GREEN HYDROGEN

INTEGRATION FOR REFINERY

DECARBONIZATION

Presented by:
Greenzo Energy India Limited

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MESSAGE FROM THE MANAGING DIRECTOR

At Greenzo Energy, we recognize that refineries are among the largest contributors to global greenhouse gas emissions and represent a critical challenge in the transition to net zero. The integration of green hydrogen offers a transformative pathway to decarbonize refinery operations, reduce emissions, and ensure long-term sustainability.

This report, "Greenzo Energy – Green Hydrogen Integration for Refinery Decarbonization", reflects our commitment to driving innovative, low-carbon solutions for one of the most emission-intensive sectors. By advancing cost-effective electrolyzers and scalable hydrogen technologies, we aim to enable industries to accelerate their decarbonization journey while contributing to global climate goals.

Together, we can build a cleaner and more resilient energy future.

Sandeep Agarwal
Founder & Managing Director

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Green Hydrogen Integration for Refinery Decarbonization

"Transforming crude oil refineries into net-zero facilities with electrolysers, CCUS, and clean hydrogen"

1. EXECUTIVE SUMMARY

Crude oil refineries are among the largest contributors to global greenhouse gas (GHG) emissions, significantly accelerating climate change and its associated risks to public health and environmental safety. Between 2000 and 2021, refinery operations emitted an estimated 34.1 Gt of GHGs, with the top ten enterprises alone responsible for nearly 34–38% of this total. The continuous expansion of refinery capacity worldwide has intensified this challenge, positioning the sector as a critical focus area in the journey toward net-zero emissions.

This study highlights the environmental impact of refinery-based GHG emissions, identifies emission trends in the top-emitting countries and corporations, and outlines practical pathways for mitigation. Research indicates that efficiency improvements could yield a reduction of 532 Mt CO_2 in the top 10 countries and up to 928 Mt CO_2 globally by 2030.

2. USE OF HYDROGEN IN OIL PRODUCTION

Green Hydrogen Integration in Subsurface Applications

The illustration shows how green hydrogen can transform conventional subsurface processes into sustainable pathways. Instead of relying on fossil-fuel–derived hydrogen or natural gas, electrolysers powered by renewable energy generate clean hydrogen, which can then be utilized across various underground and industrial applications:

2.1 Steam Generation (with Green Hydrogen)

Green hydrogen is combusted or used in fuel cells to produce clean heat and power for generating steam, eliminating the carbon footprint of conventional steam generation.

2.2 Steam Flood (Enhanced Oil Recovery)

Traditionally powered by natural gas, steam flooding can now be enabled by hydrogen-based steam, significantly reducing CO_2 emissions.

2.3 In-situ Oil Sands Gasification

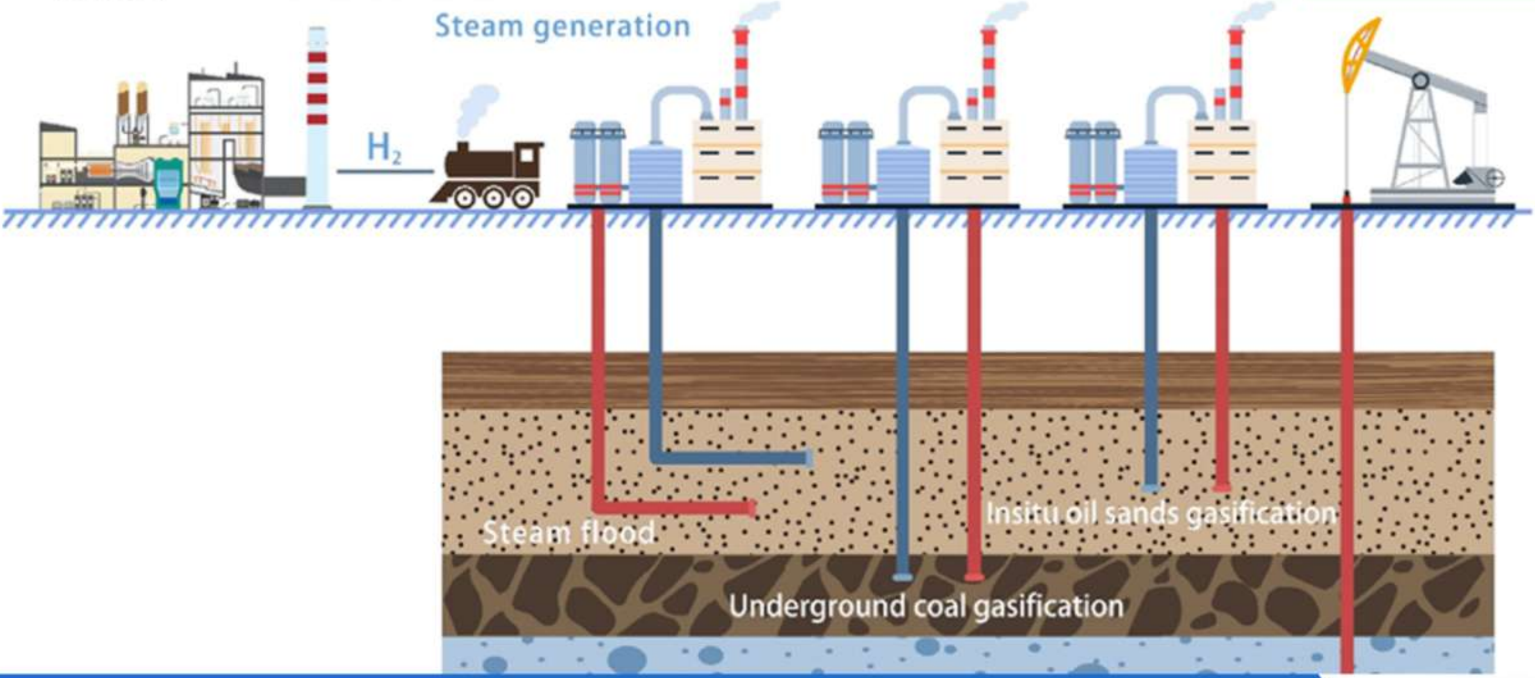
Green hydrogen can be directly injected into oil sands to support partial upgrading and reduce the intensity of extraction, cutting greenhouse gas emissions compared to conventional processes.

2.4 Underground Coal Gasification (UCG) Replacement

Instead of producing syngas rich in CO_2, hydrogen from renewable electrolysis can subsitute, creating a cleaner pathway for hydrogen supply without relying on coal gasification.

2.5 Natural Hydrogen Co-production

Green hydrogen can be blended with naturally occurring underground hydrogen reservoirs, enhancing supply security while ensuring a carbon-neutral fuel mix.



3. WHY HYDROGEN IS USED IN REFINERIES

Hydrogen is essential in modern refineries because it enables the production of cleaner, lighter, more stable, and more valuable fuels and chemicals. Its uses can be grouped into seven broad categories:

3.1 Removing Impurities (Hydrotreating)

Purpose: Hydrogen is used to purify crude oil fractions before they are upgraded or blended, ensuring clean fuels and protecting downstream catalysts.

Key Processes:

- **Hydrodesulfurization (HDS):** Removes sulfur → H_2S, essential for ultra-low sulfur diesel (ULSD) and clean gasoline.
- **Hydrodenitrogenation (HDN):** Removes nitrogen → NH_3, preventing catalyst poisoning and enabling stable downstream processing.
- **Hydrodeoxygenation (HDO):** Removes oxygen → H_2O, especially important for treating renewable feeds such as bio-oils.
- **Hydrodemetallization (HDM):** Eliminates metals (Ni, V) that can deactivate FCC and hydrocracking catalysts.

Benefits:

- Produces low-sulfur, low-nitrogen fuels that meet Bharat Stage VI / Euro VI standards.
- Extends catalyst life in reforming, FCC, and hydrocracking units.
- Ensures a clean, stable feedstock for further refining and petrochemical processing.
- Without hydrogen, modern clean fuels could not be produced, and catalysts would deactivate rapidly due to impurities.

3.2 Upgrading Hydrocarbons

Hydrogen directly reacts with hydrocarbons to transform heavy or unstable molecules into cleaner, lighter, and higher-value products.

Key Processes:

- Hydrocracking: Breaks down heavy hydrocarbons (vacuum gas oil, residue) into lighter fractions such as diesel, jet fuel, and naphtha. Hydrogen stabilizes the cracked molecules and prevents coke formation.
- Hydrogenation: Saturates unsaturated hydrocarbons (olefins, diolefins, aromatics), improving fuel stability, storage life, smoke point, and cetane/octane quality.
- Isomerization: With hydrogen present, n-paraffins are rearranged into iso-paraffins (e.g., n-butane → iso-butane), which are used in alkylation to produce high-octane gasoline.
- Aromatic Hydrogenation: Converts aromatics into naphthenes (cycloalkanes), enhancing diesel cetane number and jet fuel smoke point.

Benefits:

- Maximizes production of valuable light fuels.
- Improves overall fuel performance, stability, and quality.
- Prevents unwanted coke formation and extends catalyst life.

3.3 Fuel Quality & Environmental Compliance

Hydrogen is vital for producing premium quality, environmentally compliant fuels:

- Ultra-Low Sulfur Fuels: Enables production of ultra-low sulfur diesel (ULSD <10 ppm sulfur) and low-sulfur gasoline, reducing SOx emissions.
- Cleaner Combustion: Hydrogenation reduces aromatics and olefins in fuels, leading to less smoke, fewer particulates, and better combustion efficiency.
- Meeting Global Standards: Essential for compliance with international fuel quality norms such as Bharat Stage VI, Euro VI, and IMO standards for marine fuels.
- Improved Fuel Properties: Hydrogenation enhances thermal stability, raises diesel cetane number, improves jet fuel smoke point, and lowers freezing point for aviation applications.
- Lubricants & Specialty Products: Hydro finishing with hydrogen improves the color, stability, oxidation resistance, and removes unsaturated from lubricants, base oils, and waxes.
- Longer Storage Life: By saturating unstable molecules, hydrogenation prevents gum formation and improves the storage stability of fuels.

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3.4 Producing Petrochemical Feedstocks & Synthetic Fuels

Hydrogen is not limited to fuel refining — it is also a building block for producing petrochemicals and synthetic hydrocarbons. With refineries moving toward Refinery–Petrochemical Integration, hydrogen plays a central role:

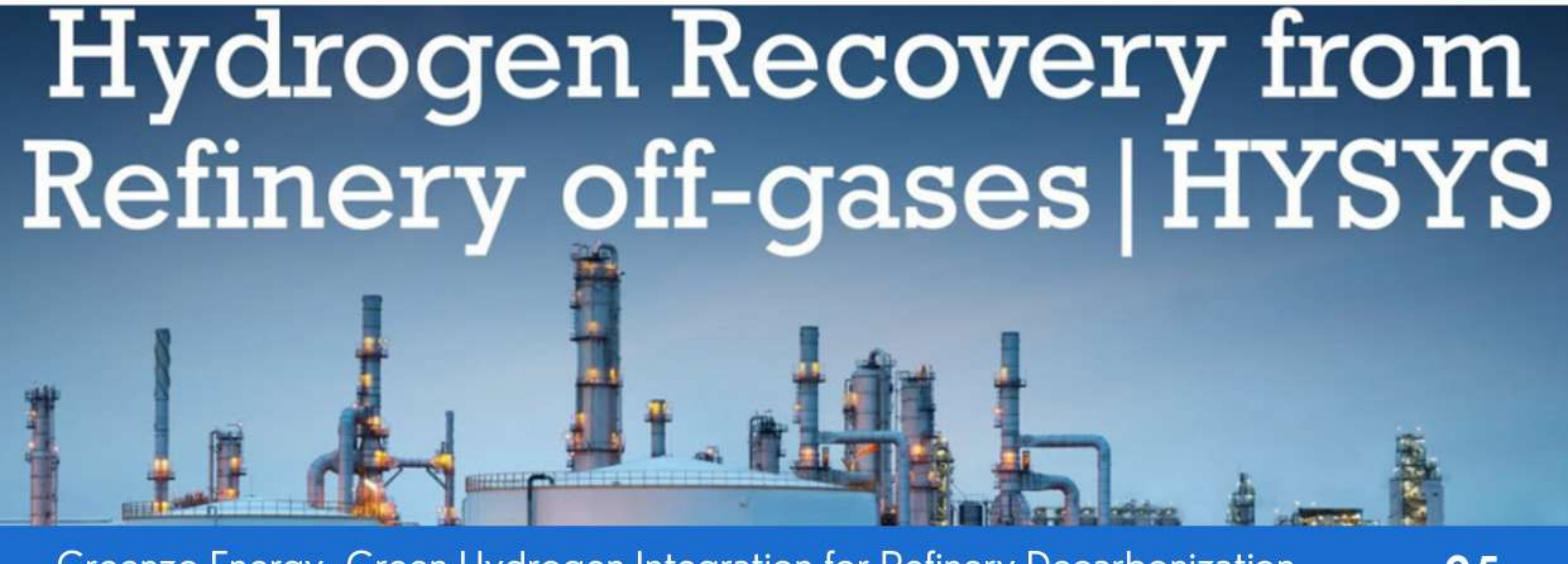
- Methanol Production: H_2 + CO/CO_2 → CH_3OH, which can be further converted into gasoline, olefins, or used as a clean fuel.
- Synthetic Ethanol: Emerging routes use catalytic hydrogenation of CO/CO_2 with hydrogen to produce ethanol as a renewable fuel or chemical intermediate.
- Synthetic (Fischer–Tropsch) Fuels: H_2 + CO → synthetic hydrocarbons such as diesel, jet fuel, and waxes, providing drop-in alternatives to fossil fuels.
- Methanol-to-Gasoline (MTG): Methanol derived from hydrogen and CO/CO_2 is converted into gasoline-range hydrocarbons.
- Ammonia for Fertilizers: In integrated complexes, hydrogen reacts with nitrogen (H_2 + N_2 → NH_3), supplying fertilizer demand and supporting refinery–chemical synergies.
- BTX (Benzene, Toluene, Xylene) Purification: Hydrogen removes impurities, ensuring high-purity feedstocks for the petrochemical industry.
- Integration Driver: As refineries evolve into energy–chemical hubs, hydrogen serves as the bridge molecule between fuel refining and petrochemical production.

3.5. Processing Renewable Feedstocks

- Modern refineries are being upgraded to handle bio-based feedstocks and integrate renewable hydrogen, enabling production of sustainable fuels.

Key Applications:

- Hydrotreated Vegetable Oils (HVO): Hydrogen removes oxygen from bio-oils, producing renewable diesel with properties similar to fossil diesel.
- Sustainable Aviation Fuel (SAF): Bio-based oils or Fischer–Tropsch intermediates undergo hydrogenation and hydrocracking to produce drop-in aviation fuels.
- Co-processing Bio-oils: Bio-feeds blended with conventional refinery streams (e.g., VGO, diesel) require hydrogen to stabilize and upgrade them into usable fuels.



Benefits:

- Enables production of low-carbon, renewable fuels.
- Supports compliance with global decarbonization targets (CORSIA for aviation, EU Renewable Energy Directive, India's biofuel blending mandates).
- Utilizes existing refinery infrastructure while integrating future green hydrogen pathways.

3.6 Supporting Operations

Hydrogen is not only a reactant but also plays a critical role in ensuring efficient and stable refinery operations.

Key Roles:

- Carrier Gas in Reactors: Maintains hydrocarbons in vapor phase, ensures proper contact with catalysts, and prevents coke deposition.
- Catalyst Protection: Removes residual impurities (sulfur, nitrogen, metals) that could deactivate catalysts in FCC, reforming, or petrochemical units.
- Heat Balance: In certain exothermic reactions, hydrogen circulation helps control reactor temperatures and ensures safe, stable operation.

Benefits:

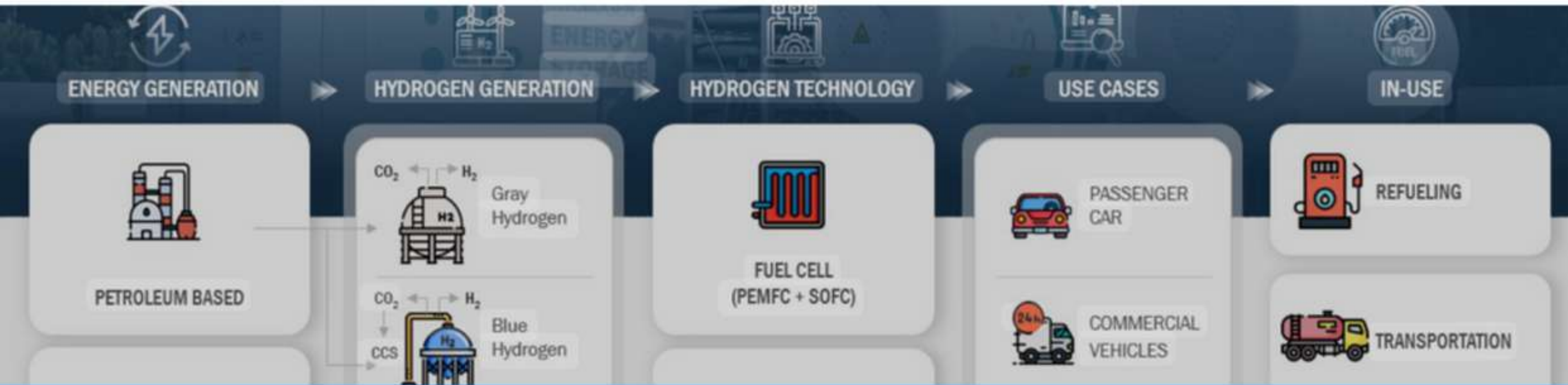
- Enables continuous and efficient operation of critical refinery units.
- Extends catalyst and equipment life.
- Supports process safety and consistent product quality.

3.7 Emerging / Future Uses

- Hydrogen demand in refineries is expected to increase significantly due to evolving fuel standards, decarbonization initiatives, and integration with renewable technologies

Key Drivers:

- Stricter Sulfur Specifications: Deeper desulfurization requirements for ultra-clean fuels.
- Expanded Hydrocracking Capacity: Increased hydrogen demand for upgrading heavier oils into lighter, high-value products.
- Bio-refineries & Sustainable Aviation Fuel (SAF) Production: Hydrogen-intensive processes for renewable and low-carbon fuel production.



CO_2 Capture & Utilization (CCU): Hydrogen reacts with captured CO_2 to produce e-fuels, methanol, and synthetic hydrocarbons, supporting decarbonization and circular carbon strategies.

Benefits:

- Supports the transition to low-carbon and renewable fuels.
- Enables refineries to meet future emission standards and sustainability targets.
- Positions hydrogen as a key enabler for integrated fuel-chemical-energy complexes.

4. THE OPPORTUNITY

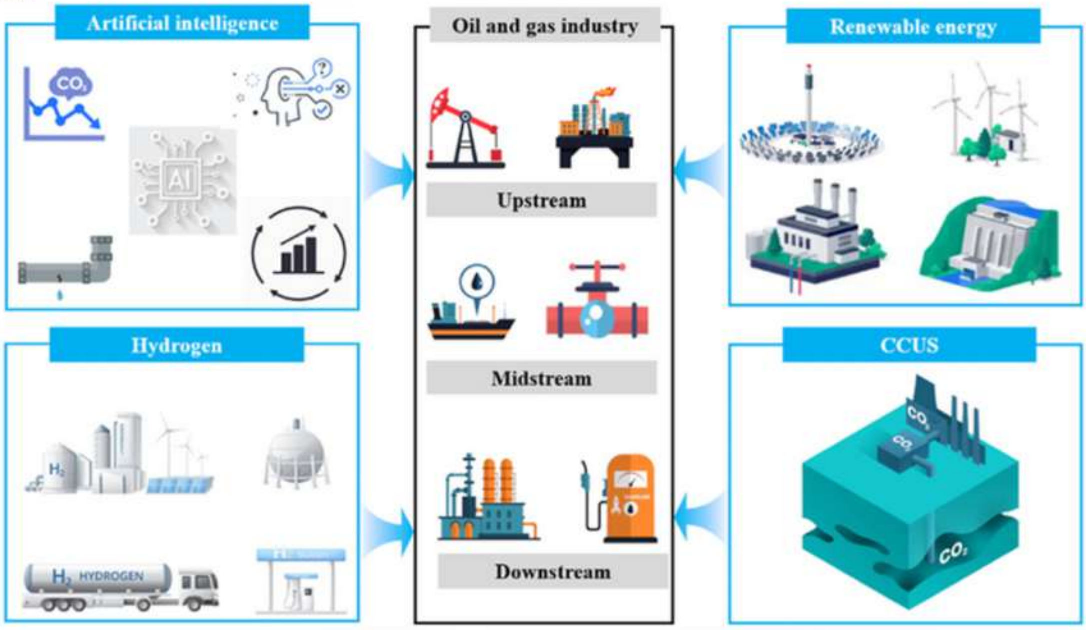
- Achieving such outcomes will depend on large-scale adoption of emerging solutions, including:
- Hydrogen-based refining processes to replace fossil-fuel-dependent operations
- Carbon capture, utilization, and storage (CCUS) technologies
- Circular economy integration across refinery operations
- Green financing and policy incentives to accelerate industry transition

As an electrolyser company, our focus is on enabling the deployment of clean hydrogen as a sustainable pathway for refineries to decarbonize their operations while maintaining production efficiency. With hydrogen playing a central role, combined with CCUS and strong policy support, the refinery sector has a realistic opportunity to move toward a net-zero future.

5. OUR CONTRIBUTION

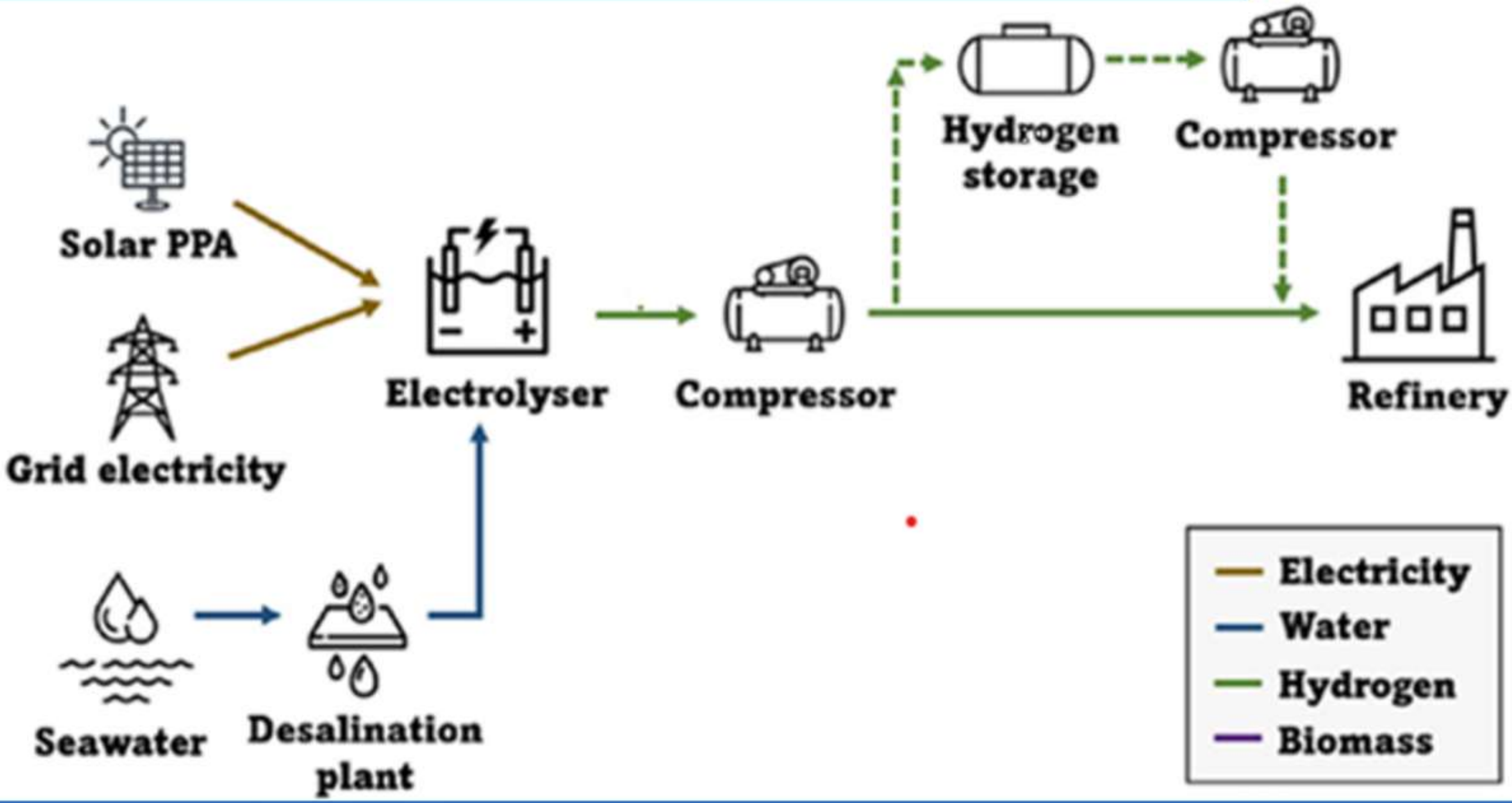
At Greenzo Energy, we are committed to enabling refineries to transition towards net-zero operations by:

- Supplying advanced electrolysers for on-site green hydrogen production.
- Designing hydrogen integration pathways for refinery operations.
- Partnering on pilot projects and large-scale deployments to cut refinery emissions.
- Supporting renewable energy integration with existing refinery infrastructure.



6. GREEN HYDROGEN PATHWAY FOR REFINERIES

The future of refinery operations lies in integrating green hydrogen as a clean energy source. The process begins with renewable electricity (solar or grid) powering an electrolyser, which splits water into hydrogen and oxygen.



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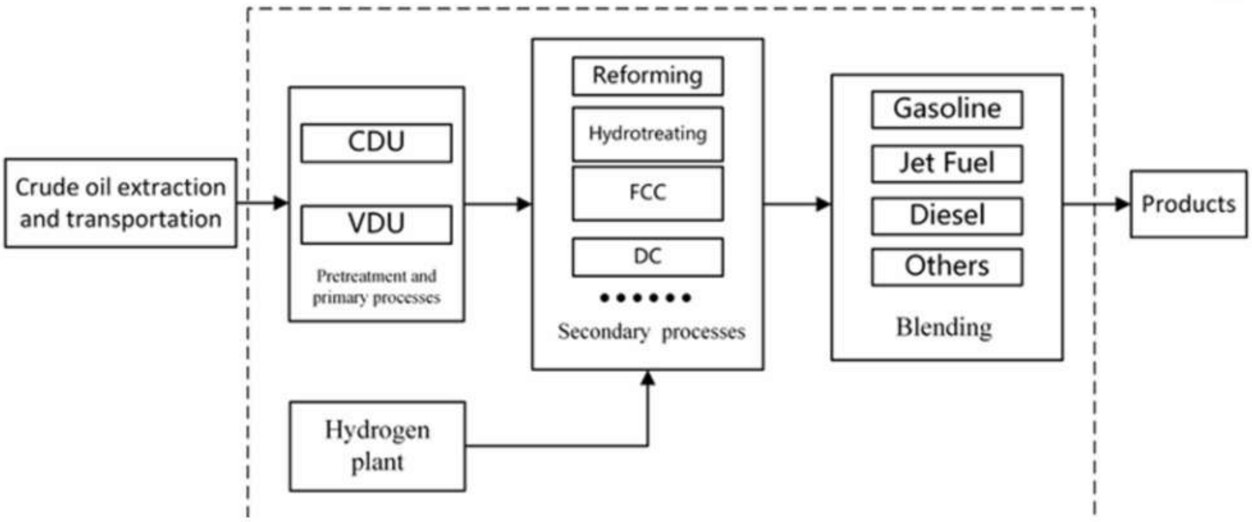
The generated green hydrogen is then compressed, stored, and supplied to the refinery, where it can replace fossil fuels in refining operations. This transition not only reduces greenhouse gas emissions, but also ensures long-term energy security and sustainability for the sector.
By closing the loop with renewable energy, water reuse, and hydrogen integration, refineries can move towards net-zero emissions while maintaining efficiency and competitiveness.

7. PROCESS FLOW OF A MODERN PETROLEUM REFINERY

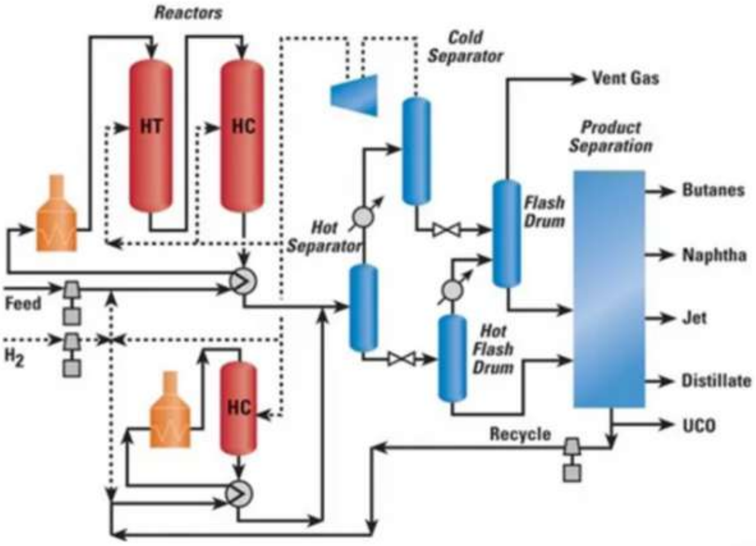
Starting from crude oil extraction to the production of finished fuels. Initially, crude oil is extracted and transported to the refinery, where it undergoes pretreatment and primary processing in the Crude Distillation Unit (CDU) and Vacuum Distillation Unit (VDU). These units separate the crude into various fractions based on boiling points.



The separated fractions then enter secondary processing units such as Reforming, Hydrotreating, Fluid Catalytic Cracking (FCC), and other conversion processes (DC), where chemical composition and quality are improved to meet product specifications. A hydrogen plant supports certain secondary processes by supplying the hydrogen necessary for hydrocracking and hydrotreating. Finally, the refined fractions are blended into marketable products, including gasoline, jet fuel, diesel, and other petroleum products, before being sent out for distribution and consumption. This flow ensures optimal utilization of crude oil and the production of high-quality fuels.

7.1 Hydrocracking Process: Transforming Heavy Oils into Valuable Fuels

Hydrocracking is a critical refining process that converts heavy crude oil fractions into lighter, high-value products such as gasoline, diesel, jet fuel, and kerosene. It combines catalytic cracking with hydrogenation, breaking down large hydrocarbon molecules under high pressure in the presence of hydrogen and a catalyst.



Key Features:

- Feedstock Flexibility: Can process heavy oils, vacuum gas oils, and residues that are difficult to refine with simple distillation.
- High-Quality Products: Produces cleaner fuels with low sulfur content, meeting stringent environmental standards.
- Hydrogen Integration: Hydrogen addition saturates molecules, preventing coke formation and improving fuel stability.
- Versatility: Adjusting catalysts and operating conditions allows refineries to tailor output to market demand.

Process Overview:

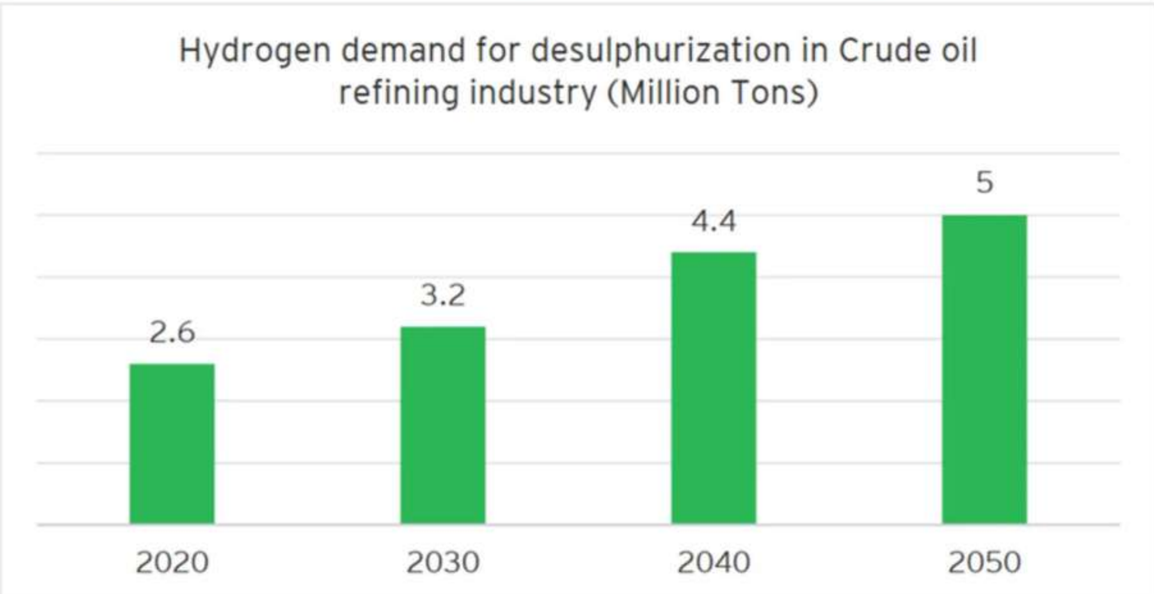
- Feed Preparation: Heavy hydrocarbons are pretreated to remove contaminants like sulfur, nitrogen, and metals.
- Hydrocracking Reactor: The feed reacts with hydrogen over a bifunctional catalyst at high temperature and pressure, breaking large molecules into smaller ones.
- Product Separation: Products are separated into gas, naphtha, diesel, and other fractions.
- Hydrogen Recovery: Unreacted hydrogen is recovered and recycled back into the process.

Advantages:

- Enhances refinery flexibility and profitability.
- Produces fuels compliant with environmental regulations.
- Reduces the production of low-value by-products.
- Integrates well with green hydrogen initiatives to lower refinery carbon footprint.

Future outlook:

- Despite its environmental benefits, green hydrogen production is more expensive than traditional methods due to higher electricity costs and the limited availability of zero-carbon power. This means that for green hydrogen to be more widely adopted in oil refining, there needs to be a decrease in power costs and an increase in the efficiency and availability of zero-carbon power sources.
- There are ongoing efforts and projects aimed at integrating green hydrogen into refinery processes. For instance, the REFHYNE project in Germany is working on installing and operating a large electrolyser at a refinery to provide bulk quantities of green hydrogen. This project is a part of a broader move towards decarbonizing the refining process and reducing emissions, a trend that is expected to continue and expand in the 2020s.
- The potential market for low-carbon hydrogen in oil refining is significant. By 2050, the demand for low-carbon hydrogen in the global refining sector could reach 50 million tonnes per annum. This transition to green hydrogen could play a crucial role in reducing up to 35% of refining carbon emissions.



Source: Hall, W., Spencer, T., Renjith, G., and Dayal, S. 2020. The Potential Role of Hydrogen in India: A pathway for scaling-up low carbon hydrogen across the economy. TERI

OGSC	Decarbonization Strategy	Description	Reference
Upstream	CCUS system	Low-carbon heat and power; de-carbonizing and reducing atmospheric CO2	[3,4]
	Renewable energy integration	Integrating renewable energy sources (wind, solar) in O&G production and operations	[5,6]
	Flare gas recycling technology	Collecting and compressing flare gas from oil production before it reaches the combustion site and cooling it down for use in the fuel gas system	[21]
	CO2 flooding technology	Injecting CO2 into oil reservoirs to enhance oil recovery	[8,9]
	Geothermal energy	Geothermal heat from O&G wells produce hot water to generate electricity	[4,10]
	Electrification of drilling through a hybrid energy system	Using renewable power to operate drill rigs and other equipment via connection to electricity grid and mini grids	[3,11]
Midstream	Renewable energy integration for Transport	Using electric vehicles in the O&G sector to cut CO2 emissions	[5,12]
	Using biomass for transport	Using wood/wood chips to transport oil via pipelines	
	Biofuels for crude oil transport	Using biofuels in the shipping and piping of crude oil transport	[6,13]
Downstream	CCUS	Acid gas is an option in CCUS in refineries and OGSC downstream	[15,16]
	Renewable energy integration	Integrating renewable energy sources (e.g., solar) in O&G downstream operations	[17,18]
		Using biofuels (e.g., biodiesel, vegetable oils) as refinery feedstock in O&G downstream	
	Integrating biofuels to refinery feedstock	Flare gases are recycled, recovered, and utilized as fuel gas or process feed	[19,20]
	Flare gas recovery	Electrification of refinery heat and power systems	[7,21]
	Electrification technology		[3]

8. IMPACT IN NUMBERS

With the right technologies, the refinery sector can achieve significant emission reductions:

- Top 10 refineries: By adopting hydrogen-based refining and efficiency upgrades, the largest refineries alone could collectively reduce 532 million tonnes (Mt) of CO_2 emissions by 2030. This is equivalent to taking more than 115 million cars off the road each year.
- Global refineries: If similar measures are applied across the sector, worldwide refineries could cut up to 928 Mt of CO_2 emissions by 2030. This is nearly the same as eliminating the annual energy-related emissions of an entire industrialized nation.

These figures demonstrate that even incremental adoption of hydrogen and CCUS technologies can deliver transformational impact on global emissions. Hydrogen is at the heart of this shift — and Greenzo Energy is positioned to make it a reality.

9. FUTURE WITH GREENZO ENERGY:

Cleaner refineries: - reducing harmful emissions while maintaining output.
Net-zero pathways: - practical roadmaps for decarbonization by 2030 and beyond.
Sustainable industry leadership: positioning refineries as pioneers in global energy transition.

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