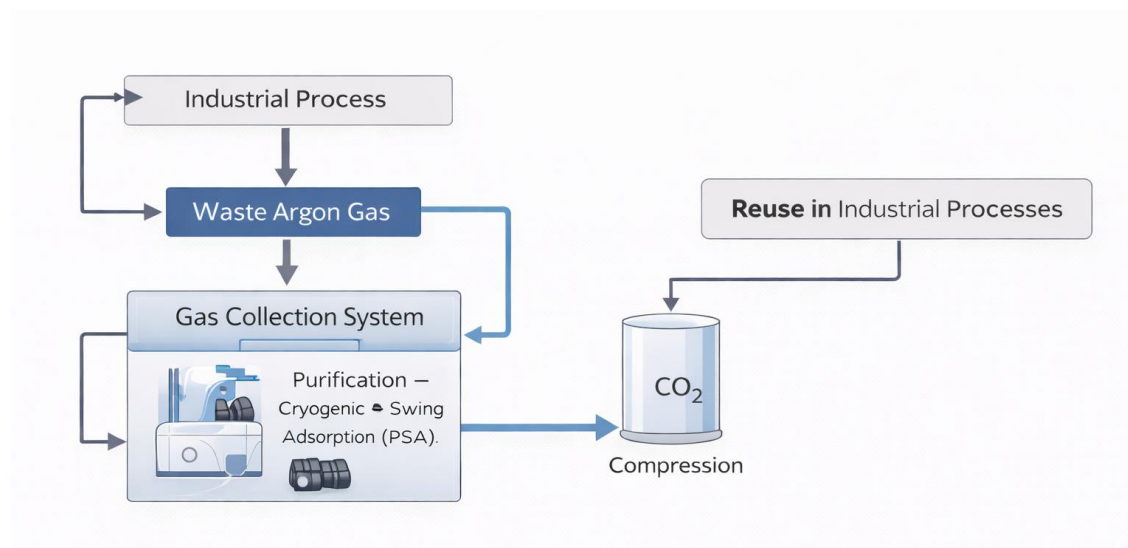


Figure 6. Industrial argon recycling system for gas recovery and reuse.

Following purification, the recycled argon is compressed and stored for reuse in industrial applications. This process significantly reduces the need for continuous production of argon through cryogenic air separation, which is highly energy intensive. By recycling argon, industrial facilities can reduce both energy consumption and greenhouse gas emissions associated with gas production (Linde plc, 2022) (Air Products, 2023) (Air Liquide, 2022). These companies operate large-scale air separation units, hydrogen production facilities, and specialty gas distribution networks that support critical industrial and energy applications worldwide.

Gas recycling systems also reduce operating costs by lowering raw material consumption and minimizing waste disposal requirements. As a result, recycling technologies provide both environmental and economic benefits. The environmental and economic advantages associated with industrial gas recycling systems are summarized in *Table 4*.

Table 4. Environmental and Economic Benefits of Industrial Gas Recycling

<i>Benefit Category</i>	<i>Impact</i>	<i>Example in Industrial Gas Systems</i>
<i>Energy Efficiency</i>	Reduces energy required for gas production	Less need for cryogenic air separation
<i>Resource Conservation</i>	Decreases consumption of raw atmospheric gases	Argon and nitrogen reused in welding and manufacturing
<i>Emissions Reduction</i>	Lowers greenhouse gas emissions from gas production	Reduced electricity demand in air separation units
<i>Cost Reduction</i>	Decreases operational costs	Lower gas purchasing and production costs

Carbon Capture and Utilization

Carbon capture and storage (CCS) technologies have emerged as another important strategy for reducing industrial emissions (International Energy Agency, 2023). CCS systems capture carbon dioxide produced during industrial processes before it is released into the atmosphere. The captured CO₂ can either be stored underground or utilized in various commercial applications. A simplified overview of the carbon capture and utilization process is illustrated in *Figure 7*.

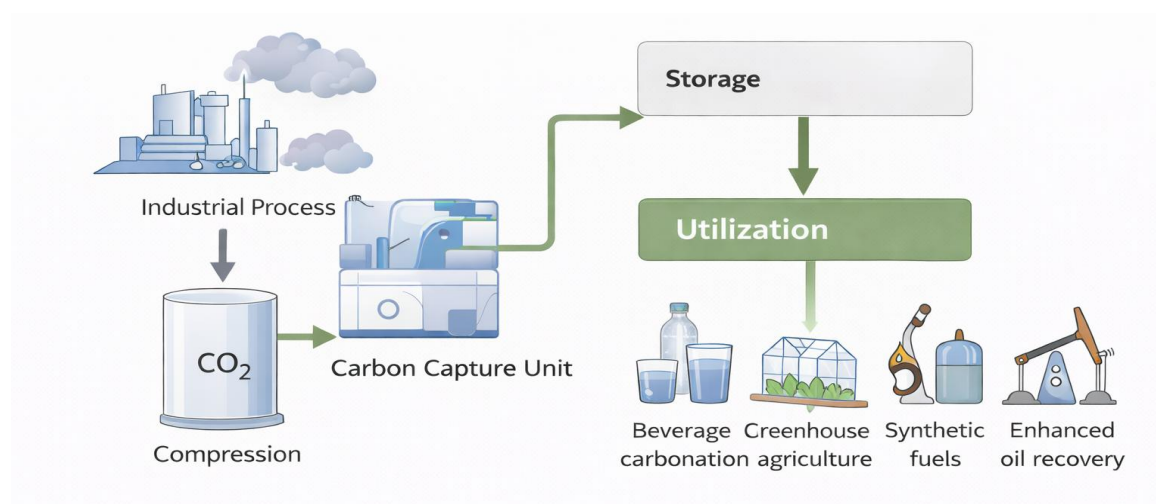


Figure 7. Overview of carbon capture and utilization pathways for captured carbon dioxide.

Captured carbon dioxide is commonly used in industries such as food processing, beverage carbonation, greenhouse agriculture, and enhanced oil recovery. The ability to sell captured CO₂ creates an economic incentive for industries to implement carbon capture technologies.

Advanced carbon capture systems can significantly reduce greenhouse gas emissions from industrial facilities, particularly those involved in hydrogen production and chemical manufacturing. Integrating CCS technologies into industrial gas production processes can therefore support both environmental sustainability and economic profitability.

From a chemical engineering perspective, carbon capture processes rely on separation principles such as absorption and adsorption. These processes are governed by equilibrium behavior, mass transfer rates, and regeneration energy requirements, all of which influence overall system efficiency and emissions reduction performance.

Simulated Case Study and Experimental Validation

In this report, hydrogen production is used as a focused case study to evaluate the impact of industrial gas technologies on air pollution. By analyzing gray, blue, and green hydrogen production pathways, this case study applies chemical engineering principles to quantify emissions and assess the effectiveness of different decarbonization strategies.

A simulated industrial case study can be developed to evaluate the environmental impact of different hydrogen production pathways under controlled operating conditions. In this approach, hydrogen production systems representing gray, blue, and green hydrogen are modeled at equivalent production rates to ensure a consistent basis for comparison.

For the gray hydrogen scenario, a steam methane reforming (SMR) system is modeled without emissions control. The blue hydrogen scenario incorporates carbon capture, utilization,

and storage (CCUS) technologies with an assumed capture efficiency of approximately 70–90%. The green hydrogen scenario is based on water electrolysis powered by renewable energy sources, resulting in minimal direct emissions.

Process simulation tools such as Aspen Plus or MATLAB can be used to model these systems by applying mass and energy balances, reaction stoichiometry, and process efficiency parameters. Key outputs from the simulation include carbon dioxide emissions (kg CO₂ per kg H₂), nitrogen oxides (NO_x), and particulate matter concentrations. All results are normalized per unit of hydrogen produced to ensure accurate comparison across systems.

Based on these models, gray hydrogen production typically results in emissions of approximately 10–12 kg CO₂ per kilogram of hydrogen produced. This is consistent with the reaction stoichiometry of steam methane reforming and the water-gas shift reaction, where carbon present in methane is ultimately converted into carbon dioxide. The integration of carbon capture technologies in blue hydrogen systems can reduce emissions by approximately 60–80%, depending on capture efficiency and system design. As previously discussed, this reduction is directly related to carbon capture efficiency, where a significant portion of produced CO₂ is removed prior to release. Green hydrogen systems, when powered by renewable energy, can achieve emission reductions of up to 90–100% due to the absence of carbon-based reactions. Because electrolysis does not involve carbon-containing feedstocks, direct CO₂ emissions are effectively eliminated.

In addition to simulation, future experimental validation can be conducted using pilot-scale systems designed to replicate industrial hydrogen production processes. Controlled experimental setups would allow for direct comparison of emissions across gray, blue, and green

hydrogen technologies. Gas analyzers and particulate monitoring equipment can be used to measure concentrations of CO₂, NO_x, and particulate matter in exhaust streams.

Experimental results would be used to validate simulation data and assess real-world system performance. By combining simulation with experimental validation, a more comprehensive understanding of the environmental benefits and limitations of hydrogen production technologies can be achieved. Sensitivity analysis can also be applied to evaluate how variations in carbon capture efficiency or energy source impact overall emissions performance.

To further evaluate the potential impact of hydrogen production pathways, a large-scale estimation can be made using U.S. hydrogen production data. The United States produces approximately 10 million metric tons of hydrogen annually, with approximately 95% currently produced through steam methane reforming (International Renewable Energy Agency, 2022).

Based on typical emissions of 10 kg CO₂ per kg of hydrogen, this corresponds to approximately 100 million metric tons of CO₂ emissions per year from hydrogen production alone.

If blue hydrogen technologies were implemented with an average carbon capture efficiency of 80%, emissions could be reduced to approximately 20 million metric tons of CO₂ annually, representing a reduction of roughly 80 million metric tons.

In contrast, a transition to green hydrogen powered by renewable energy could reduce emissions to near zero, resulting in a potential reduction of up to 100 million metric tons of CO₂ per year. This analysis demonstrates the significant impact that hydrogen production pathways can have on national-scale air pollution and greenhouse gas emissions.

Economic and Environmental Impacts

The adoption of cleaner technologies within the industrial gas industry offers significant environmental benefits while also creating economic opportunities. Improvements in energy efficiency reduce operating costs associated with gas production and distribution. Gas recycling technologies decrease raw material consumption and minimize waste generation.

Investment in renewable hydrogen infrastructure also has the potential to stimulate economic growth (International Renewable Energy Agency, 2022). The development of electrolysis plants, renewable energy facilities, and hydrogen transportation systems can generate employment opportunities across engineering, manufacturing, and construction sectors.

Additionally, the commercialization of captured carbon dioxide creates new revenue streams for industrial gas companies. By selling CO₂ for industrial applications, companies can offset the costs associated with carbon capture technologies. The broader environmental and economic impacts associated with these emerging industrial gas technologies are summarized in

Table 5.

Table 5. Economic and Environmental Impacts of Clean Industrial Gas Technologies

<i>Technology</i>	<i>Environmental Impact</i>	<i>Economic Benefit</i>
<i>Green Hydrogen Production</i>	Eliminates direct carbon emissions from hydrogen production	Expands renewable energy and hydrogen markets
<i>Carbon Capture and Storage</i>	Reduces CO ₂ emissions from industrial processes	Enables commercialization of captured CO ₂
<i>Gas Recycling Systems</i>	Reduces energy consumption and industrial waste	Lowers operational and production costs
<i>Renewable Energy Integration</i>	Decreases reliance on fossil fuels	Improves long-term energy cost stability

Environmental benefits include reduced greenhouse gas emissions, improved air quality, and decreased reliance on fossil fuels. These outcomes support global climate mitigation efforts while promoting sustainable industrial development. The environmental benefits observed in

hydrogen production technologies are directly supported by chemical engineering analysis, including reaction pathways, mass balance calculations, and system-level efficiency improvements.

Future Trends and Challenges

The industrial gas industry is expected to play an increasingly important role in global decarbonization strategies. Future trends include expanded hydrogen production, greater integration of renewable energy sources, and the continued development of carbon capture technologies (International Energy Agency, 2023).

However, several challenges remain. High capital costs associated with hydrogen production infrastructure and renewable energy systems can limit the rapid adoption of these technologies. Additionally, regulatory uncertainty and evolving environmental policies may influence investment decisions.

Continued collaboration between governments, industry stakeholders, and research institutions will be essential to overcome these challenges. Advances in technology, combined with supportive policy frameworks, can accelerate the transition toward cleaner industrial systems.

Future research should focus on large-scale industrial case studies and pilot plant demonstrations to validate simulated emission reductions. Additionally, sensitivity analysis of carbon capture efficiency and energy sources will be critical in determining the real-world effectiveness of hydrogen-based decarbonization strategies.

Conclusion

The industrial gas industry plays a vital role in mitigating air pollution through technological innovation and sustainable practices. Advances in hydrogen production, renewable energy integration, gas recycling systems, and carbon capture technologies have significantly improved the environmental performance of industrial gas operations.

Hydrogen production through renewable-powered electrolysis represents one of the most promising developments for reducing industrial emissions and supporting the transition toward low-carbon energy systems. Gas recycling technologies further contribute to sustainability by reducing resource consumption and minimizing waste. The integration of hydrogen with renewable energy systems highlights its growing role as both an industrial gas and an energy storage solution, particularly in enhancing grid stability and enabling more reliable integration of intermittent renewable energy sources in modern energy infrastructure (Umansky et al., in press).

In addition to environmental benefits, these technological innovations offer economic advantages by reducing operational costs and creating new revenue opportunities. As global demand for cleaner energy solutions continues to grow, the industrial gas industry is positioned to play a key role in supporting sustainable industrial development and reducing the environmental impact of industrial activities.

References

- Air Liquide. (2022). *Annual Report 2022*. Retrieved from <https://www.airliquide.com>
- Air Products. (2023). *Industrial Gas Applications*. Retrieved from <https://www.airproducts.com>
- Huang, Y., Zhong, H., Zhou, Q., Feng, W., Li, H., Zeng, J., . . . X. (2026). High-performance bifunctional Cr-doped cobalt phosphide for low-cost water electrolysis. *International Journal of Hydrogen Energy*. doi:<https://doi.org/10.1016/j.ijhydene.2026.154756>
- International Energy Agency. (2023). *Global Hydrogen Review 2023*. IEA. Paris: IEA. Retrieved from <https://www.iea.org/reports/global-hydrogen-review-2023>
- International Renewable Energy Agency. (2022). *Hydrogen: A Renewable Energy Perspective*. IRENA. Retrieved from <https://www.irena.org>
- Linde plc. (2022). *Sustainability Report 2022*. Retrieved from <https://www.linde.com>
- NEOM Green Hydrogen Company. (2023). *NEOM Green Hydrogen Project Overview*. Retrieved from ACWA : <https://acwapower.com/en/what-we-do/projects/neom-green-hydrogen-project/>
- Röper, K., Kunz, N., & Gast, L. (2024). Renewable hydrogen in industrial production: A bibliometric analysis. *International Journal of Hydrogen Energy*. doi:<https://doi.org/10.1016/j.ijhydene.2024.12.034>
- Sola, A., Rosa, R., & Ferrari, A. M. (2024). Green hydrogen and its supply chain: Environmental and economic impacts, challenges, and future perspectives. *Advanced Sustainable Systems*, 8(1), 2300218. doi:<https://doi.org/10.1002/adsu.202300218>
- Turan, R., Koca, A., & Aydin, Y. (2026). Recent advances in the development of SPEEK composite membrane strategies for PEM water electrolysis. *International Journal of Hydrogen Energy*, 229, 154653. doi:[10.1016/j.ijhydene.2026.154653](https://doi.org/10.1016/j.ijhydene.2026.154653)
- U.S. Department of Energy. (2023). *Hydrogen Shot Water Electrolysis Program Overview*. U.S. Department of Energy. Washington, D.C.: U.S. Department of Energy. Retrieved from <https://www.energy.gov>
- U.S. Environmental Protection Agency. (2023). *Air Pollution: Current and Future Challenges*. Retrieved from EPA: <https://www.epa.gov/air-pollution>
- Umansky, I. V., Ufa, R. A., Malkova, Y. Y., & Faiziev, T. A. (in press). Analysis of the effect of hydrogen energy storage system integration on power system stability. *International Journal of Hydrogen Energy*.

World Health Organization. (2022). *Ambient Air Pollution and Health*. Retrieved from <https://www.who.int>

Yamaguchi, S., Watanabe, H., Gotoda, R., Bonacina, C. N., & Kono, T. (2026). Year-long demonstration of green hydrogen supply chain with portable and fast-charging metal hydride tanks. *International Journal of Hydrogen Energy*.
doi:<https://doi.org/10.1016/j.ijhydene.2026.154623>

