Task D2.4 Report on Maximising Technologies with high impact in reduction of emissions from GHGs through non-combustion process

By

Raven SR Iberia

This document constitutes the formal submission of Deliverable D2.4 under the Hy2Market project.

HY2MARKET

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Executive Summary

This deliverable (D2.4) has been prepared in accordance with Task 2.1/2.2 objectives under the Hy2Market Grant Agreement, focusing on identifying and maximising non-combustion hydrogen technologies with high GHG reduction impact across participating regions.

This report presents a comprehensive analysis of advanced non-combustion technologies with significant potential to reduce greenhouse gas (GHG) emissions across various sectors, supporting the objectives of the Hy2Market programme. As climate change intensifies and global climate targets tighten, there is a growing imperative to transition from traditional combustion-based systems towards cleaner, more sustainable alternatives.

Non-combustion technologies, including green hydrogen production through water electrolysis and hydrogen production from waste and biomass through Raven's non-combustion Steam/CO_2 Reforming process, represent important pathways for decarbonising energy, industry, and transport systems. These solutions are expected to contribute to emissions reduction objectives while also presenting opportunities for enhanced air quality, energy security, and circular economy integration.

This report identifies and evaluates a broad spectrum of such technologies, highlighting their technical maturity, cost evolution, environmental performance, and policy relevance. It assesses these pathways not only in terms of hydrogen output, but also through their wider implications for lifecycle GHG reduction, waste management, resource efficiency, system integration, and regional scalability. Key areas of focus include:

- **Green hydrogen** produced via renewable-powered electrolysis, widely recognised as a central pathway in current decarbonisation strategies.
- **Waste-to-hydrogen** processes that offer combined potential for emission mitigation and sustainable waste management.
- **Emerging hydrogen types** (pink, turquoise) and related production pathways that broaden the non-combustion technology landscape.
- **Carbon capture, utilisation, and storage (CCUS)**, relevant for addressing emissions in hard-to-abate sectors.
- **Biological and electrochemical innovations** contributing to decentralised, low-carbon energy production.

The study incorporates a comparative policy analysis of the European Union and the United States, with particular emphasis on Spain as a frontrunner in green hydrogen development. While both regions prioritise electrolysis, current policy frameworks in the EU also recognise a broader set of technologies, including pyrolysis, gasification, and circular economy-linked approaches, subject to regulatory and sustainability criteria. The report therefore examines not only where policy support is concentrated, but also where regulatory definitions, sustainability requirements, and market frameworks may shape the practical deployment of alternative non-combustion hydrogen pathways.

A detailed case study of Raven SR's modular non-combustion hydrogen facility under development in Richmond, California, illustrates the socio-economic and environmental value of decentralised, waste-based hydrogen solutions. The Richmond project is presented as a planned commercial-scale deployment currently progressing through permitting and development stages, demonstrating how

such technologies may contribute to climate benefits, public health improvements, and local economic growth if regulatory frameworks evolve to support deployment at scale.

Ultimately, the report delivers actionable insights and recommendations for policymakers, investors, and industry leaders. It underscores the importance of accelerating infrastructure development, aligning incentives with environmental outcomes, and supporting a diversified mix of clean hydrogen technologies to meet mid-century climate goals. It also highlights the importance of maintaining a technology-aware and evidence-based approach to hydrogen deployment, particularly where non-combustion pathways can deliver multiple environmental and system-level benefits beyond the production of hydrogen alone.

In this context, D2.4 is intended not simply as a descriptive review, but as a substantive contribution to Hy2Market's broader objective of identifying scalable hydrogen solutions capable of reducing emissions, strengthening regional value chains, and informing future deployment across participating European regions.

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ABBREVIATIONS & GLOSSARY

ATR	Autothermal Reforming
BCF	Biomass Conversion Facility (California, US)
CAGR	Compound Annual Growth Rate
CCfDs	Carbon Contracts for Difference
CCS	Carbon Capture and Storage
CCUS	Carbon Capture, Utilisation, and Storage
CEM H2I	Clean Energy Ministerial Hydrogen Initiative
CEQA	California Environmental Quality Act
CH_4	Methane
CO_2	Carbon Dioxide
CSP	Concentrated Solar Power
DOE	Department of Energy
eGRID	Emissions & Generation Resource Integrated Database
EISMEA	European Innovation Council and SMEs Executive Agency
FT	Fischer-Tropsch
GHGs	Greenhouse Gases
GoOs	Guarantees of Origin
H^+	Protons
HRA	Health Risk Assessment
HTSE	High-Temperature Steam Electrolysis
IPCC	Intergovernmental Panel on Climate Change
IPCEI	Important Projects of Common European Interest
IPHE	International Partnership for Hydrogen and Fuel Cells in the Economy
IRA	Inflation Reduction Act
LCA	Life Cycle Assessment
LCFS	Low Carbon Fuel Standard (California, US)

LHV	Lower Heating Value
LOHCs	Liquid Organic Hydrogen Carriers
MWh	Megawatt-hour
N_2O	Nitrous Oxide
NCTC	Non-Combustion Thermal Conversion
NO_x	Nitrogen Oxides
PEM	Proton Exchange Membrane
POX	Partial Oxidation
PRC	Public Resources Code (US)
PSA	Pressure Swing Adsorption
PV	Solar Photovoltaics
RDII	Recast Renewable Energy Directive
RED	Renewable Energy Directive (EU)
RPS	Renewable Portfolio Standards
RWGS	Reverse Water-Gas Shift
SAF	Sustainable Aviation Fuel
SLCP	Short-Lived Climate Pollutant
SMR	Steam Methane Reforming
SMRs	Small Modular Reactors
SR	Steam Reforming
SOEC	Solid Oxide Electrolyser Cell
TRL	Technology Readiness Level
WGS	Water-Gas Shift
YSZ	Yttria-Stabilised Zirconia

1. Introduction

Climate change is one of the most pressing challenges facing humanity today. The continuous rise in atmospheric concentrations of greenhouse gases (GHGs), particularly carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) is driving global temperature increases, leading to more frequent and intense extreme weather events, accelerating biodiversity loss, and disrupting ecosystem balance. These environmental consequences pose serious threats to food security, water resources, human health, and economic resilience.

In response, governments, industries, and international organisations have committed to urgent climate action, guided by the Paris Agreement, which aims to limit global warming to well below 2°C, and ideally to 1.5°C, above pre-industrial levels. Achieving these targets requires a rapid and fundamental transformation of energy systems, shifting from fossil fuel-based combustion towards non-combustion, low-carbon technologies.

Among the most promising solutions for decarbonisation is the deployment of green hydrogen produced through electrolysis of water using renewable electricity as a clean and versatile energy vector. Unlike traditional hydrogen production methods such as steam methane reforming, electrolysis powered by wind, solar, or hydroelectric energy results in a zero-emission fuel that can be utilised across sectors including transport, industry, heating, and power generation. It also serves as an effective medium for energy storage and grid balancing, especially in systems with high shares of variable renewable energy.

In parallel, waste-to-hydrogen technologies are gaining strategic importance. These processes convert municipal solid waste, industrial residues, or biomass into hydrogen through a range of thermochemical and reforming pathways, including distinct non-combustion approaches such as Raven SR's Steam/CO_2 Reforming process. Waste-to-hydrogen[1] not only contributes to GHG reduction by displacing fossil fuels but also addresses another environmental issue, namely waste management, by diverting waste from landfills and reducing methane emissions associated with organic decomposition. When combined with carbon capture and storage (CCS) or when sourced from biogenic feedstocks, waste-to-hydrogen pathways can even deliver carbon-negative outcomes.

Both electrolytic and thermochemical hydrogen production methods represent vital components of a broader non-combustion strategy aimed at decarbonising high-emission sectors, enhancing circular economy principles, and supporting the transition to climate-neutral societies.

This report assesses the technological, economic, and policy landscapes of non-combustion solutions, with a particular focus on hydrogen-based systems, in the context of the HY2MARKET programme. It pays particular attention to the comparative role of electrolysis and waste-based non-combustion pathways, including Raven SR's Steam/CO_2 Reforming process, in achieving emissions reduction, resource efficiency, and regional scalability across participating Hy2Market regions.

[1] **Hydrogen Europe** (2023). *Waste-to-Hydrogen: A Circular Solution for Sustainable Energy*. Brussels. Available at: https://hydrogeneurope.eu

2. Global Climate Targets and Greenhouse Gas Emissions

2.1. Overview of Greenhouse Gas (GHG) Emissions and Their Impact

Greenhouse gases, particularly carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), are primary drivers of global warming due to their heat-trapping properties. In 2023, CO_2 accounted for approximately 76% of total global emissions, followed by methane at 16%, and nitrous oxide at 6% (IPCC AR6).

Atmospheric CO_2 levels now exceed 423 ppm, the highest in at least two million years. Without immediate mitigation, average global temperatures could rise by 2.6°C to 3.1°C by the end of the century, triggering irreversible environmental tipping points such as polar ice sheet collapse, ecosystem degradation, and ocean acidification.

2.1.1. Impact on Climate Change[2]

The accumulation of GHGs in the atmosphere enhances the greenhouse effect, leading to global warming and climate change. Consequences include rising global temperatures, melting glaciers and ice caps, sea-level rise, and an increase in the frequency and severity of extreme weather events such as hurricanes, droughts, and heatwaves. These changes disrupt ecosystems, threaten biodiversity, and pose significant risks to human health, agriculture, and water supplies. These impacts also carry significant economic and social consequences, including growing risks to infrastructure, food systems, water security, and public health.

2.1.2. Current Trends and Data

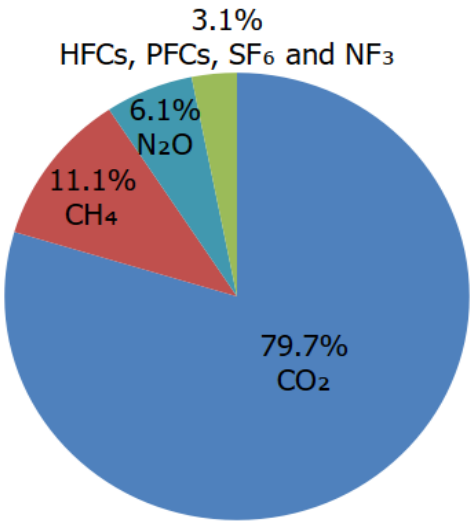
Recent data indicates that global GHG emissions increased to approximately 57.1 billion metric tons of CO_2 equivalent in 2023[3]. Atmospheric CO_2 concentrations have risen to 150% of pre-industrial levels. The primary sources of these emissions include fossil fuel combustion, deforestation, and industrial activities.

Greenhouse Gas Emissions Overview, by Type of Gas in 2022[4]

[2] NASA. (n.d.). *Climate Change: Vital Signs of the Planet*. Retrieved from https://science.nasa.gov/climate-change/

[3] World Meteorological Organization, 'Carbon dioxide levels increase by record amount to new highs in 2024', 15 October 2025. Retrieved from https://wmo.int/news/media-centre/carbon-dioxide-levels-increase-record-amount-new-highs-2024

[4] United States Environmental Protection Agency. (n.d.). *Overview of Greenhouse Gases*. Retrieved from https://www.epa.gov/ghgemissions/overview-greenhouse-gases.



GHGs are emitted from multiple sectors:

- Power Generation: Approximately 15.1 gigatonnes of CO_2e annually, with coal-fired plants being the largest contributors.
- Industry: Responsible for roughly 11% of total global GHG emissions in 2023, excluding industrial process emissions counted separately.
- Transport: Around 15% of total global GHG emissions in 2023.
- Deforestation and Land Use Change: A significant additional contributor.

Recent data from the IEA and Global Carbon Project (2024) indicate total global GHG emissions reached 57.1 billion metric tonnes CO_2 equivalent in 2023. The United States, China, and India remain top emitters, with China responsible for nearly 30% of global emissions. Although the U.S. has reduced its emissions by 17% since 2000, it remains the largest historical emitter[5]. In addition, global energy-related CO_2 emissions rose by 0.8% in 2024 to 37.8 Gt CO_2, underscoring the continued difficulty of bending the global emissions curve downward.[6]

2.1.3. Global and EU Emissions Context[7]

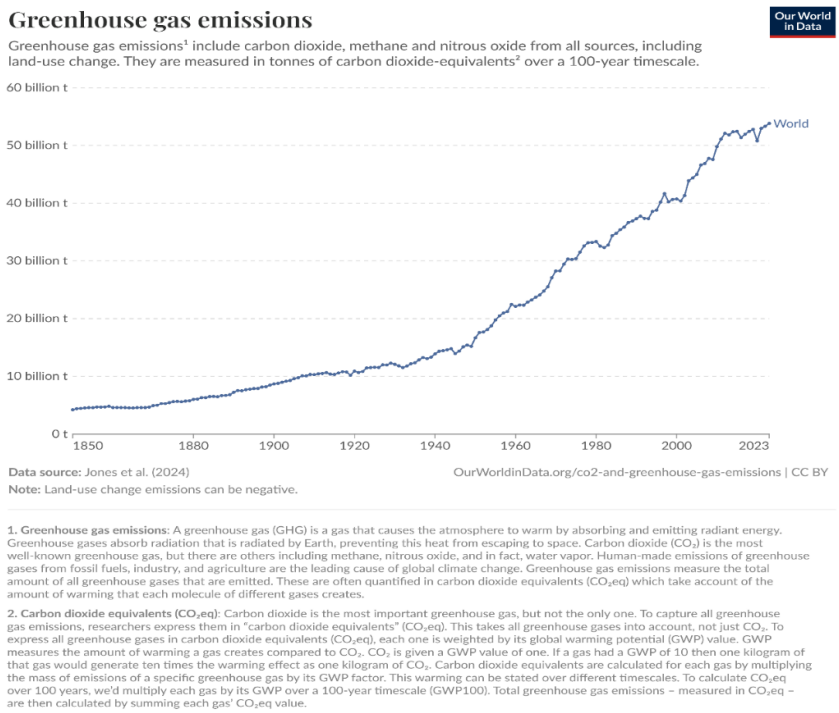
Evolution of Greenhouse gas emissions worldwide 1850-2023[8]:

[5] Statista. (n.d.). Global greenhouse gas emissions. Retrieved from https://www.statista.com/topics/5770/global-greenhouse-gas-emissions/

[6] International Energy Agency (IEA), Global Energy Review 2025: CO2 Emissions, IEA, Paris, 2025. Available at https://www.iea.org/reports/global-energy-review-2025/co2-emissions

[7] Ritchie, H., Rosado, P. and Roser, M. (2023). CO_2 and Greenhouse Gas Emissions. Our World in Data. Available at: https://ourworldindata.org/co2-and-greenhouse-gas-emissions

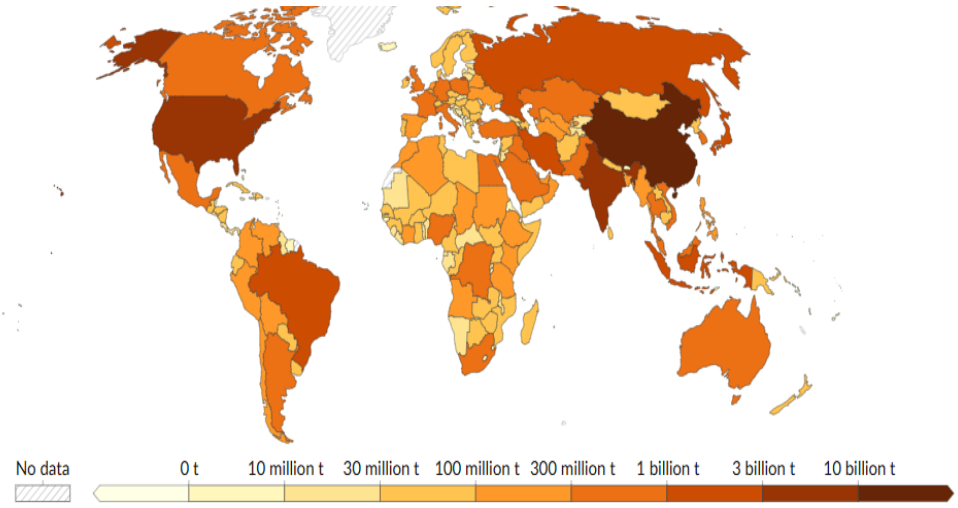
[8] Data source : Jones et al. (2024)



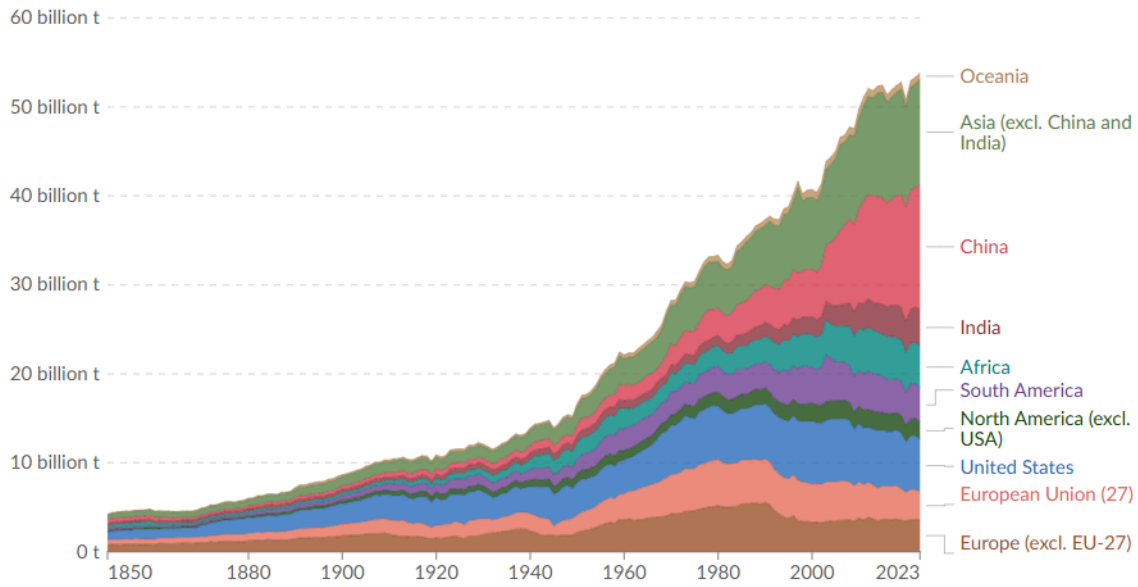
Source: Jones et al. (2024)

Greenhouse gas emissions by countries in 2023:

Greenhouse gas emissions include carbon dioxide, methane and nitrous oxide from all sources, including land use change. They are measured in tonnes of carbon dioxide equivalents over a 100-year timescale.

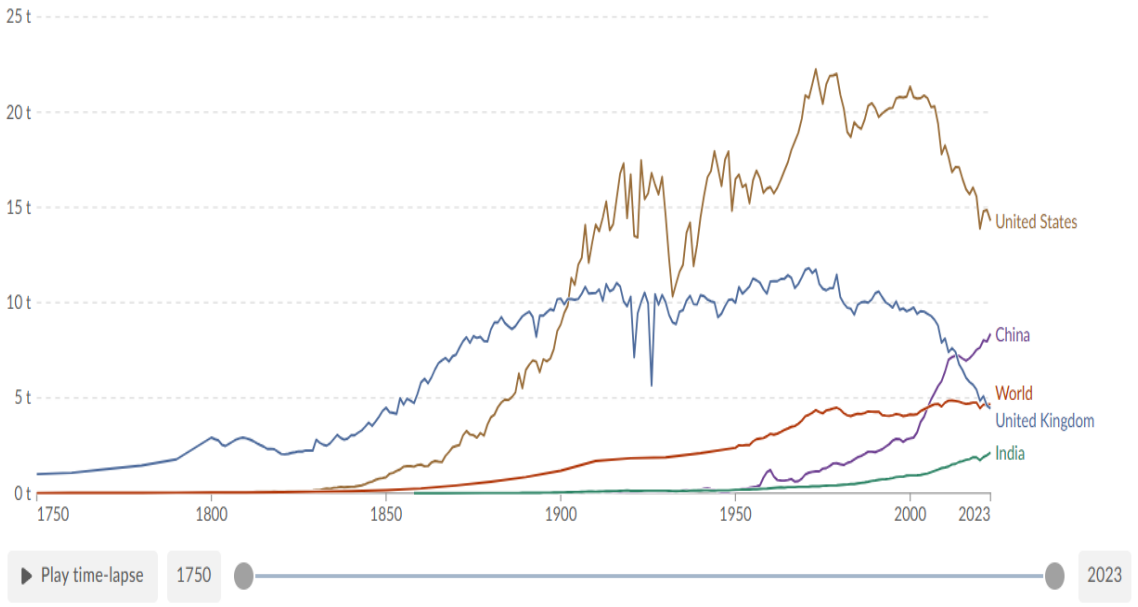


Evolution of Annual greenhouse gas emissions by world region 1850- 2023:



Analysis of regional data from 1850 to 2023 shows the shifting centres of emissions, with North America and Europe historically dominant, but now overtaken by Asia. This trend underscores the importance of targeted policies in high-emission regions to meet global climate goals.

Per capita CO_2 emissions in main countries 1750-2023[9]:



Data source: Global Carbon Budget (2024); Population based on various sources (2024)

In the European Union, emissions have declined over recent decades through a combination of energy transition policies, efficiency improvements, industrial restructuring, and carbon regulation. However, the EU continues to face major decarbonisation challenges in hard-to-abate sectors such as heavy industry, long-distance transport, and dispatchable energy supply. This context is particularly relevant to Hy2Market, which is concerned not only with hydrogen

[9] **Ritchie, H., Rosado, P. and Roser, M. (2023)** *CO_2 and Greenhouse Gas Emissions*, *Our World in Data*. Available at: https://ourworldindata.org/co2-and-greenhouse-gas-emissions

production, but with the role of hydrogen in enabling broader regional decarbonisation pathways.

2.2. Global Emission Challenges

Reducing global emissions requires coordinated efforts across sectors, including energy, transportation, and industry. Key challenges include reliance on fossil fuels, slow policy implementation, and financial constraints in transitioning to clean energy.[10]

Key barriers to emissions reduction include:

- **Scale and Urgency:** The pace and scale of required emissions reductions are unparalleled in human history, demanding rapid deployment of technologies and policies.
- **Sectoral Complexity:** Deep decarbonization of heavy industries (such as steel, cement, and chemicals), long-haul transportation (shipping and aviation), and agriculture presents significant technological and economic hurdles.
- **Fossil Fuel Dependency:** Many nations rely heavily on fossil fuels for energy security, economic stability, and employment, complicating transition efforts.
- **International Cooperation:** Achieving global targets requires coordinated action and equitable burden-sharing amongst nations with differing capabilities and historical responsibilities.
- **Policy Fragmentation:** Inconsistent regulations and lack of harmonized policies across jurisdictions undermine collective progress.
- **Investment Needs:** Substantial public and private investment are essential to develop, commercialize, and scale low-carbon technologies and infrastructure.

Addressing these challenges requires international cooperation, robust policy frameworks, and significant public and private sector investment.

2.3. Role of Non-Combustion Processes in Emissions Reduction

Non-combustion processes avoid the direct release of CO_2 by utilising alternative energy sources (e.g., electricity, waste heat) or entirely different chemical reactions. They are particularly suited for applications where combustion is inefficient or polluting.

These technologies enable:

- Electrification of industrial processes and heating systems, reducing reliance on fossil fuels.
- Production of green hydrogen via electrolysis powered by renewables, offering a versatile decarbonization pathway.
- Production of hydrogen and other low-carbon energy products from qualifying waste and biomass through non-combustion conversion pathways.
- Reduction of air pollutants, improving air quality and public health.
- Integration with renewable energy and smart grid systems, enhancing overall energy efficiency and flexibility.

[10] International Energy Agency (IEA) GHG Overview: IEA Global Energy Review 2023

This foundational shift supports both emissions reduction and broader sustainable development goals.

2.4. Green Hydrogen as a Key Solution for Global Climate Targets

Green hydrogen, produced via the electrolysis of water powered exclusively by renewable electricity sources such as wind, solar photovoltaic (PV) or hydropower, has rapidly emerged as a cornerstone of the global decarbonisation agenda. Unlike grey hydrogen (derived from fossil fuels) or blue hydrogen (with carbon capture), green hydrogen is entirely free of greenhouse-gas emissions at the point of production, making it uniquely well suited to drive deep emissions reductions across multiple sectors.

However, in the context of this report, green hydrogen should be understood within a broader discussion of non-combustion pathways capable of reducing emissions. While electrolysis currently receives the greatest policy attention in Europe, other non-combustion hydrogen pathways may also contribute to decarbonisation, particularly where they address additional challenges such as waste management, methane avoidance, land constraints, water use, or regional energy resilience.

Firstly, green hydrogen serves as a versatile energy carrier, capable of storing surplus renewable electricity when generation outstrips demand. By converting excess power into hydrogen, energy systems gain seasonal storage capacity far beyond the duration limits of batteries. Stored hydrogen can then be transported via pipelines, ships or trucks to regions with high energy needs or used later to generate electricity in fuel cells or turbines, producing only water vapour as a by-product. This intrinsic flexibility plays a vital role in grid balancing, mitigating the intermittency of wind and solar power and unlocking “stranded” renewable resources in remote areas.

Secondly, in industrial feedstock applications, green hydrogen offers a clean substitute for grey hydrogen in processes such as the Haber–Bosch synthesis of ammonia, the direct reduction of iron ore in steelmaking, methanol production, and refinery operations. By replacing fossil-derived hydrogen, green hydrogen can drive near-zero-carbon output in hard-to-abate sectors that currently account for a substantial share of global CO_2 emissions.

Thirdly, as a clean fuel for transport and power, green hydrogen enables heavy-duty road haulage, rail locomotion, maritime vessels and even aviation to transition away from diesel or jet fuel. Fuel-cell electric vehicles (FCEVs) offer rapid refuelling and extended range for long-haul trucks and coaches, while hydrogen-ready gas turbines provide dispatchable, low-carbon power generation to meet peak demand.

Critically, hydrogen’s climate mitigation potential is immense: by 2050 it could abate up to 80 gigatonnes of CO_2 cumulatively, with an annual abatement potential of 7 gigatonnes equivalent to about 20 per cent of the total emissions reductions needed that year. Realising this requires the deployment and consumption of roughly 660 million tonnes of green and other low-carbon hydrogen by mid-century, representing some 22 per cent of final global energy demand[11].

Achieving these targets demands a rapid scale-up of infrastructure:

- Electrolysis capacity must expand to 3–4 terawatts (TW) by 2050.

[11] **Hydrogen Council (2021) Hydrogen for Net Zero.** London: Hydrogen Council. Available at: https://hydrogencouncil.com/wp-content/uploads/2021/11/Hydrogen-for-Net-Zero.pdf

- Renewable generation dedicated to hydrogen production will need to total 4.5–6.5 TW, accounting for up to 25 per cent of the 27 TW of new renewables required globally to reach net zero.
- Low-carbon reforming capacity (for blue hydrogen) of 140–280 million tonnes will be needed alongside infrastructure to capture and store 1–2.5 gigatonnes of CO_2 annually.

Geographically, China, Europe and North America are projected to lead demand, together comprising around 60 per cent of global hydrogen consumption by 2050. To meet ambitious climate goals and transition towards a sustainable, low-carbon economy, policymakers and industry must now accelerate investment in electrolyser manufacturing, renewable generation, hydrogen transport networks and storage facilities, while also assessing the contribution that other non-combustion hydrogen pathways may make in specific regional and sectoral contexts.

3. Technologies for Emissions Reduction Through Non-Combustion Processes

This section expands upon the primary non-combustion technologies applicable for reducing GHG emissions. It includes detailed technical, economic, and environmental profiles of each, focusing on hydrogen production pathways that avoid direct combustion.

3.1. Definition and Importance of Non-Combustion Technologies in Decarbonisation

Non-combustion technologies are decarbonisation methods that operate without burning fossil fuels or biomass. Instead, they leverage alternative principles – electrochemical, mechanical, thermal, or biological – to generate energy or transform materials without generating combustion-related emissions. These technologies are essential to achieving climate neutrality because they avoid the direct release of greenhouse gases (GHGs), including CO_2, NO_x, and particulates.

By avoiding direct oxidation and fuel burning, non-combustion technologies enable clean hydrogen production, efficient waste valorisation, and low-emission energy generation. They offer distinct advantages in air quality improvement, energy system integration, and compatibility with circular economy models.

These approaches are increasingly vital in sectors considered “hard to abate,” such as cement, steel, transport, and chemicals, where direct electrification is not always feasible. Their deployment contributes significantly to the EU Green Deal objectives and aligns with the REPowerEU plan for energy security and industrial decarbonisation.

3.2. Non-Combustion Technologies vs. Combustion Technologies

The distinction between combustion and non-combustion technologies lies in their fundamental operating principles and their environmental impact, particularly regarding greenhouse gas (GHG) emissions, energy efficiency, and air quality.

Combustion Technologies

Combustion technologies rely on exothermic chemical reactions, primarily involving fossil fuels and atmospheric oxygen, to generate energy in the form of heat. While these processes are well-established and widely used across power generation, transport, and industrial applications, they are inherently emissions-intensive:

- Emissions Profile: High emissions of CO_2, methane (CH_4) from upstream leaks, nitrogen oxides (NO_x), sulphur oxides (SO_x), particulate matter (PM), and carbon monoxide (CO).
- Efficiency: Generally lower due to thermodynamic limitations (Carnot efficiency) and energy lost as waste heat.
- Examples: Internal combustion engines, gas turbines, coal-fired power stations, domestic gas/oil boilers, industrial furnaces.

Non-Combustion Technologies

Non-combustion technologies operate without direct fuel burning. Instead, they rely on electrical, mechanical, thermochemical, or electrochemical principles to generate or utilise energy. These technologies significantly reduce or eliminate direct emissions at the point of use:

- Emissions Profile: Minimal or zero at the point of use, particularly when powered by renewable energy sources. Lifecycle emissions depend on supply chains and energy inputs (e.g., electricity grid mix).
- Efficiency: Often higher, as energy is directly converted into useful work or chemical products (e.g., electricity to hydrogen).
- Examples: Electrolysers (green hydrogen production), fuel cells, heat pumps, electric vehicles, batteries, solar PV and wind turbines, and chemical looping processes.

Key Differences at a Glance:

Feature	Non-Combustion Technologies	Combustion Technologies
Energy Source	Electricity (ideally renewable), hydrogen, mechanical energy	Fossil fuels: coal, oil, natural gas
GHG Emissions	Zero or minimal (depending on electricity source)	High (CO_2, CH_4, NO_x, SO_x)
Air Pollutants	Low or none	Significant (PM, CO, NOx, SOx, unburnt hydrocarbons)
Efficiency	High (direct conversion, fewer energy losses)	Lower (heat-based conversion with loss through exhaust)
Water Usage	Moderate (e.g., 9 L/kg H_2 in electrolysis)	Varies, but can be high in some cooling/steam processes
Scalability	Modular and decentralised deployment possible	Typically large-scale, centralised infrastructure
Land Use	May be high for renewables (e.g., solar)	Generally low per plant, but depends on pollution constraints
Examples	Electrolysers, fuel cells, batteries, solar PV, wind, heat pumps	Gasoline/diesel engines, gas turbines, coal boilers

Sustainability Considerations:

- Combustion is a mature and capital-efficient technology but is increasingly incompatible with climate goals and air quality regulations.
- Non-combustion solutions are central to achieving net-zero targets due to their ability to eliminate emissions at the point of use. However, their effectiveness depends on clean electricity availability, material sustainability, and supporting infrastructure.
- For hydrogen specifically, the comparison is not only between combustion and non-combustion end uses, but also between different non-combustion production pathways, which vary in feedstock requirements, land intensity, water demand, grid dependence, and overall system benefits.

Case Study: Comparative Analysis – Electrolysis vs. Raven SR's Reforming Technology

Feature	Electrolysis	Raven SR – Steam/CO_2 Reforming
Energy Use	~60 kWh/kg H_2 (excl. compression)	18 kWh/kg H_2 (fully compressed)
Feedstock	Water + electricity	Biomass waste + steam/CO_2
Emissions	Low (only if powered renewably)	Very low; avoids landfill methane release
Water Use	9 L per kg H_2	Zero
Land Use	~400 acres (10 tpd with solar)	4–5 acres (10 tpd)
Grid Load	High, often intermittent	Minimal; can be self-powered depending on system configuration
Critical Materials	Requires platinum, iridium	None
Cost per kg H_2	$4.5–5.1/kg (2024 est., unsubsidized)	$5.1/kg (Gen 1), $2.2/kg (Gen 2)
Scalability	Limited in land-, water-, or power-constrained areas	Highly modular; deployable near waste & demand

Source: Electrolysis vs. Steam Reforming of Raven SR. Jan 2024

While electrolysis is essential for long-term green hydrogen production, waste-based non-combustion reforming technologies like Raven SR Iberia offer an intermediate, scalable, and low-emission alternative, especially valuable in urban and waste-rich settings.

3.3. Types of Non-Combustion Technologies for Emission Reduction

Non-combustion technologies aim to reduce greenhouse gas (GHG) emissions without burning fossil fuels, playing a critical role in decarbonizing hard-to-abate sectors such as industry, mobility, and energy production. These technologies encompass a wide range of innovative solutions that either replace traditional combustion-based systems or avoid emissions altogether through alternative means. They include the electrification of industrial processes and transport using renewable energy, the use of green hydrogen and its derivatives as clean energy carriers, advanced carbon capture and storage systems, and the development of low-emission materials and production methods. By eliminating the reliance on combustion, these technologies not only reduce direct CO_2 emissions but also contribute to improved air quality and energy efficiency, supporting the transition toward a low-carbon and sustainable economy. In the context of this report, particular attention is given to hydrogen-related non-combustion pathways, including both electrolysis-based systems and qualifying

waste- and biomass-based conversion pathways that can contribute to emissions reduction while providing additional system and circular-economy benefits.

3.3.1. Hydrogen-Based Technologies

Hydrogen is increasingly recognised as a pivotal element in the global energy transition. In 2023, global hydrogen production reached approximately 97 million tonnes (Mt), with less than 1% classified as low-emission hydrogen. However, projections indicate that low-emission hydrogen production could reach 49 Mt per annum by 2030, based on announced projects.

Hydrogen-based technologies involve production, storage, distribution, and utilization of hydrogen as an energy carrier to replace fossil fuels in various industrial, transportation, and energy applications. Hydrogen is considered a crucial component of the global energy transition due to its potential to significantly reduce greenhouse gas (GHG) emissions. These technologies include not only hydrogen production itself, but also the associated infrastructure, downstream conversion pathways, and end uses that determine hydrogen's practical role in decarbonisation.

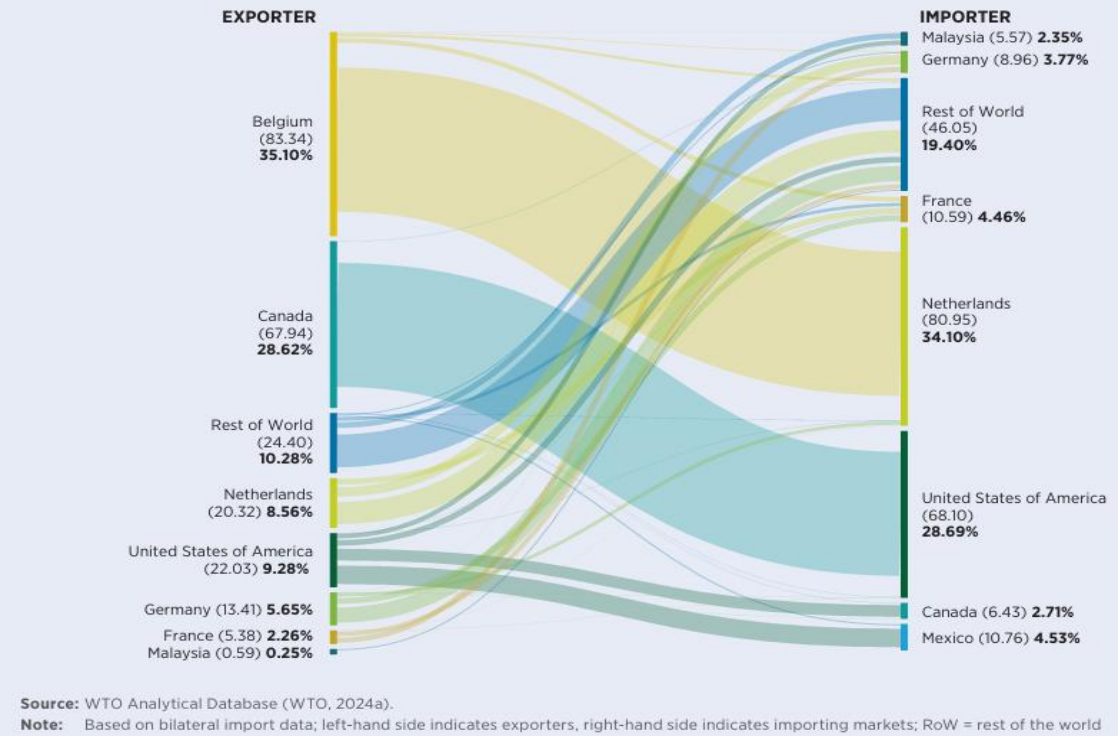
A 2023 joint assessment by IRENA and the WTO highlights the significant role that international trade is set to play in shaping global markets for renewable hydrogen and its derivatives. These hydrogen-based products, such as renewable ammonia, methanol, and e-kerosene, are considered more suitable for long-distance transport than hydrogen itself due to their higher volumetric energy density. Building on these insights, this brief explores the key enabling factors needed to support the growth of international markets for both renewable hydrogen and its associated feedstocks and e-fuels. These derivative products already serve vital functions within the current energy landscape and are expected to gain even greater importance as carriers of energy and chemical inputs in a low-carbon future[12].

International trade is set to play a vital role in the sustainable development of global energy markets, particularly in the transition towards renewable hydrogen and its derivatives such as ammonia, methanol, and e-kerosene. These commodities, currently produced from fossil fuels and widely traded, must shift to renewable production methods that rely on green hydrogen, nitrogen, and biogenic carbon. By connecting regions with abundant renewable resources, often in developing economies, to high-demand markets, international trade can reduce global investment costs by up to USD 3.7 trillion by 2050 and create approximately 22 million jobs, many of them in emerging markets.

To unlock this potential, a range of policy measures is needed, including harmonised standards, government incentives, and carbon pricing schemes, tailored to each country's economic context and goals. More than fifty governments have already proposed frameworks to develop renewable hydrogen value chains. However, inconsistent regulations across borders may hinder progress, making international cooperation essential. A coordinated approach between public and private sectors can accelerate the development of global markets, promote technology transfer, and strengthen the role of trade in achieving climate and development objectives.

Bilateral trade patterns in hydrogen (HS 280410) in 2023, USD million and %:

[12] **International Renewable Energy Agency (IRENA).** (2024) *Enabling global trade in renewable hydrogen and derivative commodities*. Abu Dhabi: IRENA. Available at: https://www.irena.org/Publications/2024/Nov/Enabling-global-trade-in-renewable-hydrogen-and-derivative-commodities



In 2023, global hydrogen imports reached a total value of USD 237 million, marking a decline of over 20% compared to the surge in trade observed in 2022. However, this figure remained 37% above the average annual import value of USD 174 million recorded between 2012 and 2022 (IRENA et al., 2023). The value of hydrogen trade is closely influenced by changes in natural gas prices, as the majority of hydrogen is still produced from this fossil fuel. In 2023, over 60% of the global hydrogen trade occurred between neighbouring countries, notably with Canada and Belgium supplying significant volumes to the United States and the Netherlands, respectively. Looking ahead, trade flows are expected to diversify as new production projects emerge in a broader range of regions. For the purposes of this report, these trends are relevant because they show that hydrogen-based decarbonisation is shaped not only by technology performance, but also by infrastructure, geography, tradability, and the degree to which different hydrogen pathways can be integrated into regional and international value chains.

3.4. Green Hydrogen

Green hydrogen refers to hydrogen produced through the electrolysis of water using electricity sourced exclusively from renewable energy. Unlike grey hydrogen (derived from fossil fuels with no emission controls) or blue hydrogen (paired with carbon capture), green hydrogen production emits no greenhouse gases (GHGs) at the point of generation, making it a genuinely zero-emission solution.

Green hydrogen plays a transformative role in decarbonisation strategies for several reasons:

- **Versatility**: It serves as both a feedstock and an energy carrier, applicable across sectors including industrial processes (e.g., steelmaking, fertiliser production), transport (fuel-cell vehicles, shipping), and energy storage.
- **Seasonal Storage**: It enables the long-term storage of surplus renewable electricity, especially important for grids with high solar or wind penetration.
- **Off-grid Use and Portability**: Hydrogen can be transported and used in regions without access to robust electrical infrastructure.

- **Displacement of Fossil Hydrogen**: It provides a clean substitute for the ~95% of hydrogen currently produced using fossil fuels (mostly via Steam Methane Reforming). However, lifecycle emissions still depend on the carbon intensity of the electricity used, water sourcing, and system boundaries.

European Context

In the European Union, green hydrogen is central to achieving net-zero targets. The REPowerEU strategy aims to produce 10 million tonnes domestically and import another 10 million tonnes of renewable hydrogen annually by 2030. Countries such as Spain, Germany, and the Netherlands are scaling up green hydrogen infrastructure through public investment, IPCEIs, and funding from Horizon Europe and national recovery plans.

3.4.1. Electrolyser Technologies

Electrolysis is a well-established electrochemical process that uses electrical energy to split water (H_2O) into its constituent elements: hydrogen (H_2) and oxygen (O_2). When the electricity used in this process is derived entirely from renewable sources such as wind, solar, or hydroelectric power, the resulting hydrogen is classified as green hydrogen, a zero-carbon energy carrier that emits no greenhouse gases at the point of production or use.

Electrolyser technologies are modular and scalable, meaning they can be deployed in a wide range of configurations, from small-scale, decentralised units for on-site hydrogen production to large-scale centralised facilities integrated into national or regional energy systems. This flexibility makes electrolysis particularly attractive for industrial users, mobility applications, and renewable energy integration.

3.4.1.1. Proton Exchange Membrane (PEM) Electrolysis

PEM technology is a key electrochemical process used in both electrolysers (for hydrogen production) and fuel cells (for energy generation). It employs a solid polymer membrane as an electrolyte to facilitate the transfer of protons while being impermeable to gases such as hydrogen and oxygen.

In a **PEM electrolyser**, water (H_2O) is split into **hydrogen (H_2)** and **oxygen (O_2)** using electricity. The core components are:

- **Anode (positive electrode):** Water is oxidised, producing oxygen, protons, and electrons.
- **Cathode (negative electrode):** Protons travel through the membrane and combine with electrons to form hydrogen gas.
- **PEM (membrane):** Allows only protons (H^+) to pass through, preventing gas crossover and maintaining system integrity.
- **Overall reaction:** $2H2O \rightarrow 2H2+O2$

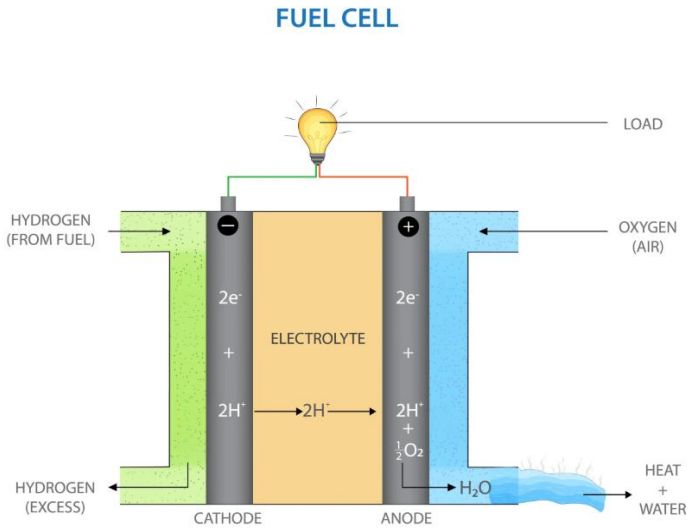
Applications of PEM Technology

- **PEM Electrolysers:**
  - Produce green hydrogen using renewable electricity (e.g., solar, wind).
  - Modular and scalable – suitable for decentralised hydrogen generation.
  - High efficiency at partial load – ideal for variable renewable inputs.

- **PEM Fuel Cells:**
  - Generate electricity by combining hydrogen with oxygen, producing only water as a by-product.
  - Widely used in electric vehicles, especially for buses, trucks, and trains.
  - Preferred for their quick start-up time and compact size.

Advantages of PEM Technology

- **High purity hydrogen output** (typically >99.99%)
- **Fast dynamic response**, allowing it to adapt to fluctuations in renewable energy supply.
- **Compact design** – suitable for both stationary and mobile applications.
- **Operation at relatively low temperatures** (~60–80°C), which improves safety and reduces materials stress.
- **Particularly well suited to** coupling with variable renewable power, although material supply constraints, especially for iridium and platinum-group metals, remain an important challenge for large-scale deployment.



Source: Laurén, S. (2024) 'What are proton exchange membrane fuel cells and how do they work?', *Surface Science Blog*, Biolin Scientific. Available at: biolinscientific.com/blog/what-are-proton-exchange-membrane-fuel-cells-and-how-do-they-work.

3.4.1.2. Alkaline Electrolyser

This is the most mature and widely used form of electrolysis. It uses a liquid alkaline solution (typically KOH or NaOH) as the electrolyte.

Core Technology:

- Electrodes: Typically **nickel-based**, occasionally coated with **Raney nickel** for improved surface area and catalytic activity.
- Electrolyte: Concentrated **aqueous KOH or NaOH** (25–30%).
- Separator: **Porous diaphragm** to prevent mixing of H_2 and O_2 gases but still allow ionic conductivity (usually zirconia-reinforced polymers or asbestos-free composites).

Advantages:

- Lower capital cost and longer system life
- Uses abundant materials (e.g., nickel instead of platinum)
- Proven track record in industrial-scale hydrogen production

Limitations:

- Slower response times
- Lower current density (larger footprint)
- Slightly lower hydrogen purity, although sufficient for most industrial uses

Established technology with lower capital costs.

3.4.1.3. Solid Oxide Electrolysis Cells (SOEC)

SOECs operate at high temperatures (typically 700–850°C), enabling them to achieve higher efficiencies by utilising both electrical and thermal energy.

Benefits:

- Up to 30% lower electricity consumption per kg of H_2 compared to low-temperature electrolysers.
- Suitable for industrial sites with access to waste heat (e.g., steel or glass industries)
- Can operate in reverse mode (solid oxide fuel cells)

Challenges:

- High material stress due to thermal cycling
- High capital costs
- Lower technological readiness level (TRL) compared to PEM or alkaline systems

Emerging Applications:

- Coupling with concentrated solar power (CSP) or nuclear heat
- Integration into power-to-X schemes (e.g., hydrogen to methanol or ammonia)

3.4.1.4. Current Market Dynamics and Future Outlook

The electrolyser market is experiencing rapid growth. Global installed capacity reached about 2 GW in 2024, up from 1.4 GW at the end of 2023. At the same time, announced projects continue to exceed near-term realised deployment, reflecting ongoing challenges around project economics, permitting, supply chains, and firm offtake. The EU continues to target 10 million tonnes of domestic renewable hydrogen production and 10 million tonnes of imports by 2030 under REPowerEU, with electrolyser deployment expected to play a central role in meeting that objective[13]. Key players include Siemens Energy (Germany), ITM Power (UK), Nel ASA (Norway), and Plug Power (USA).

Future developments will focus on:

- **Reducing capital costs**: through economies of scale, automation, and materials innovation

[13] International Energy Agency (IEA), 'Executive summary – Global Hydrogen Review 2025', 12 September 2025. Available at https://www.iea.org/reports/global-hydrogen-review-2025/executive-summary

- **Boosting efficiency**: especially under dynamic load conditions
- **Enhancing durability**: particularly for high-use or high-temperature applications

Public funding and industrial demand are aligning to accelerate electrolyser deployment, but supply chain constraints (especially for iridium and platinum) and permitting delays must be addressed. Recent IEA analysis also suggests that, while the project pipeline remains large, only a smaller subset of announced projects has reached final investment decision, meaning that deployment is advancing, but more slowly than many earlier projections assumed.[14]

3.5. Blue Hydrogen

Derived from natural gas through steam methane reforming, coupled with carbon capture and storage (CCS) to mitigate CO_2 emissions.

Blue hydrogen refers to hydrogen produced from natural gas through a process known as steam methane reforming (SMR) or autothermal reforming (ATR), combined with carbon capture and storage (CCS) technologies to reduce carbon dioxide emissions. Unlike grey hydrogen, which is also derived from fossil fuels but without emissions mitigation, blue hydrogen involves capturing the CO_2 generated during production and storing it underground in geological formations such as depleted oil and gas fields or saline aquifers. In the reforming process, methane reacts with steam at high temperatures to produce hydrogen and carbon monoxide, which is further converted into additional hydrogen and CO_2. The captured CO_2 is then compressed and transported for long-term storage, thereby significantly reducing the environmental impact of the process.

From an environmental perspective, blue hydrogen is considered a transitional solution towards a cleaner energy system. While it is not entirely emission-free due to reliance on fossil fuels and potential methane leakage, it offers a substantial reduction in carbon intensity compared to grey hydrogen. It is currently often more economically viable than green hydrogen, which is produced via electrolysis using renewable electricity, as the technologies for blue hydrogen are more mature and the production costs lower. Its overall climate performance, however, depends heavily on methane leakage rates, capture efficiency, and the permanence of CO_2 storage.

Industrially, blue hydrogen is already being deployed in sectors such as ammonia and methanol production, oil refining, and as a low-carbon fuel for heating and transport applications. Several major projects in the UK, Norway, and the United States are advancing the deployment of blue hydrogen as part of their national decarbonisation strategies. However, its long-term viability depends on factors such as the efficiency of carbon capture systems, natural gas prices, and evolving climate policies. While not the final destination in the transition to net-zero, blue hydrogen plays an important intermediary role in accelerating the reduction of emissions while renewable infrastructure and green hydrogen technologies continue to scale.

Key Technologies for Blue Hydrogen

- **Steam Methane Reforming (SMR) + Carbon Capture and Storage (CCS)**
  - The most widely used technology. Hydrogen is produced from natural gas, and CO_2 is captured to reduce emissions.

[14] International Energy Agency (IEA), Global Hydrogen Review 2025, IEA, Paris, 2025. For the full report, https://www.iea.org/reports/global-hydrogen-review-2025

- Currently represents the dominant existing route for fossil-based hydrogen production with CCS at around 60% of the global blue hydrogen market (as of 2024).

- **Autothermal Reforming (ATR) + CCS**
  - Emerging as a more energy-efficient alternative to SMR.
  - Easier to integrate with CCS and better suited for large-scale applications.
  - Increasingly favoured in new large-scale project proposals because of its process integration advantages for CO_2 capture.

- **Partial Oxidation (POX)**
  - Uses heavier hydrocarbons; often applied in refineries.
  - Less efficient but viable in existing heavy industrial infrastructures.

3.5.1. Global Market Overview

In 2024, the global blue hydrogen market was valued at approximately USD 18.6 billion according to market estimates, with forecasts suggesting an increase to nearly USD 44.5 billion by 2030. However, announced project capacity continues to exceed projects that have reached final investment decision, and the pace of deployment remains sensitive to gas prices, carbon policy, infrastructure availability, and support for CCS. Production of blue hydrogen is expected to reach about 22 million tonnes per annum by 2030, potentially accounting for almost half of all low-carbon hydrogen output. SMR continues to supply around 84 % of hydrogen globally; however, ATR is advancing rapidly and poised to dominate new projects in both North America and Europe. In this sense, blue hydrogen remains important not because it resolves all climate concerns, but because it illustrates how carbon capture can reduce emissions from incumbent fossil-based hydrogen systems while lower-emission alternatives continue to scale.

3.6. Grey Hydrogen[15]

Grey hydrogen is the most commonly produced form of hydrogen today and is generated from fossil fuels, primarily natural gas through a process known as steam methane reforming (SMR). In this method, methane reacts with steam at high temperatures to produce hydrogen and carbon dioxide. Unlike blue hydrogen, the CO_2 generated during the process is not captured but is released directly into the atmosphere, contributing significantly to greenhouse gas emissions.

Due to its low production cost and the established nature of the technology, grey hydrogen is widely used in industrial applications such as oil refining, ammonia production, and the chemical industry. However, from an environmental perspective, it is the least sustainable form of hydrogen, as its production emits large quantities of carbon dioxide typically around 9 to 12 kilograms of CO_2 per kilogram of hydrogen produced.

Grey hydrogen serves as the baseline from which blue and green hydrogen technologies aim to improve. While it continues to dominate global hydrogen production, increasing climate regulation and carbon pricing are expected to limit its future role in a decarbonised energy system. Transitioning from grey to low-carbon alternatives is a key objective for countries pursuing net-zero targets.

Main Technologies of Grey Hydrogen Production

[15] **Hydrogen Council.** (2021). *Hydrogen Insights: A Perspective on Hydrogen Investment, Deployment and Cost Competitiveness.* https://hydrogencouncil.com

The primary technology employed for the production of grey hydrogen is Steam Methane Reforming (SMR). This process remains the most commercially viable and widely adopted method due to its mature technology, cost-effectiveness, and the extensive natural gas infrastructure already in place.

3.6.1. Steam Methane Reforming (SMR)

SMR is a catalytic process that involves reacting methane (CH_4) with high-temperature steam (H_2O) to produce hydrogen (H_2) and carbon monoxide (CO). The carbon monoxide subsequently reacts with additional steam in a water-gas shift reaction to generate more hydrogen and carbon dioxide (CO_2).

- **Reaction Steps:**
  - *Reforming:*
    $CH_4 + H_2O \rightarrow CO + 3H_2$
  - *Shift Reaction:*
    $CO + H_2O \rightarrow CO_2 + H_2$
- **Advantages:**
  - Well-established and reliable technology.
  - High conversion efficiency.
  - Cost-effective at large scales.
- **Limitations:**
  - Significant CO_2 emissions, primarily from the reforming and shift reactions.
  - Environmental impact due to greenhouse gases released into the atmosphere.

3.6.2. Autothermal Reforming (ATR)

ATR combines partial oxidation and steam reforming of methane, utilizing oxygen and steam to produce hydrogen and CO_2. This process is often used in large-scale hydrogen plants.

- **Reaction Characteristics:**
  - Combines exothermic oxidation and endothermic reforming, providing a self-sustaining heat source.
  - Produces a similar hydrogen output as SMR but with different operational efficiencies.
- **Advantages:**
  - More flexible in feedstock composition.
  - Potentially lower CO_2 emissions per unit of hydrogen compared to SMR when coupled with CCS.
- **Limitations:**
  - Requires oxygen supply, typically from air separation units, increasing complexity and cost.

3.6.3. Partial Oxidation (POX)

In POX, methane is partially oxidised with a limited amount of oxygen, producing hydrogen and carbon monoxide directly.

- **Reaction:**
  $CH_4 + ½\ O_2 \rightarrow CO + 2H_2$
- **Advantages:**

- Faster reaction kinetics, suitable for smaller or specialised facilities.
- Simpler process with fewer steps.

- **Limitations:**
  - Higher oxygen consumption.
  - Similar CO_2 emissions as other fossil fuel-based methods.

Current Status of Grey Hydrogen Production

Grey hydrogen production remains the predominant method for generating hydrogen globally, accounting for approximately 99% or more of total hydrogen production as of 2023 when measured against low-emissions hydrogen output of less than 1 Mt out of 97 Mt total demand. Its widespread utilisation is primarily due to the maturity of the technology, established industrial processes, and the availability of abundant natural gas resources.

Regional Distribution:

- **Asia-Pacific:** The largest share, driven by extensive industrial activity and natural gas availability, especially in countries like China, India, and Japan.
- **North America and Europe:** Significant production, often linked to refining, ammonia synthesis, and other industrial applications.
- **Middle East:** Growing capacity due to natural gas resources and strategic investments.

CO_2 Emissions from Grey Hydrogen:

The production process emits roughly 9-12 tonnes of CO_2 per tonne of hydrogen, contributing significantly to global greenhouse gas emissions. The International Energy Agency (IEA) estimates that in 2023, hydrogen production overall emitted around 920 million tonnes of CO_2, with nearly two-thirds of production coming from unabated natural gas and about 20% from unabated coal.

3.7. Pink Hydrogen[16]

Pink hydrogen refers to hydrogen produced through electrolysis powered by nuclear energy. The electrolysis process uses electricity to split water (H_2O) into hydrogen and oxygen. When nuclear power is the source of electricity, the resulting hydrogen is labelled as 'pink'. Some definitions include high-temperature steam electrolysis (HTSE) using heat from nuclear reactors, which increases efficiency. As with other hydrogen categories, lifecycle emissions depend not only on the production pathway itself, but also on the broader energy system, plant design, and fuel-cycle assumptions.

Benefits

- Emission-free at point of production.
- Reliable 24/7 power source (unlike intermittent renewables).
- High thermal integration potential with Small Modular Reactors (SMRs).

Main Technologies:

- **Proton Exchange Membrane (PEM) Electrolysers**

[16] **International Atomic Energy Agency (IAEA)** – *Hydrogen Production Using Nuclear Energy*. Available at: https://www.iaea.org/topics/hydrogen-production

PEM electrolysers utilise a solid polymer electrolyte membrane to facilitate ion transfer between the anode and cathode, enabling the electrolysis of water into hydrogen and oxygen.

- **Alkaline Electrolysers**

  Alkaline electrolysers are one of the oldest and most mature electrolysis technologies, operating with an aqueous alkaline solution (commonly potassium hydroxide) as the electrolyte.

- **High-Temperature Steam Electrolysis (Solid Oxide Electrolysers)**

  High-temperature electrolysis, primarily via **Solid Oxide Electrolyser Cells (SOECs)**, operates at elevated temperatures (700–850°C), using ceramic electrolytes to split water into hydrogen and oxygen.

The integration with **next-generation small modular reactors (SMRs)** is being explored to enable decentralised and low-carbon hydrogen production.

Current Market of Pink Hydrogen

The pink hydrogen market is still in its infancy, with most developments at the feasibility study or pilot stage. France, the UK, and Finland are leading efforts in Europe, leveraging their existing nuclear infrastructure.

- **France** has launched initiatives to integrate nuclear energy into its hydrogen roadmap, with EDF exploring combined nuclear-electrolysis platforms.
- **The UK** is assessing the viability of coupling its advanced nuclear programme with hydrogen production, particularly in northern regions.
- **Finland and Czechia** are examining small modular reactor (SMR) deployments for decentralised hydrogen generation.

Despite political and public concerns surrounding nuclear energy, pink hydrogen is being increasingly viewed as a complementary solution for 24/7 low-carbon hydrogen production, especially in industrial clusters. Within the context of this report, pink hydrogen is relevant as an example of a non-combustion hydrogen pathway that may offer strong reliability advantages, even though it does not provide the same circular-economy or waste-management benefits as certain biomass- or waste-based pathways.

3.8. Turquoise Hydrogen

Turquoise hydrogen is a relatively emerging category within the spectrum of low-carbon hydrogen production pathways. It is produced predominantly through *methane pyrolysis*, a process that thermally decomposes methane (CH_4) into hydrogen (H_2) and solid carbon (C). Unlike grey hydrogen, which releases CO_2, or blue hydrogen, which incorporates carbon capture, turquoise hydrogen offers a pathway to produce hydrogen with minimal greenhouse gas emissions.

Production Technology

- **Methane Pyrolysis Process:**

This process involves heating methane to high temperatures (around 800–1,200°C) in the absence of oxygen, leading to the dissociation of methane molecules into solid carbon and gaseous hydrogen.

- **Reaction:**
  $CH_4 \rightarrow C\ (solid) + 2H_2$

Key technologies include:

- **Thermal Pyrolysis Reactors**: Operate at 1,000°C or higher, typically requiring an external heat source.
- **Plasma-Assisted Pyrolysis**: Uses plasma torches to initiate the methane decomposition process.
- **Catalytic Pyrolysis**: Incorporates solid catalysts to reduce energy input and enhance hydrogen yield.
- **Carbon Capture and Valorisation Systems**: To collect and utilise the solid carbon by-product for industrial applications (e.g., in batteries, construction materials).

Current Market of Turquoise Hydrogen

The turquoise hydrogen market is emerging, with limited commercial deployment but growing interest from private and public stakeholders.

- Pilot projects have been launched in Germany, Norway, and the Netherlands, often backed by industrial players in steel, chemicals, and energy sectors.
- Companies such as BASF, HiiROC, and Monolith are developing scalable pyrolysis reactors and investing in carbon valorisation technologies.
- Challenges remain in achieving cost competitiveness, scaling the pyrolysis process, and developing markets for solid carbon by-products.

The technology is attractive due to its potential for low CO_2 emissions under favourable operating conditions, and its suitability for decentralised production in industrial parks or near biogas sources. However, its climate value depends on methane supply-chain emissions, reactor energy demand, and whether the resulting solid carbon can be stably stored or commercially used at scale.

3.9. Carbon Capture, Utilization, and Storage (CCUS)

CCUS encompasses technologies that capture carbon dioxide emissions from sources like power plants and industrial processes, preventing CO_2 from entering the atmosphere. The captured CO_2 can then be stored underground or utilised in various applications, such as enhanced oil recovery or the production of synthetic fuels and chemicals. In the context of hydrogen and industrial decarbonisation, CCUS is particularly relevant where process emissions are difficult to eliminate directly, or where transitional pathways continue to rely on carbon-containing feedstocks.

Market Trends:

The global CCUS market is experiencing significant growth. In recent years, the market and project pipeline have expanded substantially, driven by increasing governmental and industrial investments aimed at achieving net-zero emissions targets. According to the IEA, around 45 commercial CCUS

facilities are already operating globally, and more than 700 projects are in development across the value chain. Announced CO_2 capture capacity for 2030 has risen to over 430 Mt per year, while announced storage capacity has reached around 620 Mt per year.[17]

Contribution to GHG Emissions Reduction:

CCUS technologies have the potential to significantly mitigate GHG emissions, particularly in sectors where direct emissions reductions are challenging. By capturing and either storing or utilising CO_2, CCUS can play a pivotal role in decarbonising industries such as cement, steel, and chemicals. However, its climate value depends on capture rates, transport and storage infrastructure, long-term storage integrity, and whether utilisation pathways lead to durable carbon retention or only temporary emissions delay.

3.10. Biological Processes

Biological processes harness microorganisms to convert organic materials into renewable energy and chemicals. Key processes include:

3.10.1. Anaerobic Digestion

In this process, organic matter is broken down by microorganisms in the absence of oxygen, resulting in the production of **biogas** (a mixture of methane and CO_2) and a solid digestate.

Applications:

- Producing biomethane for grid injection or vehicle fuel.
- Fertiliser production from digestate.
- Combined heat and power (CHP) in decentralised systems.

GHG Impact:

- Avoids methane leaks from unmanaged organic waste.
- Reduces reliance on natural gas and chemical fertilisers.

3.10.2. Biohydrogen Production

Biohydrogen can be generated through:

- Dark fermentation (using anaerobic bacteria to convert carbohydrates into hydrogen).
- Photo-fermentation (using light-activated bacteria such as Rhodobacter).
- Algal hydrogen production (from Chlamydomonas reinhardtii under nutrient-limited conditions).

Although still emerging, biohydrogen has potential as a low-impact source of clean hydrogen using organic waste as feedstock, particularly in wastewater treatment or agro-industrial zones. Its current relevance lies more in long-term innovation potential than in near-term industrial scale.

[17] International Energy Agency (IEA), 'It is time for CCUS to deliver', 15 May 2025. Available at https://www.iea.org/commentaries/it-is-time-for-ccus-to-deliver

3.10.3. Fermentation Processes

Used to produce:

- Bioethanol from sugars and starches.
- Butanol or volatile fatty acids (VFAs) for bio-based chemicals.

Such processes reduce the carbon intensity of materials and fuels and support the substitution of petrochemical-derived products.

3.10.4. Environmental and Social Co-Benefits

- Reduced methane emissions from landfills.
- Stabilisation of local waste management systems.
- Rural job creation and support for small-scale farmers.
- Biodiversity protection through organic waste recovery.

Example:
The EU supports projects like “BIOGASUP” and “WAST2BIOH2” to develop integrated, decentralised waste-to-energy hubs across regions with limited industrial infrastructure.

3.11. Benefits of Non-Combustion Technologies

The transition from combustion-based systems to non-combustion technologies constitutes a fundamental shift towards climate neutrality, industrial decarbonisation, and sustainable competitiveness. By eliminating or drastically reducing the use of thermal oxidation processes, these technologies unlock a broad range of environmental, technical, and socio-economic benefits.

- **Deep Decarbonisation**:

  Non-combustion technologies directly eliminate or significantly reduce emissions of carbon dioxide (CO_2), nitrogen oxides (NO_x), sulphur oxides (SO_x), and particulate matter typically associated with fossil fuel combustion. This enables substantial progress in reaching EU climate targets and supports the transformation of hard-to-abate industrial sectors such as cement, steel, and chemicals. The systematic avoidance of combustion-related emissions ensures not only lower carbon footprints but also a reduced burden on carbon capture systems and emission offset mechanisms.

- **Energy Efficiency:**

  A wide range of non-combustion processes—including heat pumps, induction heating, electrochemical synthesis, and microwave-assisted methods—can offer greater energy efficiency compared to traditional thermal technologies. These methods often operate under more controlled conditions, at lower temperatures, and with minimal energy loss. Furthermore, their compatibility with renewable electricity allows for greater integration into decarbonised energy systems, optimising overall energy performance and reducing operational costs in the long run.

- **Process Innovation:**

  The shift towards non-combustion technologies fosters the development of new industrial processes that are inherently cleaner, safer, and more efficient. This includes novel production

routes based on electrification, plasma processing, non-thermal separation techniques, or even solid-state manufacturing. Such innovations drive technological leadership, particularly within the European Union, enhancing its global position in clean industrial technologies while stimulating research and development across academic and commercial spheres.

- **Reduced Air Pollution:**

  By eliminating the combustion of fuels, these technologies substantially reduce emissions of pollutants such as NO_x, SO_x, carbon monoxide (CO), and volatile organic compounds (VOCs), which are major contributors to smog, acid rain, and respiratory diseases. Their widespread adoption can result in significant improvements in local air quality, particularly in densely populated or industrialised areas, thereby delivering direct public health benefits and reducing healthcare costs linked to pollution exposure.

- **Resource Efficiency & Circularity:**

  Non-combustion pathways often allow for better control over material flows and improved integration of circular economy principles. For example, they can enhance the recovery of critical raw materials, facilitate the use of secondary feedstocks, and support the substitution of fossil-based inputs with alternatives such as green hydrogen, bio-based materials, or industrial by-products. This contributes to waste reduction, improved lifecycle performance, and the diversification of resource supply chains, all of which are vital for long-term industrial sustainability.

- **Economic Competitiveness:**

  The implementation of non-combustion technologies reinforces the competitiveness of EU industry by enabling the production of low-emission goods, accessing green premium markets, and lowering energy and emission compliance costs over time. These technologies also stimulate new value chains, encourage industrial modernisation, and support high-quality job creation in emerging sectors such as clean tech manufacturing, advanced engineering, and energy services.

- **Energy Security:**

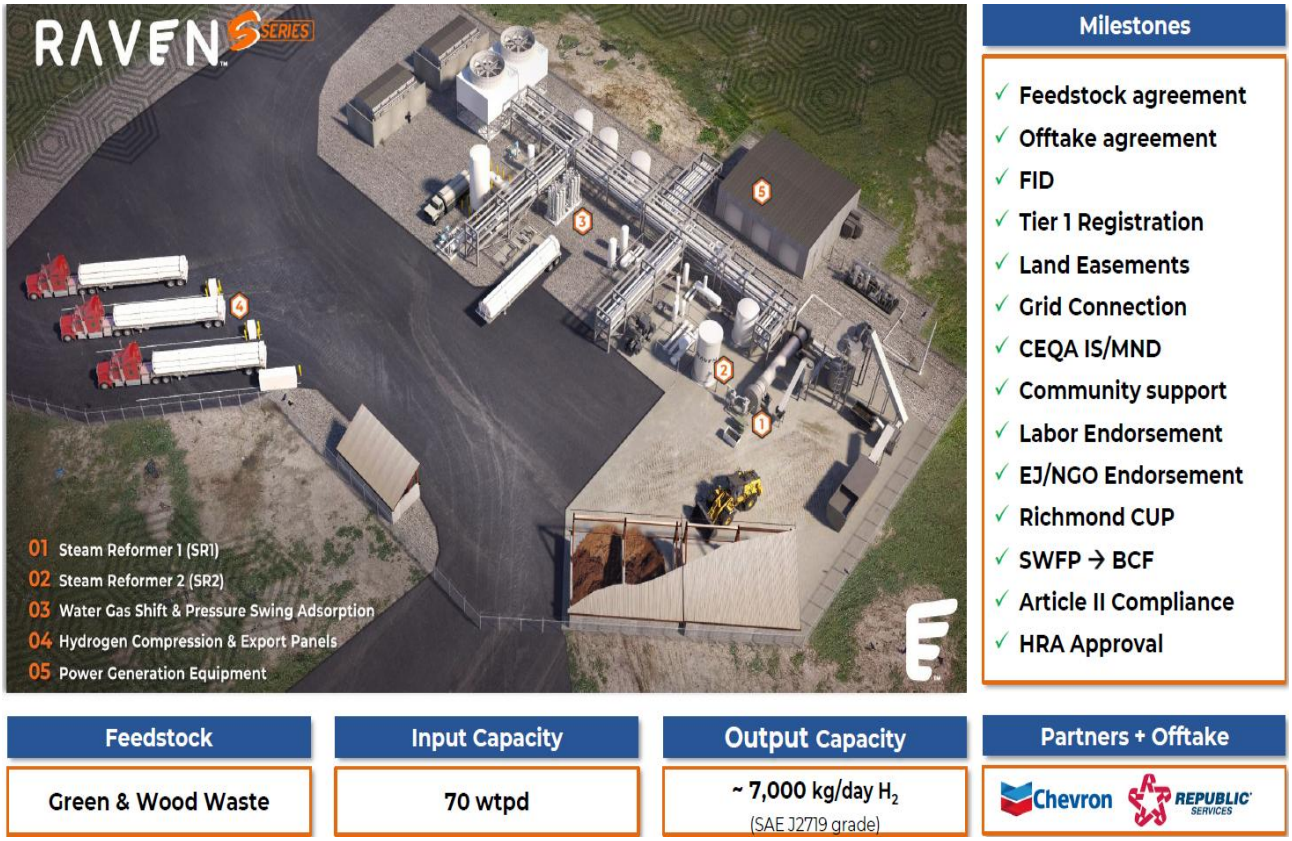
  Reducing dependence on fossil fuel combustion decreases the reliance on imported energy sources, thereby enhancing the EU's energy autonomy and resilience to external supply shocks. Non-combustion technologies can be powered by locally generated renewable electricity, offering greater control over energy inputs and contributing to national and regional energy strategies. This aligns with key objectives of the REPowerEU plan and broader geopolitical ambitions related to clean energy independence.

The adoption of non-combustion technologies is not merely a technical upgrade it represents a systemic transformation with far-reaching benefits. These solutions are central to a forward-looking, zero-emission industrial strategy that aligns environmental responsibility with economic resilience and technological sovereignty. In addition, where non-combustion pathways can integrate waste valorisation, modular deployment, or reduced dependence on constrained grid capacity, their strategic value may extend beyond emissions reduction alone.

4. Case Study in Emissions Reduction: Raven SR's Non-Combustion Hydrogen Facility

Raven SR Inc. is developing a 70-tonne-per-day S-Series hydrogen production facility in Richmond, California. The plant employs a patented, commercially ready, non-combustion process to convert organic waste into high-purity hydrogen. This decentralised, scalable technology supports climate goals, circular economy principles, and environmental justice by addressing both emissions and local public health concerns.

Raven S-Series Plant 70 wet-tpd in Richmond, CA:



4.1. Richmond Context: A Community in Need of Clean Air

Richmond, California, is representative of frontline communities disproportionately burdened by environmental pollution. With a population of over 160,000, the area is home to numerous industrial facilities, including oil refineries, ports, and transport depots.

Key Challenges in Richmond:

- One of 17 worst air pollution districts in California (California Air Resources Board, 2020)
- High asthma and heart disease rates, alongside elevated cancer risk from mobile and industrial sources
- 33% of toxic air contaminant exposure originates from local fuel refining and associated industries
- 61% of cancer-risk-weighted emissions stem from vehicles, trucks, marine, and rail transport

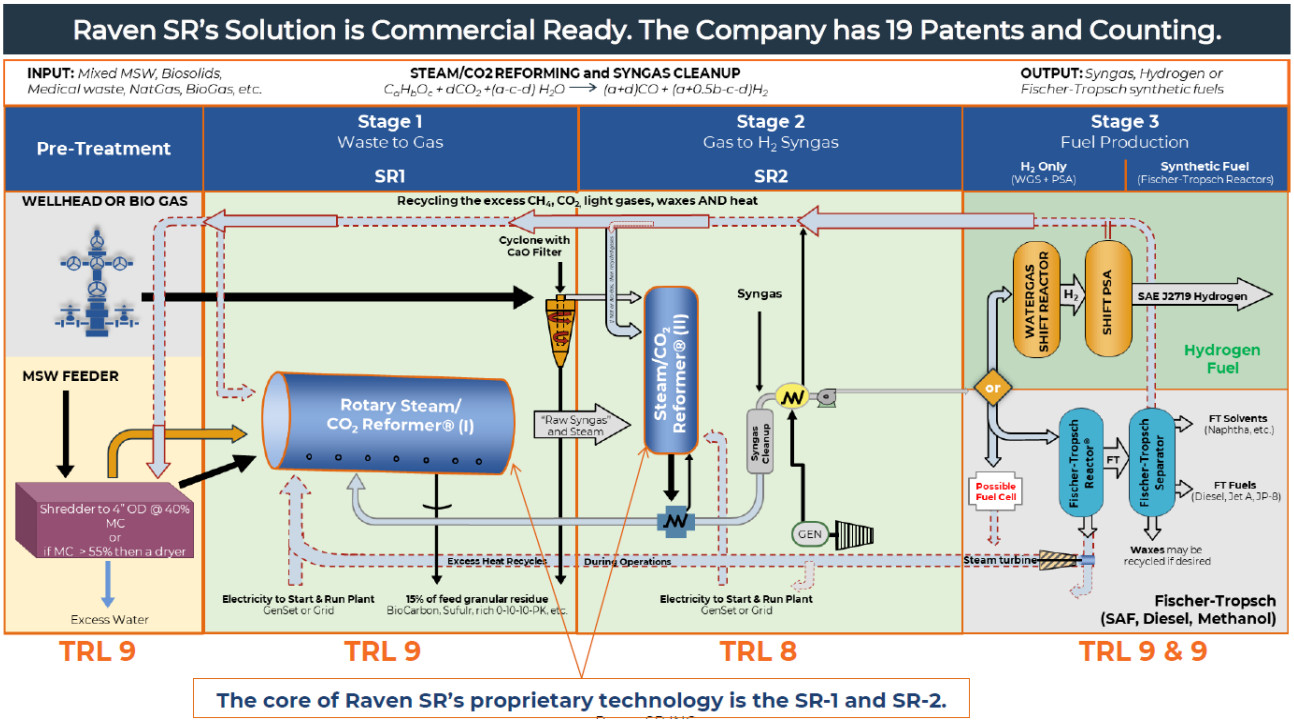
- Demographic indicators:
  - Under 18 years: 21.4% | Aged 18–64: 64.3% | Over 65: 4.3%
  - Median household income: $103,599
  - Poverty rate: ~12.7%
  - Primary employment sectors: education, healthcare, public services, hospitality, and transport

Once operational, the Raven SR facility will be positioned to help reduce health and environmental risks up to 6,000 feet (~1.8 km) away, with the potential to deliver measurable air quality improvements to a disproportionately impacted frontline community.

4.2. The Technology: Non-Combustion Reforming Process

Raven SR has developed a proprietary, commercially ready hydrogen production platform that converts organic waste into high-purity hydrogen—without combustion.

Patented Technology & Commercially Ready:

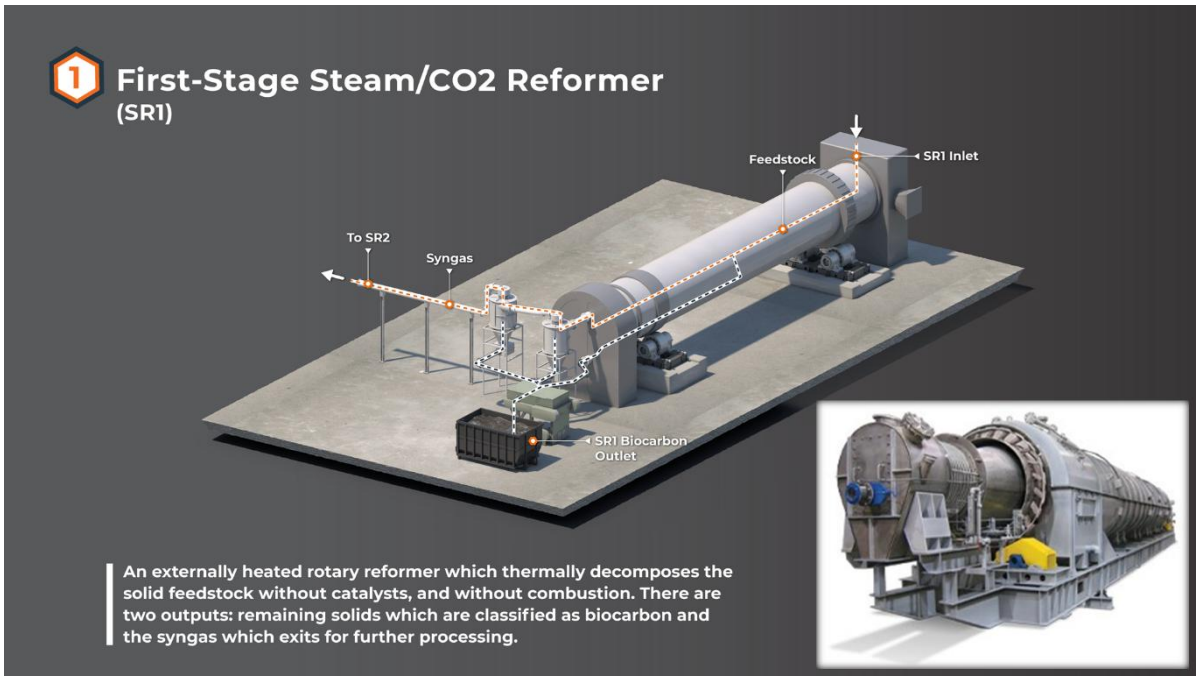


Raven SR's proprietary hydrogen production process comprises two core reforming modules, with downstream syngas-to-hydrogen conversion provided by third-party WGS and PSA systems.

- **SR-1 Electric Rotary Reformer**

  Converts solid waste into syngas and bio-carbon. Core Advantages:
  - Electric heating for precise heat control
  - Non-catalytic
  - 95% cold-gas efficiency
  - Lower temperatures + steam = no tars or slag

- Robust, modular design

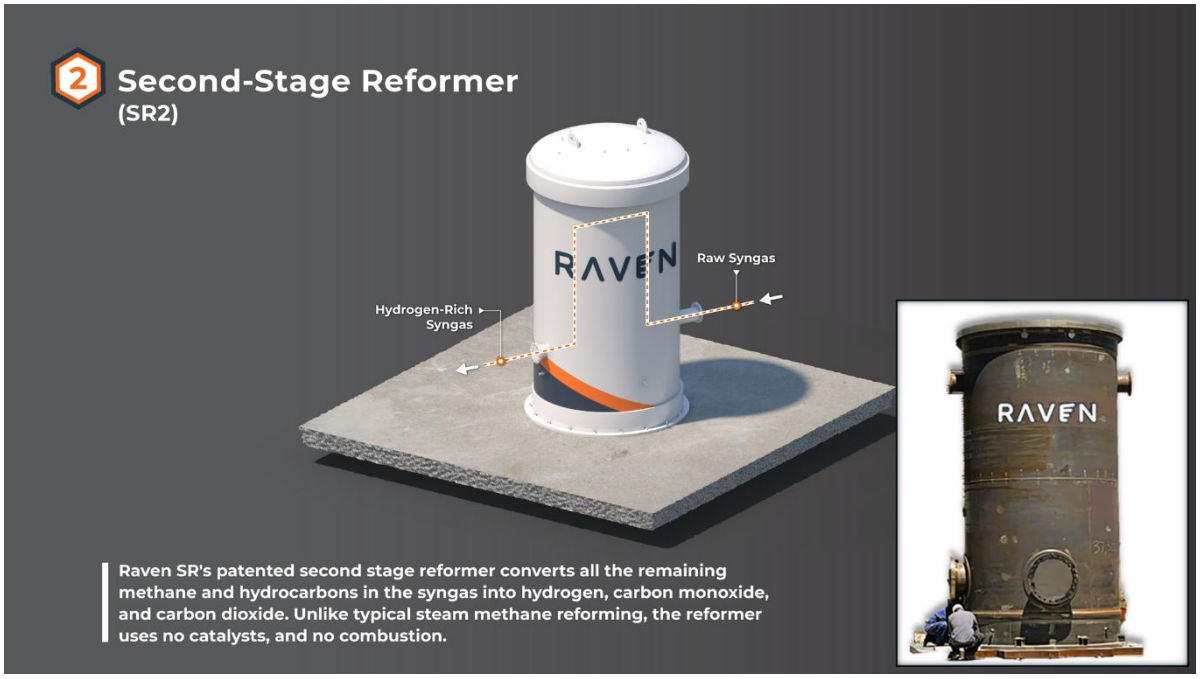


Conceptual representation of Raven SR's first-stage reformer (SR-1), accompanied by an inset of the full-scale fabricated SR1 rotary reformer (Richmond, CA).

- **SR-2 Electric Steam Reformer**

  Converts methane-rich syngas to high-purity H_2. Core Advantages:

  - Electric heating for precise heat control
  - Non-catalytic
  - >97% CH_4 conversion
  - "Designed to destroy sulphur and nitrogen impurities, and capable of high-temperature destruction of PFAS under appropriate operating conditions
  - Lower pressure than traditional SMR



Conceptual representation of Raven SR's second-stage reformer (SR2), accompanied by an inset of the full-scale fabricated SR2 reactor (Richmond CA)

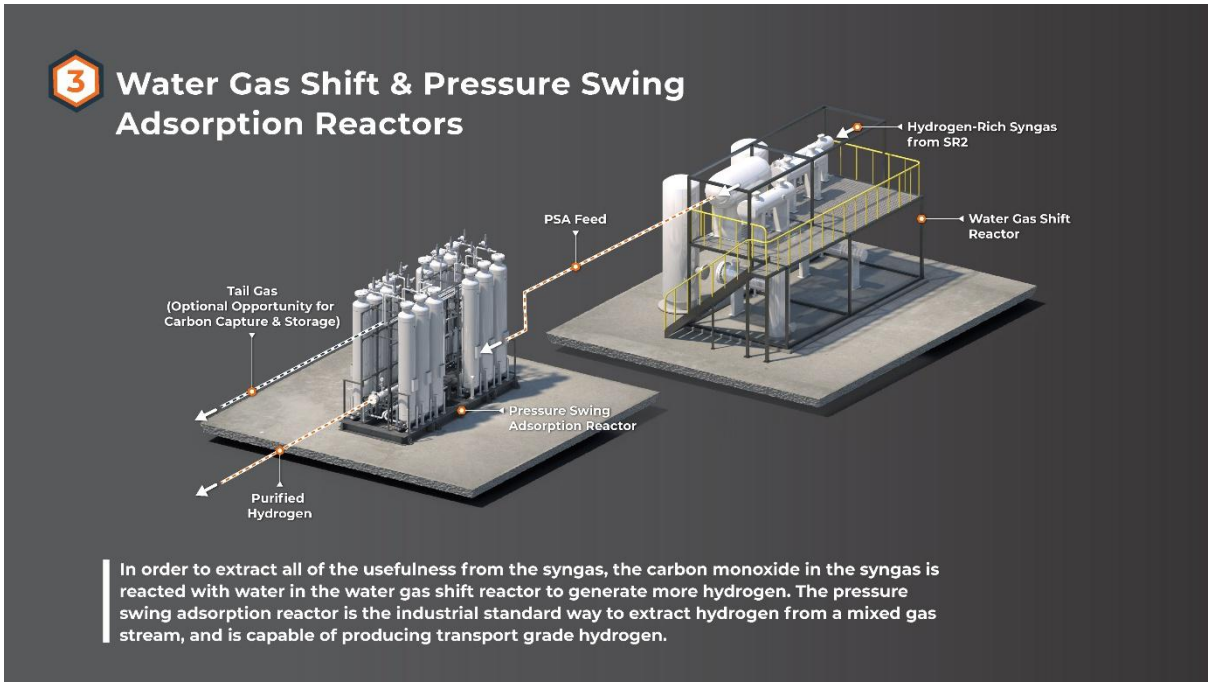
Together, SR1 and SR2 enable non-combustion hydrogen production from solid waste cleanly, efficiently, and at commercial scale.

- **Decades of proof** – Large-scale kilns have been built and run around the world
- **Strong Technology and IP** – 22 patents issued and 11 patents pending
- **Commercially Built to Scale** – SR2 reactor already fabricated and shop tested

- **Water Gas Shift and Pressure Swing Adsorption Reactors**

  Converts hydrogen-rich syngas to ultra-high-purity H_2 (up to 99.9999%). Core Advantages:

  - Integrated Water Gas Shift (WGS) maximizes hydrogen yield through CO conversion
  - Pressure Swing Adsorption (PSA) enables high-purity hydrogen separation
  - Industry-proven, bankable third-party technology
  - Modular and scalable for distributed or large-scale deployment
  - Removes residual CO, CO_2, CH_4, moisture, and trace contaminants
  - Integrated compression enables delivery at required pressure for storage, transport, or end use



Conceptual representation of the syngas-to-hydrogen conversion stage, incorporating Water Gas Shift (WGS) and Pressure Swing Adsorption (PSA) for hydrogen enrichment and purification.

4.3. Climate and Environmental Impact

- **High Climate Impact**

  Raven SR's non-combustion biomass-to-hydrogen technology significantly reduces greenhouse gas emissions. For every tonne of organic waste processed, up to 1.07 metric tonnes of CO_2 equivalent ($MTCO_2e$) are avoided. This makes the process:

  - Three times more effective than composting
  - Five times more effective than diverting waste from landfill

  At commercial scale, each Raven plant can reduce emissions by more than 275,000 $MTCO_2e$ annually, directly contributing to California's Short-Lived Climate Pollutant (SLCP) objective of reducing landfill methane emissions by 40% by 2030.

- **Regulatory Challenges and Policy Needs**

  While Raven's technology is fully developed and compliant, its expansion is hindered by outdated regulations. Under current California law (PRC §40106), biosolids and food waste are not included as acceptable feedstocks. Amending this regulation would:

  - Enable faster permitting of low-emission hydrogen projects
  - Eliminate unnecessary Solid Waste Facility Permit (SWFP) delays
  - Support immediate compliance with Article 2
  - Accelerate California's 75% organic waste diversion mandate under SB 1383

  Permitting remains the biggest barrier to commercial scaling. Investor confidence is undermined by the perception that even fully compliant, community-backed projects cannot proceed due to regulatory friction not technological limitations.

- **Alignment with State Climate Goals**

  Raven's non-combustion hydrogen pathway directly supports state environmental targets such as:

  - SLCP (methane emissions reduction)
  - SB 1383 (organic waste diversion)
  - AB 1279 (net-zero transition)

  Key performance indicators include:

  - Lower land-use intensity compared to conventional facilities
  - Faster throughput for waste processing
  - Hydrogen production sufficient to displace diesel use in approximately 250 Class 8 trucks per year

- **Transparent Community Engagement**

  Raven SR prioritised community involvement from the outset. As part of its voluntary measures:

  - A full Health Risk Assessment (HRA) was conducted
  - Extensive community engagement was undertaken in line with California Environmental Quality Act (CEQA) guidelines

  This built trust with residents and local NGOs, resulting in broad-based support. However, lengthy permitting processes have delayed the delivery of promised benefits such as cleaner air and local employment. This experience shows the urgent need for Article 2 of the permitting code to reward transparency and compliance, not penalise it.

4.4. Socioeconomic and Public Health Benefits

Air Quality and Health Improvements

Raven SR's steam/CO_2 reforming process involves no combustion, which means:

- Negligible emissions of nitrogen oxides (NO_x), sulphur oxides (SO_x), fine particulate matter ($PM_{2.5}$), and dioxins
- No public health risk above modelled thresholds were identified in the HRA
- Local emissions concerns are instead linked to landfill gas (LFG) engines, not Raven's technology

The avoided emissions result from:

- Diverting waste (up to 1.07 $MTCO_2e$ per tonne processed)
- Reducing diesel emissions from road transport by displacing ~255 heavy-duty Class 8 trucks per year

This is especially beneficial for frontline communities such as Richmond, California, who bear a disproportionate health burden from pollution. Air Quality Gains: Raven Richmond's hydrogen output can displace diesel use from ~255 Class 8 trucks/year, reducing transport-related emissions in surrounding communities.

4.5. Local Economic Impact

The Richmond facility represents a $75 million investment, with significant socioeconomic returns:

- 16 direct full-time jobs created
- More than 40 total jobs, including indirect employment from local suppliers and contractors
- ~$12.5 million in annual regional economic activity, with a 2.08x multiplier effect
- $21–32 million in annual taxable hydrogen sales, supporting circular economy growth

4.6. Energy Independence and System Resilience

Raven's system includes on-site power generation, meeting approximately 70% of its current electricity needs, with a target of 100% self-sufficiency in future projects. This:

- Reduces strain on the local electricity grid
- Increases resilience during energy supply disruptions
- Enhances reliability of regional hydrogen infrastructure

4.7. Cost of Delays

Raven SR has developed a proprietary, commercially ready hydrogen production platform that converts organic waste into high-purity hydrogen without combustion.

Every year of permitting delay results in:

- Continued pollution exposure for communities like Richmond
- Deferred climate gains, including GHG emission reductions
- Missed economic opportunities in clean job creation and regional investment

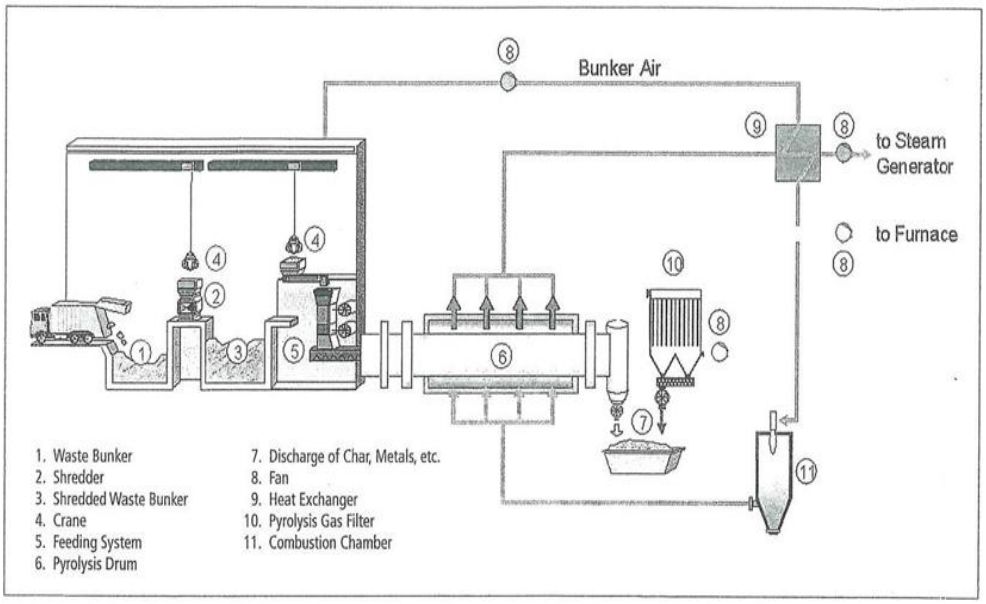
Timely policy reform and permitting efficiency are essential to unlock the full environmental and social value of Raven SR's clean hydrogen solution.

5. Integration of Pyrolysis and power generation[18]

PYROPLEQ is an advanced pyrolysis technology designed for the thermal treatment of municipal solid waste in the absence of oxygen. This process transforms waste into a high-calorific synthesis gas and a carbon-rich solid residue known as pyrolysis coke. Unlike conventional incineration, pyrolysis operates under reducing conditions, allowing for the efficient recovery of ferrous and non-ferrous metals while generating valuable energy carriers. The system employs a rotary kiln constructed with high-resistance austenitic steels, heated externally via flue gases in a muffle-type arrangement, ensuring optimal energy transfer. In the configuration described here, however, the resulting pyrolysis products are ultimately integrated with downstream combustion-based power generation. For that reason, PYROPLEQ is relevant to this report as a comparative or hybrid thermochemical pathway, but it is not equivalent to non-combustion hydrogen production routes such as electrolysis or Raven SR's Steam/CO_2 Reforming process. This section explores the key features, operational principles, and energy integration potential of the PYROPLEQ process.

[18] GIT VERLAG, Power Generation with Integrated Waste Pyrolysis, UTA International 02/98, S.104-106.

Pyrolysis Plant as an Upstream System for Conventional Power Plants



The PYROPLEQ process

Thermal treatment of waste by pyrolysis is carried out in the absence of oxygen. The products are a high- calorific gas and a coke-like residue known as "pyrolysis coke." The municipal solid waste is coarse shredded in a mechanical pretreatment stage and then charged into the pyrolysis kiln. Several tried and tested austenitic steels with high thermal and chemical resistance are available as materials of construction for the rotary kiln. The kiln designed according to the PLEQ technology is surrounded by a fixed heating muffle with separate heating chambers, which transmits the thermal energy of hot flue gases by radiation and convection to the waste inside the kiln. The pyrolysis reactor is designed such that the waste is heated to approx. 450-550 degrees and pyrolyzed in less than an hour. The resulting pyrolysis gas consists, besides the evaporated water, mainly of carbon monoxide, hydrogen and methane together with higher hydrocarbons.

MDEU`s PYROPLEQ process is characterized by the fact that the pyrolysis kiln at the rear end is equipped with a screening section which divides the solid pyrolysis residue into two fractions. The fine-particle coke, which has a carbon content of app. 25 to 30 % is discharged dry with exclusion of air. The screen oversize consists of metallic residues and coarse inert matter and is discharged wet through a water seal. The pyrolysis, which is operated under reducing conditions, enables the ferrous and non-ferrous metals and the inerts that are present in the waste to be recovered and recycled with high quality. No further solid residues are encountered in the pyrolysis plant.

Hot gas filtration using of ceramic filter cartridges ensures effective dedusting of the pyrolysis gas. A pulse injection system cleans the cartridges of adhering dust and/or particles of carbon.

A partial stream of the cleaned pyrolysis gas is burnt in a combustion chamber at a minimum of 1,200 degrees with a residence time sufficient to limit formation (de novo synthesis) of dioxins and furans. The hot gas from the combustion chamber heats the pyrolysis kiln from the outside. The cooled gases from the heating muffle around the kiln are pressure-regulated extracted.

Integration of pyrolysis and power generation

The conversion of the high calorific value pyrolysis products to energy is accomplished in the associated power plant.

The left-over pyrolysis gas which is not needed for heating the kiln is fed directly into the power plant furnace and co-combusted.

The screened, fine particle coke, the residue from the pyrolytic pre-treatment stage, has a calorific value of up to 11 GJ/t. This heat energy can also be used as well in the coal- fired power plant by mixing the pyrolysis coke with the fuel coal and burning it in the furnace.

Utilization of the waste heat of the hot gases cooled to approx. 600 degrees during heating of the pyrolysis kiln and preheating of the combustion air in the heat exchanger takes place in the power plant´s steam generator (boiler).

By linking the pyrolysis plant to a coal fired power plant and utilising the pyrolysis products in the power plant, the new installations are limited to

- The waste receiving and storage facilities (bunker)
- The rotary kiln system with the necessary heating equipment
- The resource recovery facility

The combustion unit, waste heat recovery, flue gas cleaning system and stack are jointly used by the power generation section.

The reduction in process equipment and machinery results in comparatively low capital investment and hence reduces the amount of capital to be serviced. Moreover, the labour, operating and maintenance costs for plants added upstream are lower in comparison with conventional waste incineration plants, so that operating cost are also reduced. Co-used of the power plant´s existing infrastructure is also visibly reducing costs.

Balances

A mass balance for pyrolysis of a waste with 25 % ash, 25 % water and a calorific value of 10 GJ/t gives the following results:

- Pyrolysis solid 30% wt. of which coarse fraction 12% wt., the fine fraction with a calorific value of approx. 9 .5 GJ/t 18 % wt.
- Pyrolysis gas with a calorific value of approx. 12.7 GJ/t 70 % wt.

About one third of the pyrolysis gas is burnt in order to supply, as hot gas, the 1.6 GJ/t of heat consumed in the pyrolysis process.

Hence the pyrolysis unit supplies the associated power plants with the following energy streams, in terms of the input of municipal waste:

- Pyrolysis coke: 1.7 GJ/t
- Pyrolysis gas (inclusive of sensible heat): 6.4 GJ/t
- Hot gas: 1.6 GJ/t

The difference versus the heat input of 10 GJ/t is approximately 3%. This represents the losses from cooling of the pyrolysis solids and the heat lost to the surroundings.

The energy content of the products obtained from pyrolysis of 1 t of municipal waste can be uses as input for power generation. It is equivalent to that of approx.0.3t of hard coal.

From the standpoint of this report, the significance of PYROPLEQ lies in its role as a hybrid waste-treatment and energy-recovery system. Pyrolysis occurs without oxygen in the reactor itself, but the energy valorisation of the resulting gas and coke depends materially on downstream combustion in an associated power plant. As such, PYROPLEQ may offer advantages in waste reduction, metals recovery, and partial substitution of fossil fuels, while remaining analytically distinct from hydrogen-focused non-combustion pathways whose principal outputs, emissions profile, and regulatory treatment differ fundamentally.

Composition of Waste Material:

Elementary analysis		
Heat Value H	**18100**	**KJ/kg**
Combustible		
C	42,4	weight %
H	4,7	weight %
O	10,6	weight %
N	0,7	weight %
S	0,8	weight %
Total of combustible	**59,2**	**weight %**
halogens		weight %
CI	1,62	weight %
F	0,08	weight %
Total halogens	**1,7**	**weight %**
ash		weight %
inert	16,05	weight %
Ferric-metals	7,2	weight %
non- ferric-metals	2,6	weight %
Total ash	**25,85**	weight %
humidity	**13,25**	weight %
Total	**100**	weight %

Pyrolysis coke composition:

VEW composition of waste mixture		
C-content	30,4	weight %
H content	0,8	weight %
S content	3,1	weight %
CI content	2,6	weight %
Fe content	6,4	weight %
NE content	5,9	weight %

Rest Inorganic	50,8	weight %
Total	100	weight %

Composition of Pyrolysis Gas:

Compound	Vol.%
CO	ca. 2,5
H2	ca. 3,5
CH4	ca. 9
C2H6	ca. 0,7
C2H4	ca. 3,5
C3H8	ca. 0,3
C3H8	ca. 1,1
∑ C4	ca. 0,3
∑ C5 and higher	ca. 12,9
CO2	ca. 2,5
H2 O	ca. 60,6
N2	ca. 1,1
H2S	ca. 0,3
HCl	ca. 1,5
HF	ca. 0,1
NH3	ca. 0,1
Total Sum	**100**

heat value H	Ca. 35000 KJ/Nm3
density	ca. 1,4 kg/Nm3
dust content	≤ 20 g/Nm3

With a varying waste composition, pyrolytic pre-treatment in an indirectly heated rotary kiln produces products of homogeneous quality. The higher energy conversion efficiency of coal fired power plants by comparison with conventional waste incineration plants consequently makes better use of the waste heat content. The substitution of fossil fuels by refuse-derived fuel which is converted to pyrolysis gas and coke conserves natural resources while at the same time effectively reducing the CO2 emissions.

6. Comparative Analysis of Policy Biases Towards Specific Non-Combustion Technologies (USA vs. EU)

Non-combustion technologies (NCTs) are critical to achieving deep decarbonization in industry and energy systems. These include renewable electricity generation methods, green hydrogen production via electrolysis, and alternative thermal and chemical conversion technologies such as pyrolysis, gasification, and plasma technologies. This section analyses the policy and regulatory frameworks

shaping the adoption of these technologies, highlighting key biases and strategic approaches in the USA and the European Union, with Spain as a key example within the EU context. In this report, "policy bias" does not imply improper favouritism, but rather the practical tendency of public frameworks to privilege certain technology pathways through definitions, incentives, certification rules, infrastructure assumptions, and public funding priorities.

6.1. Analysis of Biases in the USA[19]

6.1.1. Electrolysis

Bias Toward: Strong bias toward electrolysis, particularly for green hydrogen production. The Inflation Reduction Act (IRA, 2022) offers a 45V Clean Hydrogen Production Tax Credit (up to $3/kg for low-carbon hydrogen), making electrolysis projects financially attractive. The Department of Energy's (DOE) $7 billion Regional Clean Hydrogen Hubs program prioritizes electrolysis, with projects like ARCH2 and HyVelocity focusing on renewable-powered electrolyzers. DOE's H2@Scale initiative allocates significant R&D funding to improve electrolyzer efficiency, targeting cost reductions from $1,500/kW to $250/kW by 2030. This policy preference is reinforced by the structure of U.S. hydrogen incentives. Section 45V provides a production tax credit of up to $3/kg for qualifying clean hydrogen, with credit values tied to lifecycle emissions intensity, and the Bipartisan Infrastructure Law also provided $8 billion for Regional Clean Hydrogen Hubs together with dedicated support for electrolysis and electrolyser manufacturing. In practice, this has created a strong commercial and policy pull toward electrolysis-based hydrogen, especially where paired with renewable electricity. [DOE/Treasury/IRS]

Evidence: DOE strategy and program materials consistently position electrolysis as a central pathway for scaling clean hydrogen, particularly for industrial decarbonisation, grid integration, and transport applications. State-level measures in places such as California and New York have also supported hydrogen deployment through clean fuels policies, demonstration programs, and refuelling initiatives, although the strength of support varies by state. [DOE]

6.1.2. Pyrolysis

Bias Away: Limited policy focus on pyrolysis. While pyrolysis for bioenergy (e.g., biochar, bio-oil) is acknowledged in DOE's Bioenergy Technologies Office, funding is minimal compared to electrolysis. No specific federal tax credits or large-scale programs target pyrolysis. State-level policies (e.g., California's waste-to-energy incentives) provide some support, but these are fragmented and lack national coordination. Pyrolysis receives far less direct policy support than electrolysis in the United States. While thermochemical conversion pathways appear in research, bioenergy, and pilot-scale innovation programs, they do not benefit from a comparable flagship incentive architecture. There is no pyrolysis-specific federal production credit equivalent to 45V, nor a major national deployment program centred on methane pyrolysis or waste-based non-combustion reforming.

Evidence: As a result, pyrolysis remains more dependent on project-specific economics, state-level waste or low-carbon fuel policies, and niche industrial partnerships than on a clear federal scaling framework.

[19] Raven SR Inc and Raven SR Iberia, July 2025

6.1.3. Gasification

Bias Away: Moderate support but less prioritized than electrolysis. Gasification for syngas or hydrogen production is included in DOE's hydrogen hubs and ARPA-E programs, but funding is dwarfed by electrolysis allocations. The focus is often on fossil-based gasification with carbon capture rather than biomass or waste gasification, limiting its renewable NCTC role. State-level renewable portfolio standards (RPS) in some states (e.g., California) recognise gasification-derived fuels, but incentives are inconsistent. Gasification receives somewhat more policy recognition than pyrolysis, particularly where linked to syngas production, waste conversion, or carbon capture. However, it is still materially less favoured than electrolysis. In U.S. policy design, gasification is more often treated as a transitional or feedstock-specific conversion technology than as the preferred route for clean hydrogen deployment. Support is therefore more fragmented and frequently tied to broader carbon-management or waste-management frameworks rather than a dedicated hydrogen strategy.

Evidence: Where support exists, it has often been stronger for fossil-based or mixed-feed gasification coupled with CCS than for waste- or biomass-based routes positioned as renewable hydrogen pathways. This limits gasification's policy visibility within a green-hydrogen-centred narrative.

6.1.4. Plasma Technologies

Bias Away: Significant bias away from plasma technologies. These are considered emerging and high-risk, with minimal federal policy support. DOE's ARPA-E funds small-scale plasma tech R&D (e.g., plasma-assisted gasification), but no dedicated tax credits or deployment programs exist. Permitting challenges for novel technologies further hinder progress, as plasma facilities face lengthy environmental reviews. Plasma technologies face the greatest degree of policy distance among the pathways reviewed here. They are generally treated as emerging, capital-intensive, and relatively high-risk technologies, with support concentrated in early-stage R&D rather than commercial deployment. No major federal incentive framework specifically targets plasma-based hydrogen or waste-conversion pathways, and their novelty can also create additional permitting and bankability challenges.

Evidence: Accordingly, plasma remains at the margins of clean hydrogen policy in the United States, even where technically promising applications exist.

Overall USA Bias: The USA heavily favours electrolysis due to its alignment with green hydrogen goals and established technology readiness. Pyrolysis, gasification, and plasma technologies are underfunded and lack targeted policies, reflecting a bias toward immediate, scalable solutions (electrolysis) over less mature or complex technologies. Overall, the United States policy landscape shows a clear structural preference for electrolysis as the flagship clean hydrogen pathway. This preference is driven not only by technology readiness, but by the interaction of tax credits, hub investments, manufacturing incentives, and national strategy documents that consistently frame electrolysis as central to hydrogen scale-up. Other non-combustion or thermochemical pathways are not excluded, but they receive less direct support, weaker market signalling, and far fewer dedicated deployment mechanisms. [DOE/Treasury/IRS]

6.2. Analysis of Biases in the EU (with Spain Highlights)

The EU's approach to supporting non-combustion technologies is influenced by its overarching climate targets (Fit for 55, climate neutrality by 2050) and specific strategies like the Hydrogen Strategy and Circular Economy Action Plan. In practice, the EU framework tends to favour technologies that align most clearly with the regulatory category of renewable hydrogen, the expansion of renewable electricity, and the creation of an integrated hydrogen market. This creates a strong structural preference for electrolysis, while other non-combustion or thermochemical pathways receive more limited or indirect support through waste, circular-economy, innovation, or industrial decarbonisation instruments. [European Commission]

6.2.1. Electrolysis (Green Hydrogen Production)

Bias Toward: Strong bias toward electrolysis, driven by the EU's Hydrogen Strategy (2020) and REPowerEU (2022), which aim for large-scale renewable hydrogen deployment, including a target of 10 million tonnes of domestic renewable hydrogen production and 10 million tonnes of imports by 2030. [European Commission]

Evidence: Electrolysis sits at the centre of EU hydrogen policy because it fits most directly within the Union's definition of renewable hydrogen, grid-integration strategy, and industrial decarbonisation agenda. The EU's hydrogen framework, Innovation Fund support, IPCEIs, and Horizon Europe programs have all contributed to making electrolysis the flagship pathway for hydrogen scale-up. [European Commission]

Spain's Role: Spain's National Energy and Climate Plan (NECP) targets an ambitious 12 GW of electrolyzers by 2030, supported by €1.5 billion from the PERTE program, facilitating projects like Iberdrola's 100 MW electrolyzer in Puertollano. Spain's 2023 auctions included specific targets for electrolysis-derived hydrogen, reinforcing its leadership in this domain within the EU.

6.2.2. Pyrolysis

Bias Toward (Limited / Conditional): Pyrolysis receives some support in the EU, particularly where it is linked to waste treatment, bioenergy, biochar, or circular-economy objectives. However, this support is generally not equivalent to the direct policy preference given to electrolysis within the renewable hydrogen framework. In many cases, pyrolysis is treated primarily as a waste-management or resource-recovery pathway rather than as a preferred hydrogen-production route.

Evidence: EU policy instruments such as the Circular Economy Action Plan and related waste legislation create space for pyrolysis-based approaches, but they do not establish pyrolysis as a flagship hydrogen pathway. Support therefore tends to be more fragmented, project-based, and dependent on regional or thematic funding calls.

6.2.3. Gasification

Bias Toward (Limited / Moderate): Gasification is supported for waste-to-energy and syngas production under the EU's Renewable Energy Directive (RED EU/2023/2413) and related decarbonisation and circular-economy frameworks. Spain's waste-to-energy programs and NECP include gasification for bioenergy, with projects like the Valdemingómez waste-to-energy plant. EU funding (e.g., Horizon Europe) supports gasification R&D, but it remains secondary to electrolysis in the EU's renewable hydrogen narrative.

Evidence: Gasification retains a meaningful role where biomass, waste valorisation, or syngas production are at issue, but it does not enjoy the same clarity of regulatory preference, political signalling, or market design support as electrolysis. Its position is therefore stronger than that of plasma technologies, but weaker than that of electrolytic hydrogen.

6.2.4. Plasma Technologies

Bias Away: Significant bias away from plasma technologies due to their high cost and early-stage development. The EU's Innovation Fund supports pilot projects (e.g., plasma gasification for waste processing), but funding is minimal compared to electrolysis or gasification. Spain has no specific plasma tech policies, and permitting for novel technologies remains complex across the EU.

Evidence: Plasma pathways remain largely confined to R&D, pilot, or demonstration contexts. Their limited commercial maturity, higher capital intensity, and more complex permitting profile have kept them at the margins of EU hydrogen and industrial decarbonisation policy.

Overall EU Bias: The EU strongly favours electrolysis to meet green hydrogen targets, with Spain leading in deployment. Pyrolysis and gasification receive moderate support due to waste-to-energy and bioenergy goals, but plasma technologies are largely neglected due to technological immaturity and high costs. Overall, the EU framework shows a pronounced structural preference for electrolysis because it aligns most directly with renewable hydrogen definitions, guarantees of origin, market integration, and the scale-up logic of REPowerEU. Pyrolysis and gasification are not excluded and may receive support where they contribute to waste valorisation, circularity, or industrial decarbonisation, but they remain secondary in the policy hierarchy. Plasma technologies, by contrast, remain peripheral because of their lower maturity, higher cost, and weaker fit with current deployment-oriented policy instruments. Spain reflects this broader EU pattern, although its policy context also leaves room for waste-based and biomass-linked hydrogen pathways within a wider renewable and circular-economy framework. [European Commission; MITERD]

6.3. Comparison of Biases: USA vs. EU

Common Bias Toward Electrolysis: Both the USA and EU prioritize electrolysis due to its role in green hydrogen production, which aligns with decarbonization goals for industry, transport, and power. The USA's 45V tax credit and EU's REPowerEU funding reflect this focus, with Spain's ambitious electrolyzer targets reinforcing the trend.

- Divergent Bias on Pyrolysis and Gasification:
- USA: Both pyrolysis and gasification are underfunded and lack targeted policies, reflecting a bias away due to their complexity and lower technology readiness compared to electrolysis.
- EU: Moderate bias toward pyrolysis and gasification, driven by circular economy and waste-to-energy priorities. Spain's bioenergy focus gives these technologies more support than in the USA, though still secondary to electrolysis.
- Shared Bias Away from Plasma Technologies: Both regions show a strong bias away from plasma technologies, which are seen as high-risk and costly. The USA and EU allocate minimal R&D funding, with no significant deployment programs or regulatory support.
- Influence of Policy Structure:

- USA: Decentralized policies lead to uneven support, with electrolysis benefiting from federal incentives (IRA, DOE) while pyrolysis, gasification, and plasma tech rely on limited state or pilot funding.
- EU: Centralized EU policies and Spain's NECP provide a more balanced approach, supporting pyrolysis and gasification alongside electrolysis, though plasma tech remains neglected.

Overall, the comparison suggests that both jurisdictions privilege electrolysis, but for somewhat different institutional reasons. In the United States, the bias is driven heavily by tax-credit architecture, hub funding, and commercialization logic. In the European Union, it is reinforced by the regulatory construction of renewable hydrogen, integrated market-building, and the alignment of electrolysis with broader electricity-system decarbonisation goals. This means that thermochemical and waste-based non-combustion pathways are not necessarily excluded, but they must compete within policy environments that were not primarily designed around their characteristics. [DOE; European Commission]

6.3.1. Summary Table of Apparent Policy Biases

Technology	USA Bias	EU Bias
Electrolysis	Strongly Toward: Dominant focus due to 45V tax credit, DOE's multi-billion-dollar hydrogen hubs, and state hydrogen programs. Electrolysis is the clearest beneficiary of current U.S. hydrogen incentive design and commercialization policy.	Strongly Toward: Core of the EU's Hydrogen Strategy and REPowerEU, supported through renewable hydrogen market-building, Innovation Fund mechanisms, IPCEIs, and national strategies. Spain's hydrogen roadmap and related support measures reinforce this trend.
Pyrolysis	Away: Minimal federal support relative to electrolysis. Limited state-level incentives (e.g., CA waste-to-energy) and no comparable federal flagship deployment framework.	Limited / Conditional Toward: Supported by circular-economy, waste-management, and bioenergy frameworks, but not treated as a flagship renewable hydrogen pathway.
Gasification	Away: Moderate DOE support in some waste, syngas, and carbon-management contexts, but materially less favoured than electrolysis and often focused on fossil-based gasification or CCS-linked applications.	Limited / Moderate Toward: Backed by waste-to-energy, RED, and industrial decarbonisation frameworks, but still secondary to electrolysis in the EU hydrogen hierarchy.
Plasma Technologies	Strongly Away: Largely confined to R&D and pilot-stage support; no deployment programs or tax credits. Permitting challenges hinder progress.	Strongly Away: Mostly limited to pilot or innovation-stage support; no specific policies in Spain and weak fit with current deployment-oriented EU instruments.

6.3.2. Key Observations from the Comparison:

- **Electrolysis Dominance:** Both regions prioritize electrolysis due to its maturity, scalability, and alignment with hydrogen economy goals. The USA's tax-driven approach and the EU's strategic funding (with Spain playing a prominent role) reflect this bias.
- **EU's Broader Support:** The EU, particularly Spain, shows a more permissive and diversified approach by supporting pyrolysis and gasification for waste-to-energy and bioenergy, driven by circular economy goals. The USA's focus is narrower, sidelining these technologies.
- **Plasma Tech Neglect:** Both regions exhibit a strong bias away from plasma technologies due to high costs, technical complexity, and low market readiness, limiting support to small scale R&D.
- **Implications for NEC Report:** Highlight the EU's (and Spain's) more inclusive NCTC framework as a model for balanced technology support, while noting the USA's electrolysis focus as a strength but a limitation for pyrolysis, gasification, and plasma tech development.

While both the United States and European Union prioritise electrolysis, the EU framework, and especially Spain's policy context, demonstrate a more inclusive approach to non-combustion technology support. This multidimensional framework, integrating circular economy goals, industrial decarbonisation, and regional cohesion, may offer more resilience in achieving net-zero transitions.

However, to fully unlock innovation, both regions must increase support for emerging technologies like methane pyrolysis, waste gasification, and plasma processes, ensuring diversification of the hydrogen economy and minimising policy lock-in. At the same time, policy frameworks should distinguish more carefully between thermochemical pathways that depend on downstream combustion and those, such as Steam/CO_2 Reforming, that are designed as genuinely non-combustion hydrogen routes.

7. Green Hydrogen: High Impact in the Reduction of GHG Emissions

7.1. Introduction to Green Hydrogen and its Role in Decarbonisation

Green hydrogen is produced by splitting water (H_2O) into hydrogen (H_2) and oxygen (O_2) through electrolysis powered by renewable electricity. Because the process avoids fossil-based combustion, it offers a low-emission route to producing a versatile energy carrier and industrial feedstock. Green hydrogen can decarbonise refining and ammonia production by replacing grey hydrogen, support low-carbon steelmaking by serving as a reductant in place of coal, and provide high-temperature energy for heavy-duty transport modes, including trucks, buses, and potentially rail, shipping, and aviation where battery-based solutions may be constrained by weight, range, or duty cycle. It can also store surplus renewable electricity over longer durations, helping balance variable power systems, and can support dispatchable electricity generation through fuel cells or hydrogen-capable turbines during periods of low renewable output. At the same time, the actual climate benefit of green hydrogen depends on several factors, including the carbon intensity of the electricity used, electrolyser efficiency, water availability, and whether hydrogen is being applied in sectors where it offers a genuine advantage over direct electrification.

7.2. Steam/CO2 Reforming: Clean Hydrogen Production from Waste

Raven SR's Steam/CO_2 Reforming technology offers a **clean, distributed, non-combustion pathway** for hydrogen production that overcomes the permitting, resource, and infrastructure limitations of

electrolysis and combustion-based alternatives. Within the context of this report, it is important to distinguish Steam/CO_2 Reforming from both conventional gasification and pyrolysis-based systems. While those pathways may share certain thermochemical characteristics, Raven's process is designed as a non-combustion hydrogen route in which steam and CO_2 are actively used to reform carbonaceous feedstocks into hydrogen-rich syngas, rather than relying on oxidation, incineration, or downstream combustion as the primary basis of conversion.

Its integration into the EU's Hy2Market initiative would:

- Reduce emissions and waste,
- Enhance local energy resilience,
- Support regional development through circular resource utilization,
- Provide a modular pathway for regions where water, grid capacity, land availability, or permitting conditions may constrain electrolytic deployment.

By transforming waste into green fuel with a minimal footprint, Raven SR provides a compelling, near-term solution for Europe's decentralized hydrogen economy.

Strategic Fit for the Hy2Market Programme

The **Hy2Market Programme** emphasizes distributed hydrogen generation, circular economy principles, and territorial equity. Raven SR's technology directly supports these goals through:

- **Localized Deployment**: Systems can be installed at or near the point of waste generation, minimizing logistics and emissions.
- **Circular Resource Use**: Converts waste into usable hydrogen and biochar, directly supporting bioeconomy objectives.
- **Water Conservation**: Critical in drought-sensitive regions across Southern and Western Europe.
- **Grid Resilience**: Raven can self-generate electricity from waste-derived syngas using a secondary SR-1 unit, **increasing system autonomy** and **reducing pressure on regional grids**.
- **Exportable Model**: Technology is suited for underdeveloped areas lacking clean water or electricity infrastructure but with biomass availability.
- **Site Flexibility**: The modular architecture is better suited to phased deployment and regional scale-up than many large, infrastructure-intensive alternatives.

Non-Combustion Technologies for Emission Reduction

Raven SR's proprietary Steam/CO_2 Reforming (SCO_2R) technology distinguishes itself by avoiding combustion entirely, leveraging a three-pronged approach:

- **Stoichiometry Control:** By carefully managing feedstock composition, Raven optimizes the ratio of steam and CO_2 to hydrocarbons, ensuring complete conversion of organic matter to syngas.
- **Thermodynamically Favoured Reactions:** The process capitalizes on high-temperature, endothermic reforming reactions, driving the complete breakdown of hydrocarbons without the need for combustion or catalyst-based pathways.

- **Reactor Design and Residence Time:** Unlike catalytic systems prone to carbon deposition and deactivation, the reactor design focuses on extended residence times and optimized flow patterns to achieve maximum conversion efficiency. This approach minimizes tar formation and carbon buildup while maintaining consistent syngas output.
- **Process Robustness**: By avoiding dependence on catalyst activity, the system is designed to reduce fouling sensitivity, simplify operations across variable feedstocks, and improve long-term maintainability.

7.2.1. Technological Challenges and Opportunities in Steam/CO_2 Reforming (from Waste)

Steam CO_2 reforming presents unique challenges in terms of maintaining reaction kinetics and preventing carbon buildup. Raven SR addresses these challenges through a process that eschews traditional catalysts and instead employs:

- Precise Stoichiometric Balancing
- Extended Residence Time
- High-Temperature Operation
- Scalability and Feedstock Flexibility
- Modular equipment design that supports phased validation and commercial replication

In response to emissions regulations, permitting delays, and public opposition to combustion-based systems, several non-combustion pathways have emerged for low-carbon hydrogen production. These include:

- **Pyrolysis** – Operates without oxygen yet produces limited syngas and high carbon black; requires sorting and remains difficult to permit in many regions.
- **Plasma Arc** – Uses high temperatures to break down materials, with potentially low emissions but extremely high energy input and cost.
- **Hydrothermal Liquefaction** – Suitable for wet biomass; commercially immature and capital-intensive.
- **Steam/CO_2 Reforming (SCO_2R)** – Raven SR's proprietary method, which reforms carbon-based waste using injected steam and CO_2 at high temperatures, producing clean, hydrogen-rich syngas *without combustion, catalysts, or oxygen*.

Raven SR's Steam/CO_2 process is distinct due to[20]:

- No oxidation or combustion reactions
- High hydrogen yield with minimal feedstock preprocessing
- Production of small quantities of biochar (a soil amendment)
- Compatibility with strict environmental and air quality regulations
- Ability to address waste-management and hydrogen-production objectives within the same system boundary

[20] *Comparing Thermal Conversion Technologies*, Raven SR, Jan 2024

Technical Basis and Innovations in Steam/CO_2 Reforming

Raven SR's process avoids the conventional pitfalls of high-temperature waste conversion systems through the following core principles:

- **Stoichiometry Control**: Optimal balancing of hydrocarbon feedstock, steam, and CO_2 ensures full conversion to syngas without soot or incomplete reactions.
- **Thermodynamically Favoured Reactions**: High-temperature, endothermic reactions (e.g., CH_4 + CO_2 → syngas) allow full reforming without catalysts or combustion, reducing emissions and maintenance.
- **Reactor Design and Residence Time**: By engineering for extended residence times in a rotary kiln (rather than catalytic beds), Raven achieves higher conversion efficiency with minimal carbon deposition or tar formation.

This combination is important because it allows the process to be evaluated not merely as a hydrogen-production route, but as a systems-level decarbonisation tool that can integrate waste conversion, hydrogen output, lower local air-pollutant risk, and site-level resilience.

Technological Challenges and Raven's Mitigation Strategies

Known challenges for Steam/CO_2 Reforming include:

- Feedstock heterogeneity and energy density
- Reaction stability and thermal load
- Regulatory misclassification as combustion
- The need to demonstrate clear differentiation from pyrolysis, gasification, and other thermochemical routes in policy and permitting contexts

Raven SR addresses these via:

- A robust rotary kiln system, improving thermal distribution and processing capacity
- Absence of catalysts eliminating deactivation or fouling concerns
- Successful clarification with regulatory agencies (e.g., California PRC §40106) that its process is non-combustion and distinct from incineration
- Modular systems scalable from pilot to commercial scale without major design changes
- A process architecture that is intended to preserve technical performance while reducing dependence on highly constrained external resources such as ultrapure water, large grid interconnection, or extensive pretreatment infrastructure

7.3. Electrolysis: Clean Hydrogen Production from Water

Electrolysis uses electricity to split water (H_2O) into hydrogen (H_2) and oxygen (O_2). When powered by renewable electricity (solar, wind, hydro, nuclear), it produces "green hydrogen," with virtually zero greenhouse gas emissions, and is truly a non-combustion process.

7.3.1. Context in Europe: Dominance of Renewable Hydrogen Production through Electrolysis

In Europe, renewable hydrogen production via water electrolysis is rapidly becoming a central pillar of the continent's decarbonisation strategy. Electrolysis offers a non-combustion method of generating hydrogen, which, when powered by renewable electricity, produces zero direct greenhouse gas (GHG) emissions. This positions it as a critical technology for achieving the EU's climate goals under the European Green Deal and the Fit for 55 legislative packages.

The European Union aims to produce 10 million tonnes of renewable hydrogen domestically and import an additional 10 million tonnes by 2030. These targets are part of the REPowerEU Plan[21], designed to both accelerate the green transition and reduce reliance on Russian fossil fuels. Electrolytic hydrogen, also known as green hydrogen, is key to decarbonising "hard-to-abate" sectors such as steelmaking, fertiliser production, cement, and long-distance transport, where direct electrification is challenging or inefficient.

By the end of 2023, Europe had an installed electrolyser capacity of approximately 0.9 GW, with over 100 GW in the project pipeline for 2030, according to the IEA and Hydrogen Europe.

European manufacturers such as Nel Hydrogen (Norway), Siemens Energy (Germany), and ITM Power (UK) are scaling up gigawatt-scale electrolyser production facilities to meet demand.

The EU's Important Projects of Common European Interest (IPCEI) schemes have mobilised billions of euros to fund large-scale green hydrogen infrastructure across member states, including electrolysis-based industrial hubs in Germany, the Netherlands, Spain, and Portugal.

This policy dominance is highly relevant to the present report. Electrolysis is rightly treated as a central non-combustion pathway, yet its prominence in EU strategy can also narrow the field of comparison if other qualifying non-combustion routes are assessed only as secondary exceptions rather than as potentially valuable complements in specific regional contexts. In regions where land, water, grid capacity, or permitting timelines constrain electrolyser deployment, alternative non-combustion pathways may offer practical advantages that should be evaluated on their own technical, environmental, and system-level merits.

7.4. The Role of Green Hydrogen in Achieving Net Zero Goals in Europe

Green hydrogen has emerged as a central pillar in Europe's path toward climate neutrality. It is widely acknowledged as an essential solution for decarbonizing sectors where emissions are hardest to eliminate and alternatives are scarce, such as heavy industry, maritime shipping, and aviation. The recent global energy crisis has further accelerated interest in green hydrogen, emphasizing its strategic value in reinforcing Europe's energy security while reducing dependency on fossil fuels (IEA, 2024)[22].

In recognition of this potential, the European Union has taken decisive steps to support the large-scale deployment of green hydrogen. Central to this effort is the regulatory framework introduced under the *Fit for 55* package, which builds upon the EU Hydrogen Strategy. The revised Renewable Energy Directive, effective since 2023, sets legally binding targets for the use of renewable hydrogen in key

[21] European Commission (2022) *REPowerEU Plan*. Brussels: European Commission. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52022DC0230

[22] *SciencesPo* (2025, March 4). *The new European Commission and how it sees the role of renewable hydrogen*. European Chair for Sustainable Development and Climate Transition, Sciences Po. https://www.sciencespo.fr/psia/chair-sustainable-development/2025/03/04/the-new-european-commission-and-how-it-sees-the-role-of-renewable-hydrogen/

sectors like industry and transport by 2030. Complementing this, the Hydrogen and Decarbonised Gas Market Package implemented in 2024, lays the foundation for a dedicated hydrogen infrastructure and a competitive internal market for hydrogen.

Moreover, the *REPowerEU* plan, introduced in 2022, establishes ambitious targets to produce and import 10 million tonnes of renewable hydrogen each by 2030. Looking further ahead, the EU envisions that green hydrogen could supply approximately 10% of its total energy demand by 2050. Two delegated acts, adopted in 2023 and 2024, provide legal clarity by defining what qualifies as renewable hydrogen and setting out methodologies for calculating life-cycle greenhouse gas emissions from renewable hydrogen and recycled carbon fuels (European Commission, 2025b). To further accelerate investment, the EU established the European Hydrogen Bank in 2022, designed to reduce financial risks and foster global business opportunities for green hydrogen projects.

Despite these forward-looking initiatives, several challenges remain. One of the most significant is the need to develop supply, demand, and infrastructure in parallel, which is an inherently complex task (Schlund et al., 2022). Scaling up green hydrogen production is still technically and economically demanding, leading some experts to advocate for a more inclusive approach that temporarily accommodates other low-emission hydrogen types, such as blue or turquoise hydrogen, to meet interim decarbonization targets (Talus et al., 2024). In addition, the dominance of electrolysis within current policy design can narrow the comparative field if other non-combustion pathways are treated as peripheral rather than assessed according to their actual regional, environmental, and system-level merits.

Another major obstacle is the uncertainty surrounding the future price of green hydrogen. This uncertainty stems from fluctuating variables, including the availability and cost of renewable electricity, grid carbon intensity, and the pace of innovation in hydrogen technologies (Brandt et al., 2024). Moreover, green hydrogen must compete with direct electrification, particularly in the transport sector, which raises further questions about the future size of the hydrogen market and its long-term viability. These uncertainties reinforce the importance of evaluating hydrogen pathways not only in terms of theoretical decarbonisation potential, but also in terms of infrastructure requirements, resource constraints, permitting conditions, and regional deployment practicality.

7.5. Comparative Greenhouse Gas Emissions in Hydrogen Production

Hydrogen production in 2023 was a significant source of global carbon dioxide emissions, contributing approximately 920 million tonnes of CO_2. The majority of this hydrogen, close to two-thirds, was generated from unabated natural gas, a process that typically emits between 10 and 12 kilograms of CO_2 equivalent (CO_2-eq) for every kilogram of hydrogen produced. An additional 20% of global hydrogen output relied on unabated coal, which is even more carbon-intensive, releasing approximately 22 to 26 kg CO_2-eq/kg H_2[23].

The bulk of these emissions, between 75% and 95%, occur at the site of hydrogen production. Technologies such as carbon capture, utilisation and storage (CCUS) offer potential reductions at this stage. In the case of steam methane reforming, typical abatement costs range from USD 60–85 per tonne of CO_2 for modest capture rates (around 55–70%), rising to USD 85–110 per tonne for higher

[23] **International Energy Agency (IEA)**. (2024). *Global Hydrogen Review 2024*. Paris : IEA. https://www.iea.org/reports/global-hydrogen-review-2024

capture rates exceeding 90%. Nevertheless, addressing point-source emissions alone is insufficient; it is also essential to tackle upstream and midstream emissions throughout the supply chain.

By contrast, hydrogen produced via electrolysis, especially when powered by renewable electricity, results in no direct emissions during the production phase. However, the carbon intensity of the electricity source becomes critical. To outperform steam methane reforming in terms of emissions, the electricity used should emit no more than 200–240 grams of CO_2 per kilowatt-hour (g CO_2/kWh). While renewables are generally emission-free during operation, embedded emissions from their manufacturing and construction can contribute an additional 0.4 to 2.7 kg CO_2-eq per kilogram of hydrogen, although these are not always accounted for in current certification schemes.

Energy losses associated with converting hydrogen into transportable forms are also considerable, typically ranging from 45% to 70%. This means that the carbon footprint of the electricity used to power electrolysers can effectively double or triple by the time the hydrogen is delivered and utilised. The lowest lifecycle emissions are associated with hydrogen converted to liquid form due to its higher overall efficiency, followed by ammonia and liquid organic hydrogen carriers (LOHCs).

In the case of synthetic fuels derived from hydrogen and carbon, the emission benefits are maximised when the carbon source is biogenic or captured directly from the atmosphere. To ensure a lower carbon footprint than conventional fossil fuels, electricity used in the production of synthetic methanol should have an emissions intensity below 160–190 g CO_2-eq/kWh, and even lower thresholds apply to synthetic methane and kerosene, at around 95–140 g CO_2-eq/kWh. Additionally, the method of allocating CO_2 emissions across various stages of fuel production and transport significantly influences the final emissions attributed to each product. These comparisons are important for the present report because they show that the climate value of hydrogen depends not only on whether a pathway is labelled “green” or “low-carbon,” but on the full system boundary, including energy inputs, feedstock origin, transport form, upstream emissions, and the final use case. In this respect, non-combustion waste-based pathways should be assessed on a lifecycle basis alongside electrolysis, rather than excluded simply because they do not fit the dominant policy shorthand currently associated with renewable hydrogen.

7.5.1. Preliminary RED II and GREET-Based Perspective on Biomass-to-Hydrogen

Preliminary lifecycle work conducted for Raven SR under RED II- and GREET-based frameworks suggests that non-combustion biomass-to-hydrogen pathways may deliver substantially greater GHG reductions than are commonly assumed in hydrogen policy discussions centred only on electrolysis. In Raven’s case, the climate benefit is not limited to the carbon intensity of hydrogen production itself. It also derives from the avoidance of emissions associated with landfilling or other lower-value waste-management outcomes, especially where biogenic waste streams would otherwise generate methane or require additional transport and handling.

This is important because it points to a double-impact pathway. First, the process can generate low-carbon hydrogen from biogenic or waste-derived feedstocks through a non-combustion route. Second, it can reduce short-lived climate pollutants and related waste-sector emissions by diverting methane-generating biomass away from landfill or similar disposal pathways. In practical terms, this means that biomass-to-hydrogen should not be evaluated only as an alternative hydrogen production technology, but also as a waste-management and methane-mitigation strategy with additional system-level

climate value. This broader framing is especially relevant in jurisdictions where landfill methane reduction is itself a major climate-policy objective.

A preliminary RED II assessment prepared for Raven's earlier Richmond S1 design basis estimated a well-to-wheels carbon intensity of 11.37 g CO_2e/MJ, compared with the RED II fossil comparator of 94.00 g CO_2e/MJ, corresponding to an 88% reduction. That analysis reflects an earlier project configuration and should therefore be treated as indicative rather than final. Nevertheless, it provides an important directional signal regarding the magnitude of potential lifecycle benefit. In particular, it shows that, even on an earlier design basis, the pathway appears capable of materially outperforming the RED II fossil comparator.

Complementary GREET- and LCFS-based work on an earlier municipal solid waste-to-hydrogen design pathway points in the same direction. In that case, the total well-to-tank carbon intensity was calculated at 2.60 gCO_2e/MJ after accounting for avoided landfill emissions and biochar-related carbon retention. The same body of work explicitly notes that the hydrogen pathway's carbon intensity would be higher if feedstocks without methane-avoidance value were used, underscoring the importance of feedstock selection and counterfactual waste fate in lifecycle analysis. Because this analysis was conducted on a different design basis and under a different methodological framework, it should likewise be treated as supportive and directional rather than directly interchangeable with the RED II result.

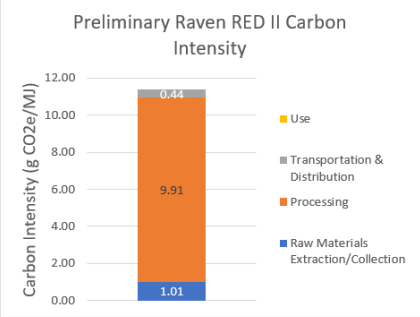
Preliminary 45V scoping work prepared for Raven likewise indicates that the lifecycle performance of the pathway depends materially on boundary assumptions, including treatment of landfill gas, direct process emissions, electricity inputs, and potential biochar credit. This reinforces the broader point of this report: the climate value of hydrogen pathways cannot be judged adequately by technology label alone. It must be assessed across the full system boundary, including biogenic feedstock origin, avoided emissions, short-lived climate pollutants, co-products, and end use. The 45V scoping also underscores that methodological treatment of biogenic CO_2, methane, landfill-gas counterfactuals, and co-product handling can materially affect the final carbon-intensity result.

For that reason, a fuller RED/GREET comparison should be developed in a subsequent version of this report using the Aragón-relevant design basis and updated assumptions. Even at this preliminary stage, however, the available analyses are sufficient to show that biomass-to-hydrogen can provide a broader emissions-reduction benefit than frameworks focused solely on renewable electricity inputs may capture. A project-specific Aragón update would allow this report to move from indicative comparative evidence to a more robust regional assessment aligned with the actual intended deployment case.

This broader climate value is especially relevant in regions where methane reduction from organic waste diversion is itself a policy priority, since the pathway may contribute simultaneously to hydrogen decarbonisation, landfill avoidance, and short-lived climate pollutant reduction. This is particularly relevant where policy frameworks seek not only lower-carbon fuels, but also reduced landfill dependence, lower methane emissions, and improved circular use of biogenic resources.

Functional REDII Reporting Unit
MJ

REDII Life Cycle Stages	Unit Process	Carbon Intensity (g CO_2e/MJ)	
		Raven Fuel Pathway	REDII Fossil Fuel Benchmark[1]
Raw Materials Extraction/Collection	Raw Materials Extraction/Collection	1.01	--
Processing	Processing	9.91	
Transportation & Distribution	Transportation & Distribution	0.44	
Use	Use	0.00	
Well-to-Wheels		**11.37**	**94.00**
Difference in Carbon Intensity Between Raven and RED II Benchmark		**82.63**	
Percent Emission Reduction		**88%**	



The results from preliminary analysis of Raven's waste steam/CO2 reforming technology for hydrogen production show a significant reduction in emissions compared to the RED II benchmark. Raven's process uses only biogenic organic waste, which significantly reduces emissions as RED II does not consider biogenic CO2 emissions from fuel production and combustion. The Raven process also generates electricity through internal generation by combustion of biogenic landfill gas.

Notes:

[1] The RED II benchmark is sourced from RED II legislation, Annex VI, Section 19. It represents the fossil fuel comparator value for biomass fuels used as transport fuels. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv:OJ.L_.2018.328.01.0082.01.ENG. Accessed 2023.

Preliminary RED II lifecycle comparison for Raven's biomass-to-hydrogen pathway versus the RED II fossil comparator. The analysis reflects an earlier Richmond S1 design basis and is included here as indicative evidence of lifecycle reduction potential, not as a final certified pathway result.

8. Policy and Regulatory Frameworks for Non-Combustion Technologies[24]

The successful deployment of non-combustion technologies hinges not only on technical readiness but also on robust policy frameworks, aligned regulation, financial incentives, and cross-border cooperation. Public authorities play a central role in derisking investment and creating the enabling environment for industrial transformation. At the same time, regulatory frameworks do not support all non-combustion pathways equally. In practice, definitions of renewable hydrogen, certification rules, infrastructure assumptions, and public funding mechanisms often favour some pathways more clearly than others.

8.1. European Union (EU)

The role of green and low-carbon hydrogen is gaining unprecedented importance in the global energy transition. As of mid-2025, over 55 countries have enacted or announced policies specific to renewable hydrogen, including 14 launched between 2024 and 2025.

The European Union has taken a leading position in legislating for the hydrogen economy and non-combustion innovation. Key instruments include:

- **REPowerEU Plan (2022):** In response to energy security and climate goals, REPowerEU sets targets of producing 10 million tonnes of renewable hydrogen domestically and importing an additional 10 million tonnes by 2030. It prioritises infrastructure development and industrial use cases[25].
- **EU Hydrogen Bank (launched 2023):** A financing mechanism allocating €3 billion to support early-stage green hydrogen projects through competitive bidding (auctions) to reduce offtake risk and narrow the cost gap with fossil alternatives[26].

[24] European Commission – Hydrogen strategy for a climate-neutral Europe (2020). Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020DC0301
[25] REPowerEU Plan: https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal/repowereu_en
[26] EU Hydrogen Bank (DG CLIMA): https://climate.ec.europa.eu/eu-action/european-hydrogen-bank_en

- **Important Projects of Common European Interest (IPCEI Hy2Use and Hy2Tech):** Funding mechanisms facilitating cross-border infrastructure for hydrogen generation, storage, and end-use integration.
- **Carbon Border Adjustment Mechanism (CBAM):** Introduced as a tool to prevent carbon leakage and ensure a level playing field for green industrial production within the EU.
- **EU Emissions Trading System (EU ETS):** Strengthened under the "Fit for 55" package, the ETS incentivises the transition by pricing emissions, especially in sectors like steel, cement, and chemicals[27].
- **RED III Directive (2023):** Mandates binding sub-targets for renewable hydrogen in industry (42%) and transport (1% of energy supply) by 2030[28].

Taken together, these instruments create a strong enabling framework for electrolysis-based renewable hydrogen, while support for other non-combustion pathways is often more indirect, conditional, or linked to separate policy domains such as waste, circularity, or industrial innovation.

Notable Member State Strategies:

- **Spain:** National Hydrogen Roadmap (2020) with €8.9 billion allocated to green hydrogen. Projects like "Valle del Hidrógeno Verde" in Murcia and the "Hydrogen Corridor" in the Ebro Valley are models of integrated industrial hydrogen ecosystems[29].
- **Germany:** National Hydrogen Strategy updated in 2023, doubling its electrolysis capacity target to 10 GW by 2030, with €20 billion in funding. Germany also leads in SOEC development and retrofitting gas infrastructure for hydrogen.
- **Netherlands & France:** Strong focus on offshore wind-to-hydrogen and port-based ammonia terminals (e.g., Rotterdam and Le Havre).

For the purposes of this report, the key point is that the EU framework is advanced and comparatively broad, yet still structurally centred on electrolysis. Alternative non-combustion pathways may fit within this framework, but they typically do so less directly and often through narrower entry points.

8.2. United States

The U.S. strategy is investment-driven, structured around three legislative pillars:

- **Inflation Reduction Act (IRA, 2022):** Provides up to $3/kg of clean hydrogen tax credits depending on carbon intensity (45V section)[30].
- **Infrastructure Investment and Jobs Act (2021):** Invests $9.5 billion in hydrogen infrastructure and electrolyser cost reduction.
- **Regional Clean Hydrogen Hubs (H2Hubs):** Eight hubs awarded in 2023 to pilot technologies including SMR+CCS, biomass-to-hydrogen, and electrolysis[31].

Challenges include:

[27] Carbon Border Adjustment Mechanism (CBAM): https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32023R0956
[28] Renewable Energy Directive (RED III – 2023): https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32023L2413
[29] Spain's Hydrogen Roadmap (2020): https://energia.gob.es/en-us/Participacion/Paginas/DetalleParticipacionPublica.aspx?k=343
[30] US Department of Treasury – Clean Hydrogen PTC (45V): https://home.treasury.gov/policy-issues/inflation-reduction-act/clean-hydrogen
[31] US DOE – Hydrogen Hubs Selections (2023): https://www.energy.gov/hydrogen/articles/biden-harris-administration-announces-7-billion-national-hydrogen-hub-selection

- Regulatory fragmentation across federal and state levels
- Lack of a national hydrogen certification scheme (awaiting 45V guidance)
- Public resistance to CCUS siting and permitting

Compared with the EU, the U.S. framework is more commercially driven and more dependent on incentive architecture. This has created strong momentum for pathways that fit clearly within tax-credit and hub structures, especially electrolysis, while leaving other non-combustion technologies with weaker and less targeted support.

8.3. China

China is advancing rapidly in hydrogen production scale and electrolyser manufacturing:

- **14th Five-Year Hydrogen Plan (2021–2025):** Targets 200,000 tonnes of hydrogen consumption in transport and at least 100 refuelling stations by 2025.
- **Alkaline Electrolyser Production:** China accounts for over 60% of global manufacturing capacity, reducing capital costs worldwide.
- **Coal + CCUS Integration:** Developing large-scale hydrogen from coal gasification with partial carbon capture.

However, less transparency in emissions reporting and limited alignment with international green hydrogen certification remain barriers. China is therefore highly significant from a scale and manufacturing standpoint, but less central as a policy model for a report focused on renewable and non-combustion pathways in the European context.

8.4. Latin America

Latin America's potential lies in abundant renewable resources:

- **Chile:** Green hydrogen roadmap targets 25 GW of electrolysis by 2030; pilot exports underway to Asia and Europe[32].
- **Brazil:** Developing hydrogen integration with ethanol and ammonia, supported by Germany's H2Global initiative.
- **Uruguay:** Coordinating a green hydrogen roadmap with support from the Inter-American Development Bank (IDB).

Obstacles:

- Limited infrastructure and port capacity
- Fragmented regulatory landscape

This region is important as a future supply base and export partner, particularly for Europe, but less directly relevant to the present analysis than the EU, Spain, and the United States.

8.5. Global Trends and Instruments

- **Guarantees of Origin (GoOs):** Being developed by CertifHy in the EU and through voluntary registries in the US and Asia.

[32] HIF Global – Haru Oni Project: https://www.hifglobal.com/project/haru-oni/

- **Carbon Contracts for Difference (CCfDs):** Piloted in Germany and the Netherlands to provide price stability for green hydrogen producers[33].
- **Multilateral Platforms:**
  - Clean Energy Ministerial Hydrogen Initiative (CEM H2I)
  - International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE)
  - Mission Innovation's Clean Hydrogen Mission

Across these frameworks, one consistent pattern emerges: policy is moving fastest where technologies fit clearly within certifiable renewable hydrogen categories, marketable infrastructure models, and large-scale industrial deployment narratives. This benefits electrolysis most directly. By contrast, non-combustion pathways based on waste and biomass may offer strong climate, circular-economy, and regional-resilience benefits, but they often require a more tailored regulatory interpretation in order to compete on equal footing.

9. Conclusion

The transition to net-zero emissions by 2050 will require a systemic overhaul of the way energy is produced, stored, and consumed. Non-combustion technologies are fundamental to this transformation. They provide pathways not only to eliminate direct emissions but also to rethink how resources are used, recovered, and valorised within industrial and urban systems.

This report has demonstrated that non-combustion approaches, particularly those centred on hydrogen production through renewable-powered electrolysis and qualifying waste- and biomass-based non-combustion pathways, offer significant GHG abatement potential. Electrolytic hydrogen, while still developing in terms of cost and scale, represents a long-term solution for energy storage, grid balancing, and industrial feedstocks. At the same time, technologies like Raven SR's non-combustion steam/CO_2 reforming present immediate, scalable opportunities to reduce emissions from waste, avoid methane-generating disposal pathways, and decentralise energy production.

Comparative policy analysis indicates that, although both the European Union and the United States recognise electrolysis as strategically important, existing policy frameworks remain structurally oriented toward electrolytic hydrogen pathways. A more balanced approach is needed, one that also supports genuinely non-combustion waste- and biomass-based pathways, together with other relevant technologies where appropriate, in order to accelerate innovation, improve regional applicability, and reduce the risk of unnecessary policy lock-in. In this regard, Spain, through its ambitious hydrogen strategy and PERTE-backed investments, offers a useful example of more integrated policy support, even though the broader EU framework continues to favour electrolysis most directly.

To unlock the full benefits of non-combustion technologies, several cross-cutting actions are required:

- Streamlining permitting and regulatory pathways, particularly for waste-to-hydrogen and decentralised systems
- Scaling up electrolyser manufacturing and renewable electricity infrastructure

[33] Agora Energiewende – CCfD Design and Implementation Report (2022): https://www.agora-energiewende.de/en/publications/carbon-contracts-for-difference/

- Investing in R&D for emerging technologies
- Supporting international trade in green hydrogen derivatives to optimise resource distribution
- Enhancing public-private collaboration to align industrial demand with low-carbon supply
- Refining lifecycle accounting and certification frameworks so that waste- and biomass-based non-combustion pathways are assessed on their full system merits, including methane avoidance, circular-economy value, and regional resilience benefits.

Non-combustion solutions are not a singular technological fix but a portfolio of interconnected innovations that must be supported collectively. Their deployment can deliver emissions reductions, economic growth, and improved environmental quality simultaneously, while also strengthening energy security, reducing waste burdens, and expanding the practical range of decarbonisation options available to different regions. In that sense, the challenge is not simply to scale hydrogen, but to ensure that policy and investment frameworks remain sufficiently open, evidence-based, and technology-aware to support the most effective non-combustion solutions for each regional context.

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