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# India's Green Fuels: Baseline Market Study and Roadmap

Unlocking the Potential of Clean Energy

Prepared for:

**Trade Council of Denmark, India**

# Acknowledgements

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In the report, an attempt has been made to comprehensively cover the trends & developments, opportunities, challenges, and recommendations pertaining to the India's green fuels market in consultation with industry and other stakeholders in this sector.

At the end, Trade Council of Denmark acknowledges the contributions made by all those associated with the report.

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# Foreword

## From the Ambassador's desk

India and Denmark share a strong and forward-looking commitment to sustainability, embodied in the **Green Strategic Partnership (GSP).** This partnership, launched in 2020, is a unique model of international collaboration that combines Denmark's expertise in green technologies with India's scale and ambition in achieving a low-carbon future. As part of this commitment, Denmark is working closely with India to accelerate the transition to green fuels, which are crucial in decarbonizing hard-to-abate sectors such as steel, cement, shipping, and heavy transport.

Recognizing the immense commercial potential and strategic value of this collaboration, the Trade Council of Denmark in India initiated **Green Fuels Alliance India (GFAI) in 2024 now transitioned as Green Transition Alliance India (GTAI).** This initiative brings together Danish companies with cutting-edge technologies in green hydrogen, biofuels, and Power-to-X solutions to partner with Indian industries in their decarbonization efforts. India's growing demand for sustainable energy solutions presents an unprecedented opportunity for Danish companies to contribute meaningfully to this transformation while also fostering economic and technological cooperation between our two nations.

**This Baseline Report on Green Fuels** in India provides a comprehensive assessment of the current state of green fuels in India, mapping out existing capacities, key stakeholders, policy frameworks, and emerging opportunities. It serves as a vital resource for industry leaders, policy makers and investors to shape the next phase of India's green fuel journey. The report also outlines a deep dive analysis into five fuels (2G Ethanol, Green Hydrogen, Green Ammonia, Green Methanol and Sustainable Aviation Fuel) that are contributing to the India's decarbonization efforts. By leveraging Danish expertise and India's ambitious clean energy goals, we can collectively build a greener and more resilient future.

I extend my appreciation to all stakeholders who have contributed to this report and to the continued strengthening of the India-Denmark Green Strategic Partnership. The collaboration between our two nations is not just about sustainability—it is also about fostering innovation, creating green jobs, and ensuring long-term economic growth through a shared commitment to decarbonization.

I look forward to seeing the impact of our joint efforts as we work together to make green fuels a key driver of India's energy transition.

**H.E Rasmus Abilgaard Kristensen**

Ambassador of Denmark to India

# Executive Summary

The transformation of the global energy landscape is driven by the imperative to reduce greenhouse gas (GHG) emissions, enhance energy security, and accelerate climate action. **Green fuels, such as biofuels and synthetic fuels (e-fuels), are used as replacements to petroleum and gas products and have emerged as pivotal solutions in this transition.** They represent a transformative pathway to reduce carbon emissions and secure a sustainable energy future. In essence, these fuels, produced from renewable resources, offer significant potential to decarbonize the industrial, transportation, and power sectors, where emissions have traditionally been hard to abate.

**One of the largest energy consumers globally, India seeks to reduce its reliance on fossil fuels and leverage on renewable resources in alignment with its commitment to achieve net-zero emissions by 2070. It has put strategic focus on biofuels, synthetic fuels including green hydrogen, and sustainable aviation fuels (SAF).**

Key policies in India that support the objectives of decarbonization and development of green fuels are developed at the federal-level. This is applicable to biofuels, particularly bioethanol, with the National Policy on Biofuels from 2018, amended in 2022, that support the blend of first-generation (1G) biofuels with conventional gasoline and diesel.

For second-generation (2G) biofuels and synthetic fuels, the blending is more recent and therefore the policy and regulation landscape is still in development and requires structure. Policies or roadmaps, such as the **National Hydrogen Mission or the Methanol Economy Program** can be considered preliminary in their development and require strengthening in the national legislation to ensure recommendations are binding for multiple stakeholders, including the private sector. Nevertheless, they are good indicators of India's current and potential market for green fuels opportunities.

India, as a member of the International Civil Aviation Organization (ICAO), also follows the requirements related to sustainable aviation as per the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), notably for the adoption of Sustainable Aviation Fuels (SAF).

This report focuses on five green fuels that have been further analyzed based on their potential and market dynamics in India. The key findings are summarized below:

| Fuel | Key findings |
|---|---|
| Advanced or Second-generation (2G) bioethanol | The 2018 National Policy on Biofuels led by the Ministry of Petroleum and Natural Gas (MoPNG) initially set blending targets — **20% ethanol and 5% biodiesel by 2030.** The government updated the policy in 2022, advancing the 20% bioethanol blending target to 2025-26. **The market is still dominated by first generation bioethanol.** |
| | To support advanced biofuels development, the PM JI-VAN Yojana was launched to facilitate investments in second generation bioethanol from agricultural residues and to support the achievement of the bioethanol blending targets and tap on the important yields from crops residues. Annual surplus crop residues in India are estimated at 230 million tonnes, mainly from rice, wheat, maize and sugarcane crops that account for 42, 35, 16 and 6 million tonnes of annual residue respectively. |

| Fuel | Key findings |
|---|---|
| Low carbon Hydrogen and Ammonia | • In India, about 5 million tonnes of hydrogen is consumed annually, of which about 99% is used in petroleum refining and ammonia production.<br>• India's ammonia production reached around 19 million tonnes in 2023 (95% dedicated to fertilizer production) and is expected to grow annually by 3.9% until 2034 to reach 28 million tonnes. Currently, all the ammonia produced is derived from reforming natural gas.<br>• Led by the Ministry of New and Renewable Energy (MNRE), the **National Green Hydrogen Mission (NGHM) focuses on the green hydrogen value chain** and is expected to drive the growth of green hydrogen and ammonia in the country through government initiatives and industry demand. **As of 2025, the main driver to ensure its success is to guarantee the demand, stimulated by large tenders from public corporations such as India Oil Corporation (IOCL) or various fertilizer companies.**<br>• Nevertheless, the focus of green hydrogen and ammonia is currently in heavy industries for the conventional use of hydrogen (chemical, refineries, steel) for energy purposes but has yet to take off. |
| Low carbon Methanol | • India has a methanol production capacity of approximately 1-2 million tonnes. As of 2021, about 75-80% of methanol use in the country was met through imports. The Indian methanol market is expected to grow by 4.73% by 2030, driven by government initiatives to promote the chemical as a cleaner transportation fuel.<br>• **The Methanol Economy Program from NITI Aayog, which has yet to be formalized as an established policy equivalent to NGHM,** focuses on production and utilization of methanol as a clean green fuel suggesting (i) blending 15% of methanol in gasoline and (ii) blending 20% DME (Di-Methyl Ether, a derivative of methanol) in liquified petroleum gas (LPG).<br>• **The bio-route for methanol production appears to be most likely due to the current biomass potential and limited availability of biogenic captured carbon dioxide for e-fuel production.** |
| Sustainable Aviation Fuels | **India is engaged in promoting SAF adoption, aligned with the IACO-CORSIA roadmap that aims to 1% SAF in jet fuel for international flights by 2027, doubling to 2% by 2028 and 5% by 2030.** To achieve these targets, the country requires approximately 140 million liters of SAF annually.<br><br>Key players of SAF include Indian Oil Corporation, who aims to achieve at least 1% SAF blending in jet fuel by July-September 2025. Production capacities for SAF in India, however, remain limited for now. |

International companies would benefit from having a presence in India with existing or to-be-developed partnerships with local companies (that can ensure reliable demand) to facilitate green fuels opportunities development in the country.

India is a fast-growing market with a constantly developing policy yet politically stable landscape. Coupled with available financing mechanisms that support capital-intensive structure and its government's commitments, the country holds multiple facets that enable opportunities in the green fuels market for private companies.

In order to take advantage of the current trends and to limit the risks of strong competition from local developers, newcomers that would not benefit from existing presence in the country may first develop direct partnership with well-established stakeholders (either investors/ developers or off-takers that can ensure reliable demand) to gain trust from local market (notably in case of limitation of real case projects).

## Definitions

**Alternative Fuels:** Also known as non-conventional and advanced fuels, alternative fuels are fuels derived from sources other than petroleum.

**They include:**

Gaseous fossil fuels like propane, natural gas, methane, and ammonia

**Biofuels like biodiesel, bioethanol, and refuse-derived fuel**

**Other renewable fuels like hydrogen and electricity**

These fuels are intended to substitute for more carbon intensive energy sources like gasoline and diesel in transportation and can help to contribute to decarbonization and reduction in pollution. While there is no standardized definition for green fuel, this report will further refer to "green fuels" for alternative fuels that originated from renewable sources and/or low-carbon technologies such as biofuels (with a focus on 2G and 3G biofuels) and synthetic fuels (particularly produced through use of renewable electricity and carbon capture solutions).

**Ammonia:** A chemical compound of nitrogen and hydrogen with the formula $NH_3$. Around 70% of ammonia produced industrially is used to make fertilizers in various forms and composition while other applications include refrigeration, antimicrobial agent for food products and as a fuel. Ammonia can also be used as a carrier for hydrogen, being liquid at ambient temperature.

**Bioenergy:** A source of energy from the organic material that makes up plants, known as biomass. Bioenergy is often defined as "Traditional" or "Modern" as per the categorization below:

Traditional biomasses include wood, agricultural by-products, traditional charcoal and dung burned for cooking, and heating purposes.

Modern bioenergy includes liquid biofuels produced from bagasse and other plants, bio-refineries, biogas, wood pellet heating systems, and other technologies.

**Biofuel:** A fuel that is produced over a short time span from biomass, rather than through slow natural processes involved in the formation of fossil fuels such as oil. Biofuel can be produced from plants or from agricultural, domestic or industrial biowaste. The two most common types of biofuels are bioethanol and biodiesel. Biofuels are generally classified as conventional or advanced biofuel where:

First-generation biofuels are generally made from food crops grown on arable land. The crops' sugar, starch, or oil content is converted into biodiesel or ethanol, using transesterification, or yeast fermentation.

Second and third-generation biofuels are made from a wide range of waste feedstocks usually derived from agriculture and forestry activities residues to produce advanced biofuels through biochemical and thermochemical processes.

**While biofuel is commonly used to refer to liquid biofuel, biogas according to definitions may also be considered as a biofuel.**

**Biodiesel:** A methyl or ethyl ester of fatty acids derived from non-edible vegetable oils, acid oil, used cooking oil, animal fat, or bio-oil. Biodiesel is a fuel that has almost no sulphur, no aromatics, and has about 10% built-in oxygen[1].

**Bioethanol[2]:** Ethanol ($C_2H_5OH$) produced from biomass such as sugar containing materials, like sugar cane, and, cellulosic materials such as bagasse, wood waste, agricultural and forestry residues or other renewable resources like **industrial waste, vegetable wastes,** industrial waste off gases or any mix combination of above feedstock.

**E-fuel or Synthetic fuel:** A result from the combination of 'green or e-hydrogen' produced by electrolysis of water with renewable electricity and $CO_2$ captured either from a concentrated source (e.g., flue gases from an industrial site) or from the air (via direct air capture (DAC).

**Biogas:** Biogas is a gaseous renewable energy source produced from raw materials such as agricultural waste, livestock manure, municipal waste, etc. Biogas is produced by anaerobic digestion with anaerobic organisms or methanogens inside an anaerobic digester, biodigester or a bioreactor. The gas composition is primarily methane ($CH_4$) and carbon dioxide ($CO_2$).

**Bio methanol:** Produced from biomass, an alternative biofuel for internal combustion and other engines, in combination with gasoline or independently. Methanol ($CH_3OH$) is more toxic than ethanol and has a lower energy density than gasoline. Methanol is an intermediate to produce value-added chemicals like acetic acid, MTBE, DME, and formaldehyde.

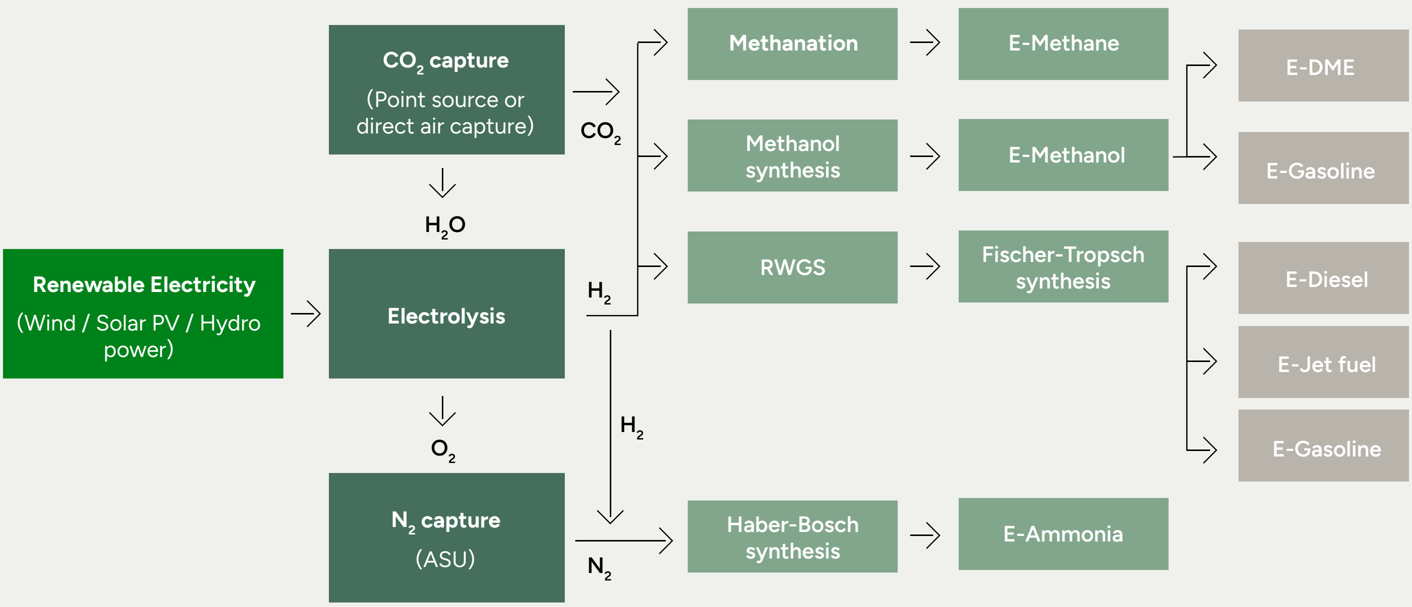
**Lower-Carbon Aviation Fuels (LCAF) and Sustainable Aviation Fuels (SAFs):** Liquid aviation fuels with the same properties as conventional jet fuel that originate from renewable energy resources, either bioenergy or renewable electricity.

To distinguish SAF and LCAF, SAF enables emissions reduction in the combustion phase of the fuel lifecycle while LCAF enables emissions reduction in the production phase of the fuel lifecycle.

**Financial Currency Conversions:**

1 Indian rupee (INR) = 0.012 USD (as of 20 December 2024)

**Figure 1:** Summary of the main e-fuels and the required feedstocks for production[3]



# Contents

# 1

# Introduction

The transformation of the global energy landscape is driven by the imperative to reduce greenhouse gas (GHG) emissions, enhance energy security, and accelerate climate action. As one of the world's fastest-growing economies, India's energy needs are substantial and diverse. In 2023-24, 88 percent of the country's total primary energy needs are met by coal and oil. This dominance is expected to reduce gradually as the energy mix from renewable energy sources is making a significant progress by adding renewable energy capacity (incl. large hydro) into the primary mix. As a result, the renewables now hold a 3.4 percent share in the primary energy supply.

At the same time, alternative pathways, such as green fuels—including **biofuels and synthetic fuels (e-Fuels)** produced using electricity—are emerging as pivotal solutions to replace petroleum and gas products. These fuels, produced from renewable resources, offer significant potential to decarbonize the industrial, transportation, and power sectors, where emissions have traditionally been hard to abate.

With the launch of key initiatives such as the **National Green Hydrogen Mission, the PM JI-VAN Scheme,** and various national and state-level biofuel programs aimed at achieving net-zero emissions, India is at the forefront of the transition to cleaner and renewable energy sources. This critical shift is driven by the country's ambitious climate goals and the need to reduce its dependency on fossil fuels.

With growing interest from international partners such as Denmark under the **Green Fuels Alliance in India (GFAI),** there is an increasing focus on understanding the country's green fuel sector, addressing challenges, and seizing emerging opportunities.

**The Green Strategic Partnership between India and Denmark** further strengthens this collaboration, enabling Danish industries to contribute their expertise in advanced technologies for green fuel production, high-efficiency capital equipment, fuel transformation, grid and storage infrastructure, and off-take agreements in the transport sector. Further, this partnership can facilitate knowledge sharing, setting up standards for green fuels, policy alignment, and joint research initiatives, fostering a robust ecosystem for accelerating India's transition to sustainable energy solutions.

This report, commissioned by the Trade Council of Denmark in India, provides comprehensive insights into India's green fuels sector, including **advanced bioethanol, low-carbon hydrogen & ammonia, low-carbon methanol and sustainable aviation fuel (SAF). The key objective of the study is to present a baseline on the current state of green fuels in India in terms of techno-commercial and market viability,** as well as, to replete Danish stakeholders with strategic next steps on evaluating and selecting fuels that have a fast-evolving market in India.

The study also provides detailed insights on the stakeholders involved in the value chain and the financing mechanisms that can facilitate green fuel ventures in India. By mapping the current market landscape, technology availability, policy environment and with additional insights from selected key players in the different markets, this study will facilitate informed decision-making and strategic market positioning for companies interested in contributing to India's green fuel initiatives.

# 2

# Green fuels current state assessment

As of 2023, India's total primary energy supply represented approximately 1,118 million tonnes oil-equivalent (Mtoe).[4,5] This primary energy mix is dominated by fossil fuels, with coal contributing 49% of the total supply in 2023, followed by oil at 22% and natural gas at 6%. Bioenergy represents around 18-20% (around 208 Mtoe) of the energy mix.

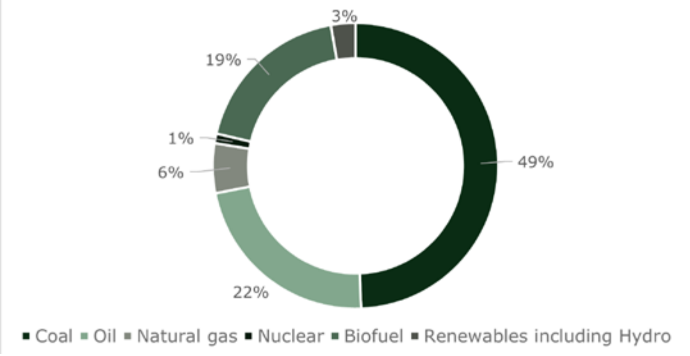
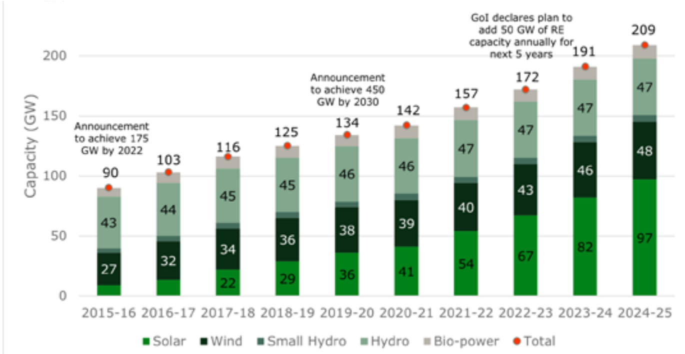



**Figure 2:** Total primary energy supply in 2023 – India

**Figure 3:** Renewable energy installed capacity (utility) - India[6]




2.1

## Renewable Energy consumption

Renewable energy (RE) encompasses a diverse range of sources, including solar, wind, hydro, bioenergy, and waste-to-energy. India has emerged as a leading player in the global RE sector, ranking fourth worldwide in installed renewable energy capacity. As of October 2024, the country's total installed RE capacity stood at 203 GW, accounting for 45% of India's total electricity installed capacity of 454 GW.

Among the various renewable sources, solar power holds the largest share, contributing 45% of the total RE capacity. Wind and hydro power follow, each representing 23%, while bioenergy and small hydro account for 6% and 3%, respectively.

In India, as outlined in the Indian Energy Scenario report published by the Government of India, the entire RE production is utilized for electricity generation, catering to residential, commercial, and industrial needs. Consequently, there is limited data on the availability of renewable energy feedstock for e-fuel production. However, studies conducted by the Ministry of New and Renewable Energy (MNRE) highlight the potential RE power requirements for producing various e-fuels. For instance, the National Green Hydrogen Mission report estimates that achieving the target of producing 5 million tonnes of green hydrogen would require approximately 125 GW of renewable energy capacity.

2.2

## Biomass Consumption

India, as the second-largest producer of agricultural residues globally (China is first), generates approximately 990 million metric tons (MMT) of biomass annually. A significant portion of this biomass is used for traditional applications like combustion, packaging, and paper production, with about 230 million tonnes remains surplus, indicating an untapped potential for biofuel production. The total biomass usage in India surpassed 208 Mtoe in 2023 against 184 Mtoe in 2019[7].

Biomass consumption is dominated by solid biofuels that represent approximately 99% of the total, mainly from households and industries. As a result, biogas and biofuels represent a minute portion of biomass and ultimately, energy consumption. In 2023, bioethanol represented 5.08 billion liters or 2.6 Mtoe (followed by an increase up to 7.07 billion liters or 3.6 Mtoe reported in 2024) and biodiesel 0.2 million tonnes or 0.17 Mtoe in 2023[8].

In total, liquid biofuels represent approximately 0.5% of the volume of energy consumed from oil products.

Bioethanol current production, blending rate and feedstock trends:

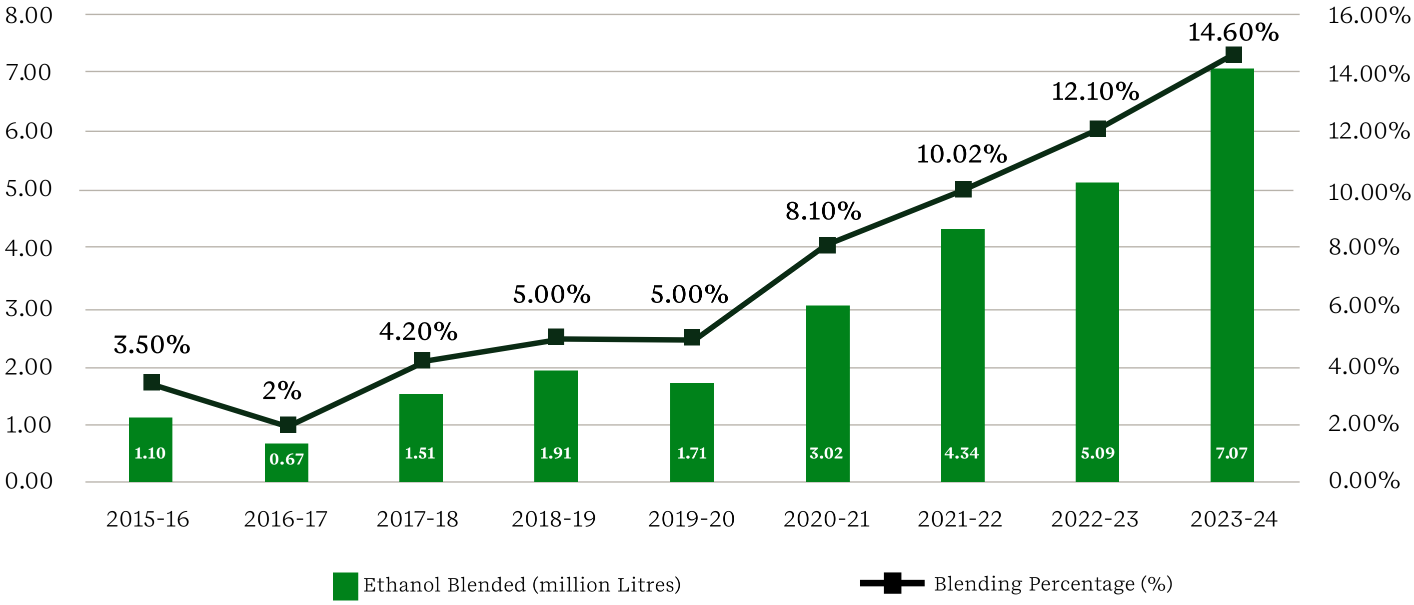



**Figure 4:** Ethanol blending with petrol

Bioethanol produced in India is mainly first-generation (1G) ethanol that originates from sugar, maize and rice crops.

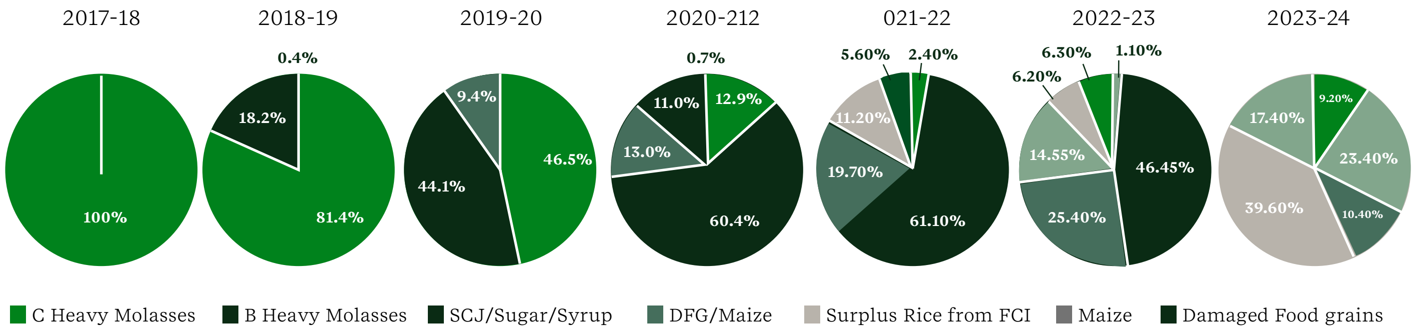



**Figure 5:** Bioethanol main feedstock in India

*Notes:*

- *B-Heavy Molasse is an-intermediate by-product produced during production of sugar having purity of molasses between 48 percent to 52 percent.*
- *C-Heavy molasse is a final by-product produced during production of sugar having purity of molasses between 28 percent to 32 percent.*
- *SCJ: Sugarcane Juice; DFG: Damaged Food Grains; FCI: Food Corporation of India*

## Progress in applications of biofuels for various sectors

Biofuels have diverse applications across sectors, as a sustainable alternative to conventional fossil fuels. While the transport sector continues to rely heavily on oil and has limited penetration to electricity from infrastructure constraints and slow adoption of electric vehicles, bioethanol and biodiesel can replace petrol and diesel as fuel options, particularly for cars, trucks, and rail.

Biofuels are now emerging as a critical enabler of energy diversification, particularly in the transport sector, where ethanol-blended petrol is gaining prominence.

Additionally, biofuels such as compressed biogas (CBG) are gaining traction in heavy-duty transportation and as a substitute for natural gas in industrial operations. The aviation industry is exploring sustainable aviation fuel (SAF) as a complement for conventional jet fuel, with India targeting 1–2% blending by 2028.

2.2

## Other green fuels are in the premices, though still dominated by conventional technologies

India's strategic focus on biofuels, synthetic fuels, green hydrogen, and SAF is aimed for the decarbonization of hard-to-abate sectors that remain dependent on high-emission fossil fuels, such as aviation, marine, and heavy-duty vehicles.

**As of now, hydrogen, ammonia and methanol are still largely produced from fossil-fueled based pathways and used for their chemical characteristics rather than as a fuel.** Conversely, the development of e-fuels is limited from the lack of commercial-scale dedicated carbon capture, utilization and storage (CCUS) projects in India. Therefore, its commercial adoption remains limited, with no indication of upcoming large-scale production projects or its significant production reported as of 2024.

**Table 1:** Summary of the production and consumption of green fuels in India

| Fuel | Current Production and Consumption Levels |
|---|---|
| Hydrogen | • About 5 million tonnes of hydrogen are consumed annually, of which about 99% is used in petroleum refining and ammonia production.<br>• Currently, levelized cost of green hydrogen is estimated between INR 320 (3.78USD) and INR 330 (3.90USD) per kilogram in India[9].<br>• As of end of 2024, no large-scale low-carbon hydrogen production capacities is reported. Nevertheless, various large conglomerates plans are developing projects for industrial-scale green hydrogen and derivatives plants.<br>• The Indian government has set out an ambitious green hydrogen production target of **5 million metric tonnes per annum by 2030,** with an associated renewable energy capacity of about 125 GW by 2030. |
| Ammonia | • Ammonia consumption reached around 19 million tonnes in 2023 and is expected to grow annually by 3.9% until 2034 to reach 28 million tonnes[10]. Part of the ammonia is directly imported notably from Middle East countries (in 2021, imports represented 2.4 million, equivalent to 15% of the production volume)[11]. It is estimated that 95% of ammonia was dedicated to fertilizer production, while the remaining 5% for other applications.<br>• All ammonia produced and used in India is grey ammonia, derived from reforming natural gas. The total emissions from ammonia production were estimated to be around 25 $MtCO_2$ eq in the fiscal year 2022–23[12]. |
| Methanol | • India has a methanol production capacity of approximately 1-2 million tonnes. This is derived from the combined production capacity of methanol plants owned by Assam Petrochemical, Rashtriya Chemicals and Fertilizers, and Gujarat State Fertilizers & Chemicals.<br>• As of 2021, about 75 to 80 % of methanol use in the country was met through imports from the Middle East. The country's methanol demand is projected to grow to 4.67 million tonnes by 2030[13]. |
| Sustainable Aviation fuels | • Some airlines have already used blended ATF–SAF in their demo flights[14].<br>• As of 2024, with 1% blending it is expected that 34 million liters per annum will be required and by 2028 the blending targets could be 2% leading to a requirement of 103 million liters of SAF annually at a CAGR of 11% to the 2024 levels. |

3

# Current Policy Framework on Green Fuels

India does not have a single, unified piece of legislation dedicated to green fuels. The country relies on the combination of legislations at the central and state levels, with additional schemes and programs that collectively address various aspects of fuels productions, distribution and utilization. It follows a federal structure instead, where policymaking responsibilities are divided between the central and state governments. This distinction influences the development and implementation of green fuel policies, where national-level initiatives set overarching goals, while state governments adapt and execute them based on regional priorities and resources[15].

3.1

## Key Institutional Stakeholders

Key institutional stakeholders involved in the green fuels development in India are presented in the table below:

**Table 2:** Key institutional stakeholders for green fuels development in India

| Stakeholder | Description |
| --- | --- |
| Ministry of New and Renewable Energy | Supervises the National Green Hydrogen Mission (NGHM) and has implemented several policy frameworks, including waiving interstate transmission charges for renewable energy used in green hydrogen production, facilitating renewable energy banking, and granting time-bound open access and connectivity to green hydrogen projects. |
| Ministry of Petroleum and Natural Gas (MoPNG) | Has the responsibility to (i) coordinate biofuels policies (such as the National Policy on Biofuels) or schemes to support the manufacturing of biofuels, (ii) set up a National Bio-fuel Development Board and (iii) strengthen the existing institutional mechanisms and research, development and demonstration on transport stationary and other applications of biofuels. The MoPNG also leads the Pradhan Mantri Yojana, a program aimed to promote the production of 2G ethanol using agricultural residues as feedstock. |
| Ministry of Civil Aviation | Has adopted the ICAO's environmental protection guidelines by DGCA (Directorate General of Civil Aviation) for the formation of Bio-Aviation Turbine Fuel (ATF) Programme Committee to promote clean fuels and achieve Carbon Neutrality and Net Zero. |
| Ministry of Road Transport and Highways | Issues notifications notably to promote electric mobility and green fuels, including exempting battery-operated vehicles and vehicles running on methanol or ethanol fuel. |
| NITI Aayog | NITI Aayog (the National Institution for Transforming India) is a policy think tank of the Indian government providing policy recommendations such as the **Methanol Economy** program[16]. |

3.2

## Main policies related to green fuels

India's policy landscape is in constant evolution to facilitate the development of the industry for green fuels. While the landscape for biofuels and more particularly bioethanol has been established for more than a decade and already serves as starting point for advanced biofuels, only preliminary policies and/or non-binding roadmaps have been prepared for synthetic fuels.

This table below lists down and describe selected policies and roadmaps that are expected to share for the upcoming years the sector of the alternative bio- and e-fuels as follows.

Regarding carbon capture, utilization and storage (CCUS), there is, at the time of preparation of this report, no major policy or regulation developed at national scale specific to the technology. India's planning commission, NITI Aayog, has preliminary works involving industry clusters and employment generation to identify potential policy instruments and financial incentives to help its adoption on a commercial scale, with the potential for India to reach a CCUS capacity of 750 million metric tonnes per year by 2050[17]. The Commission plans to produce a comprehensive policy in the near future to address various aspects of CCUS implementation, such as capture standards, transportation, storage, and utilization of $CO_2$[18].

**Table 3:** Established policies for green fuels development in India

| Key policies | Description |
|---|---|
| National Policy on Biofuels 2018/2022 | • **Type of policy/regulation:** Policy passed by the cabinet and in effect from 2022, from its initial version in 2018.<br>• **Key stakeholder in charge:** Ministry of Petroleum and Natural Gas (MoPNG)<br>• **Focus on:** Biofuels (including bioethanol and biodiesel)<br>• **Main objective:** The National Biofuels Policy 2018 aims to promote the use of biofuels for energy security, reducd carbon emissions, and foster rural development, while the 2022 amendment accelerates the target through blending ethanol with petrol to 20% by 2025-2026 to further reduce fossil fuel dependency and emissions.<br>• **First implementation and last amendment:** Approved in 2018, amended in 2022<br><u>Additional policies and regulation for biofuels:</u><br>• **Pradhan Mantri JI-VAN Yojana (2019)[19]:** The Pradhan Mantri JI-VAN[20] Yojana initiative emphasis is on boosting domestic production of ethanol from diverse feedstocks.<br>• **Ethanol Blended Petrol Programme:** This policy was implemented by the government of India throughout the country, where Oil Manufacturers Companies (OMC) sells the petrol with 10% ethanol blended.<br>• **Long Term Ethanol Procurement Policy[21]:** This policy was introduced under ethanol blended petrol (EBP) in 2019, aimed to achieve multiple outcomes, such as address environmental concerns, reduce import dependency and boost the agricultural sector. |

| Key policies | Description |
|---|---|
| National Policy on Biofuels 2018/2022 | • **Integrated Biorefinery Model**[22]**:** This Integrated Biorefinery Model aims to support the development and commercialization of biorefineries to de-risk new and emerging technologies and improve cost competitiveness. |
| National Green Hydrogen Mission 2023 | • **Type of policy/regulation:** The National Green Hydrogen Mission, a policy initiative launched by GOI, serves as a strategic framework to promote green hydrogen production, usage, and infrastructure development but is not binding.<br>• **Key stakeholder in charge:** Ministry of New and Renewable Energy<br>• **Focus on:** Green hydrogen value chain, including green ammonia<br>• **Main objective:** The main objective of the India Green Hydrogen Mission is to promote the production, use, and export of green hydrogen to achieve energy independence, reduce carbon emissions, and position India as a global hub for green hydrogen production.<br>• **First implementation:** The mission was approved and launched in January 2023. |
| Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) | • **Key stakeholders in charge:** The International Civil Aviation Organization (ICAO), with the Directorate General of Civil Aviation (DGCA) responsible for implementing and ensuring compliance with CORSIA guidelines in India.<br>• **Focus on:** The scheme focuses on monitoring, reporting, and offsetting carbon emissions from international aviation to achieve carbon-neutral growth and reduce the sector's environmental impact.<br>• **Main objective:** The main objective of CORSIA is to stabilize net $CO_2$ emissions from international aviation at 2020 levels by requiring airlines to offset their emissions growth through certified carbon credits and promote the adoption of SAF and other emission reduction measures. The scheme requests indicative blending targets of 1% by 2027, 2% by 2028 and 5% by 2030 of Sustainable Aviation Fuel in Traditional Aviation Fuel for international flights.<br>• **First implementation:** CORSIA was first launched in 2021 as part of its pilot phase, and it will be fully implemented in phased stages until 2035.<br>• DGCA adopted guidelines for environmental protection developed by ICAO (including CORSIA) on 24$^{th}$ July 2023[23]. |

Other policy recommendations and roadmap developed by Niti Aayog regarding methanol and carbon capture are listed below:

| Key Policy recommendations | Description |
|---|---|
| NITI Aayog's 'Methanol Economy' Programme | **Type of policy/regulation:** The 'Methanol Economy' Programme is a strategic initiative launched by NITI Aayog to promote the use of methanol as a green fuel, focusing on its production, utilization, and infrastructure development. It is not binding and acts as a policy framework.<br><br>**Main objective:** The programme aims to reduce India's dependency on imported fossil fuels, promote the use of methanol as a cleaner and more sustainable alternative, and foster the growth of the methanol value chain, including production, distribution, and consumption.<br><br>**First release:** The programme was first introduced in 2018 and has seen continuous development since then.<br><br>**Key features:** The programme was launched in 2018 and aims at reducing India's oil import bill, greenhouse gas (GHG) emissions, for production and utilization of methanol as a clean green fuel, focusing on its use in transport, power generation, and industrial applications. [24]. It proposes to:<br>• Blend 15% of methanol in gasoline; and<br>• Blend 20% DME (Di-methyl Ether, a derivative of methanol) in LPG. |
| Carbon Capture, Utilization and Storage: Policy Framework and its Deployment Mechanism | **Type of policy/regulation:** Policy Framework and Deployment Mechanism (in Proposal stage)<br><br>**Main objective:** The framework aims to facilitate the development and deployment of CCUS technologies in India to reduce $CO_2$ emissions and support decarbonization across key industrial sectors.<br><br>**First release:** The report was published in 2022 and is still at the proposal stage<br><br>**Key features:** The framework aims to accelerate the adoption and scaling of CCUS technologies across various sectors. It includes financial incentives, such as subsidies for $CO_2$ sequestration, enhanced oil recovery (EOR), and $CO_2$ utilization, to reduce the costs of CCUS projects. It promotes the adoption of proven technologies while supporting R&D for emerging applications like $CO_2$ conversion into chemicals and synthetic fuels. The establishment of the Carbon Capture Finance Corporation (CCFC) is a key component, designed to provide long-term funding through government grants, bonds, and a **"Clean Energy Cess"** on coal, ensuring the scalability and sustainability of CCUS projects[25]. |

Additional and secondary policies and regulations can also be found in Appendix B.

Policy development in India has been quite dynamic over the past years. Specific trends can be observed in terms of incentives provided on specific green fuels. In the following sections, an in-depth analysis is provided for a series of green fuels selected based on potential for further development in India and their relevance to Danish companies' activities and expectations.

The five selected green fuels are:

1

Advanced or Second-Generation (2G) Bioethanol

2

Low carbon hydrogen

3

Low carbon ammonia

4

Low carbon methanol

5

Sustainable Aviation Fuels (SAF)


4

# Advanced Bio-Ethanol

4.1

## Definition

Advanced bio-ethanol refers generally to bio-ethanol from agricultural residues rather than from food crops (sugarcane or food grains). It is also known as second-generation ethanol or cellulosic ethanol and produced from the cellulose found in plant materials. Advanced bioethanol thus has the potential to maximize the value of by-products and raw materials which are not directly consumed by humans, ultimately reducing competition with food production.

This is an alternative to first-generation (1G) ethanol, which is derived from food sources like corn and sugarcane. Bioethanol can be blended up to certain proportions with gasoline without major modifications of vehicles engines. India has emerged as the world's third-largest ethanol producer and consumer, nearly tripling production over five years between 2019 and 2023[26].

With supportive policies, it can further expand by controlling costs and ensuring sustainable feedstocks. While the biofuels market, particularly for bio-ethanol, is still dominated by first generation types, incentives have been implemented to support the development of second-generation bio-ethanol (2G) from agricultural residues.

4.2

## Market Dynamics

Current stage of ethanol blending:

Where available, petrol with 10% ethanol blend (E10) is currently being retailed by various Oil Marketing Companies (OMCs) in India. By ethanol supply year (ESY) 2022–2023, the blending rate reached 12%[27].

When the National Policy on Biofuels was launched in 2018, India's average ethanol blending rate with petrol was 2% while the 2019-2020 level of average ethanol blending in the country was 5% (ESY 2019-2020)[28].

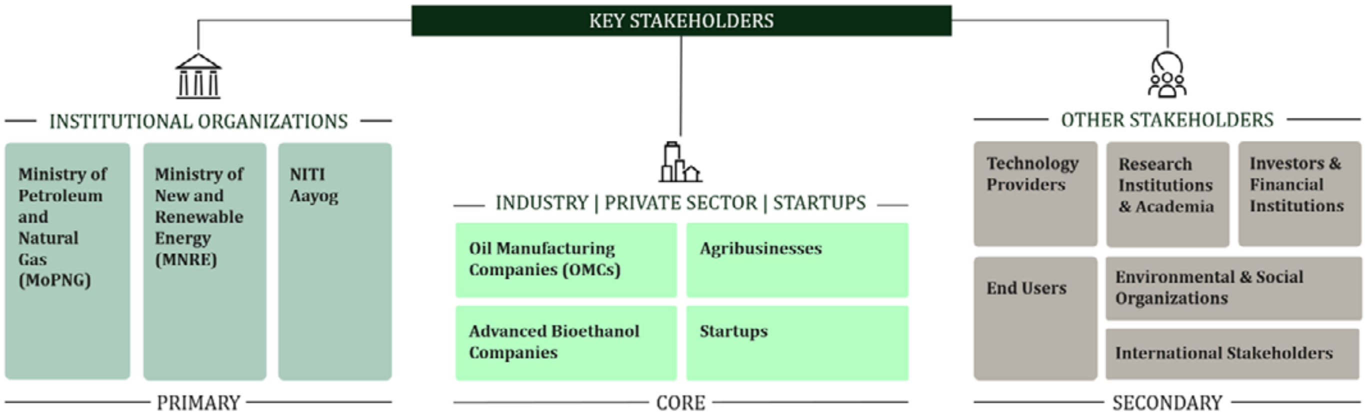
In June 2021, NITI Aayog released the Roadmap for Ethanol Blending in India 2020-2025. The roadmap indicates a 20% ethanol blending target by 2025. It outlines a yearly strategy to boost domestic ethanol production, aligning with the goals of the revised National Policy on Biofuels (2018) and the Ethanol Blended Petrol (EBP) Program to achieve 20% ethanol blending in petrol by 2025-2026.

In 2019 by the Ministry of Petroleum & Natural Gas launched the Pradhan Mantri Ji-Van Yojana program. The program aims at providing financial support to Integrated Bioethanol Projects using lignocellulosic biomass and other renewable feedstock.

Key stakeholders involved in advanced bio-ethanol:

Key stakeholders involved in the that are active and/or may play a critical role in the development of green hydrogen in India are shown in Figure 6 on the next page.

**Figure 6:** Stakeholders landscape for advanced bioethanol in India




<u>Key outputs and selected projects from the Pradhan Mantri JI-VAN Yojana</u>

Under the "Pradhan Mantri JI-VAN Yojana", six commercial 2G bio-ethanol plants and four demonstration 2G bio-ethanol plants have already been approved. The details are in the table below:

**Table 5:** Biomass volume from agriculture crops in India

| No. | State/ District | Entities | Project Type | Additional info. |
|---|---|---|---|---|
| 01 | Haryana/ Panipat | Indian Oil Corporation Ltd. | Commercial | Capacity of 100KL of ethanol per day (using rice straw)<br><br>Investment of approx. USD 110 million |
| 02 | Odisha/ Bargarh | Bharat Petroleum Corporation Ltd. | Commercial | Using biomass from non-edible whole plants or food grain residues for 2G ethanol and sugarcane juice, molasses & damaged grains for making 1G ethanol |
| 03 | Odisha/ Bargarh | Bharat Petroleum Corporation Ltd. | Commercial | Capacity of 100KL of ethanol per day<br><br>Cost of INR 14 billion (approx. USD 170 million) |
| 04 | Assam/ Numaligarh | Numaligarh Refineries Limited | Commercial | Capacity of 50,000 tonnes of ethanol per year |
| 05 | Karnataka/ Davangere | Mangalore Refinery and Petrochemicals Ltd | Commercial | Capacity of 60,000 liters of ethanol per day<br><br>Cost of INR 10 billion (approx. USD 120 million) [29] |

| No. | State/ District | Entities | Project Type | Additional info. |
|---|---|---|---|---|
| 06 | Andhra Pradesh/ Nandyal | RCPL | Commercial | Not identified |
| 07 | Haryana/ Panipat | Indian Oil Corporation Ltd. | Demonstration | Not identified |
| 08 | Bihar/Sagauli | Hindustan Petroleum Corporation Ltd. | Demonstration | Not identified |
| 09 | Maharashtra/ Sangli | Lignopura Agrotech Pvt Ltd | Demonstration | Not identified |
| 10 | Karnataka/ Sameerwadi | Godavari Biorefineries Ltd | Demonstration | Not identified |

PM JI-VAN Yojana was expected to remain open until its financial year 2023-2024, or after all 12 Commercial projects and 10 Demonstration projects are approved for financial assistance, whichever earlier. It must be noted that produced 2G Ethanol cannot be exported. It will be necessarily supplied to OMCs and for that, proper connectivity is to be ensured before commissioning the project.

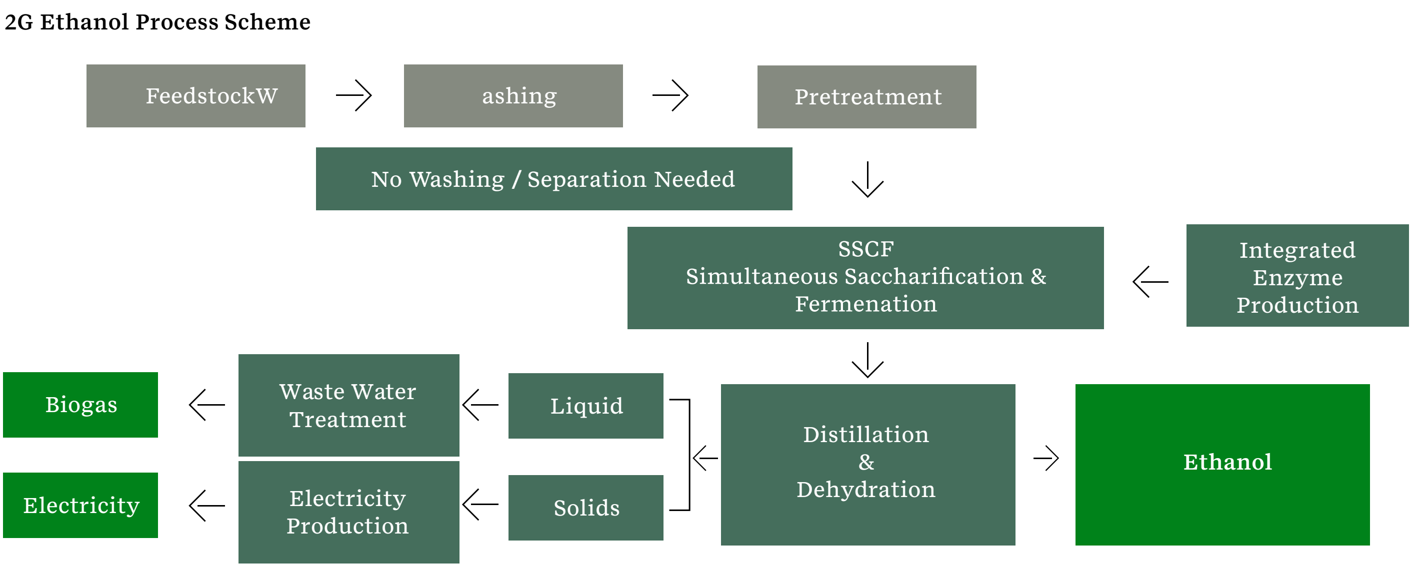
4.3

## Technical Considerations

Sugarcane-derived molasses and broken or surplus grains like rice and maize are primarily used to generate ethanol.  At present, these two feedstocks can generate about 6.84 billion liters of ethanol collectively, and proposed to expand to 15 billion liters by 2025. This, in turn, will necessitate the production of about 16.5 million metric tonnes of grains and 6 million metric tonnes of sugar in the year 2025 for ethanol utilization.

Regarding second-generation bioethanol, lignocellulosic biomass is the main feedstock, but it is also possible to use industrial byproducts, such as whey or crude glycerol. Lignocellulosic bioethanol production process can be summarized into in four stages as follows: (i) Pretreatment, (ii) Enzymatic Hydrolysis, (iii) Fermentation, and (iv) Distillation.

**Figure 7:** Second generation bioethanol production basic process diagram



## Biomass Feedstocks and Availability

Potential feedstocks for second-generation bioethanol in India include (but are not limited to):

1. Agricultural wastes, such as cereal straw and mills' by-products (stover, wheat straw, corn cob, rice husk) or also bagasse from processing sugar cane. Overall availability of feedstock from agricultural residues can be found in tables below.

2. Other types of waste, including:

- Forest-based woody wastes and forest biomass and hardwood chips, or waste from parks and gardens (e.g., leaves, grasses, and branches)
- Industrial wastes, such as brewer's spent grains and spent grains from distilleries, and municipal solid wastes such as food waste, kraft paper, and paper sludge

Based on a study by ASCI for the Ministry of New and Renewable Energy (MNRE) in 2017-2018 the total biomass production is the country was about 754 million metric tonnes per annum[30]. The annual surplus of agriculture-based biomass from major crops available after its utilization for domestic use, cattle feeding, compost fertilizer, etc., is about 230 million metric tons (MMT). [31,32]

**Table 5:** Biomass volume from agriculture crops in India

| Crops | All Crops | Rice | Wheat | Maize | Sugarcane |
|---|---|---|---|---|---|
| Total Production (kilotonne/ yr) | 754,485 | 184,539 | 192,339 | 69,739 | 17,887 |
| Total Surplus production (kilotonne/yr) | 228,517 | 41,726.9 | 33,373 | 15,207 | 6,379 |

**Table 6:** Surplus biomass residues in india from major crops per state

| Crops | All Crops | Rice | Wheat | Maize | Sugarcane |
|---|---|---|---|---|---|
| Andhra Pradesh | 17,093 | 2,571 | -- | 2,389 | 394 |
| Gujarat | 21,740 | 111 | 981 | 116 | 156 |
| Haryana | 10,908 | 3,003 | 2,002 | 12 | 93 |
| Karnataka | 14,049 | 750 | 62 | 1,876 | 750 |
| Madhya Pradesh | 19,928 | 1,941 | 6,311 | 2,152 | 1,941 |
| Maharashtra | 21,494 | 43 | 610 | 39 | 858 |
| Punjab | 22,251 | 18,786 | 3,093 | 203 | 92 |
| Rajasthan | 10,211 | 108 | 4,122 | 25 | 6 |

| Crops | All Crops | Rice | Wheat | Maize | Sugarcane |
|---|---|---|---|---|---|
| Tamil Nadu | 12,217 | 3,086 | -- | 2,124 | 257 |
| Telangana | 13,762 | 1,369 | 5 | 2,350 | 46 |
| Uttar Pradesh | 21,601 | 1,035 | 13,039 | 36 | 2,212 |
| West Bengal | 16,277 | 1,225 | 270 | 756 | 20 |

4.4

## Policies

The 2018 National Policy on Biofuels by the Ministry of Petroleum and Natural Gas implemented on 16th May 2018 aims to advance biofuel adoption by categorizing them into "Basic Biofuels" (1G ethanol, biodiesel) and "Advanced Biofuels" (2G ethanol, MSW fuels, 3G biofuels, bio-CNG)[33]. It broadens ethanol production inputs to include sugarcane juice, sugar or starch materials, and surplus or damaged food grains, with approval for blending with petrol during surplus phases.

The recent amendment (May 2022) in the policy states the move of its ethanol blending target to 20% of petrol containing ethanol by 2025-2026. It allows more feedstocks for biofuels and the promotion of biofuel production in India under the "Make in India" program, enabling the country to be well-positioned in SAF production[34].

<u>Support for investment provided by the policy:</u>

As the National Policy on Biofuels, the initial proposed target was to achieve 20% ethanol blending in petrol and 5% blending in diesel by 2030, through the following actions:

- Strengthening the supply of ethanol and biodiesel by boosting domestic production
- Establish 2G generation of bio refineries
- Develop a new feedstock for biofuel production
- Advance new technologies for biofuel conversion
- Create a conducive environment for biofuels and their integration with conventional fuels

Bioethanol refinery projects require high capital expenditure (CAPEX). The total CAPEX needed for building a 36.5 million liters cellulosic ethanol facility in India is INR 8.8 billion (USD 118 million) and INR 13.8 billion (USD 187 million) for a 70 million liters capacity facility.

To boost 2G ethanol, the policy offers a viability gap funding (VGF) of INR 50 billion (approx. USD 600 million) over six years, tax incentives, and higher purchase prices. It promotes biodiesel supply chains from non-edible oilseeds, used cooking oil, and short-gestation crops and outlines roles for ministries to streamline efforts. The VGF is under the Pradhan Mantri Ji-Van Yojana program, launched in 2019 by the Ministry of Petroleum & Natural Gas.

The policy has several intervention and enabling mechanisms which aims to increase the feedstocks for biofuels in India and implementing blending and bio-refineries program such as Ethanol Blended Petrol Programme, Second Generation (2G) Ethanol, Biodiesel Blending Programme and other biofuels (drop-in fuels, Bio-CNG, Bio-Hydrogen, Bio methanol, DME, etc.).

The policy outcome is to support 12 Commercial Scale and 10 demonstration scale 2G ethanol Projects with the VGF (Viability Gap Funding) and a total financial outlay of INR 19.7 billion (approx.

USD 240 million) for the period 2018-19 to 2023-2024. The outlay of INR 19.7 billion is broken down as follows:

**INR 18 billion**

for supporting 12 Commercial projects

(approx. USD 216 million)

**INR 1.5 billion**

for supporting 10 demonstration Projects

(approx. USD 18 million)

**INR 190 million**

to Centre for High Technology (CHT) as administrative charges

(approx. USD 2 million)

The financial assistance or grant component for the commercial projects are released in four stages of achievement:

**Table 7:** Payment milestones for VGF scheme

| Project Milestones | % of Grant payment |
|---|---|
| Erection/ Installation of Proprietary equipment | 25% |
| Completion of mechanical erection of the Project | 25% (total 50%) |
| On reaching 25% of annual production capacity of design value after mechanical completion and commissioning of Project | 25% (total 75%) |
| On reaching 75% of annual production capacity of design value | 25% (total 100%) |

Comparison of required investment and levelized cost of bioethanol with and without VGF support

**Table 8:** Estimated levelized production cost of cellulosic ethanol in India[35]

| Scenario | 36.5M capacity INR per liter (USD per liter) | 70M capacity INR per liter (USD per liter) | Range from other studies INR per liter (USD per liter) |
|---|---|---|---|
| No VGF support | 92 – 94 (1.26) | 79 – 81 (1.08) | INR 40 – 157 per liter (USD 0.5 – 2.1 per liter) |
| With VGF support | 80 - 82 (1.1) | 73 – 75 (1.0) | India's highest fixed ethanol price is INR 62.65 per liter or USD 0.85 per liter) |

**Table 9:** Total and per liter ethanol capital cost, fixed operational cost, variable operational cost[36]

| | | 36.5M capacity | 70M capacity | Range from other studies |
|---|---|---|---|---|
| CAPEX | Total capital investment million INR (million USD) | 8,768 (118) | 13,800 (187) | - |
| | INR (USD) per liter capacity | 240 (3.24) | 198 (2.67) | 110 – 430 (1.5 – 5.8) |
| Fixed OPEX | Total annual cost<br>Million INR (million USD) | 194.4 (2.6) | 306.3 (4.1) | - |
| | INR (USD) per liter ethanol | 5.3 (0.07) | 4.4 (0.06) | 2.1 – 27.4 (0.03 – 0.37) |
| Variable OPEX | Total annual cost<br>million INR (million USD) | Total annual cost<br>million INR (million USD) 839 – 855<br>(11.3 – 11.5) | 1,601 – 1,691 (21.6 – 22.8) | 1 |
| | INR (USD) per liter ethanol | 23 – 24.3 (0.31 – 0.33) | | 1.7 – 70.5 (0.02 – 095) |

4.5

## Conclusion

The 2018 National Policy on Biofuels initially set blending targets — 20% ethanol and 5% biodiesel by 2030 — outlined feedstock requirements and assigned coordination roles to 11 ministries. It also introduced guaranteed pricing, long-term contracts, technical standards, and financial aid for facility development. B**uilding on its success, the government updated the policy in 2022, advancing the 20% ethanol blending target to 2025-2026[37].**

With a blending target of 20% in petrol by 2025–2026, India's bioethanol production could triple in five years, supported by the Ethanol Blended Petrol (EBP) Programme. To achieve this target, approximately 10 billion liters for blending and a total demand of approximately 14 billion liter is requireds, necessitating an ethanol production capacity of approximately 17 billion liters at 80% efficiency. The demand aligns with projected growth in petrol-driven two-wheelers and passenger cars and rising fuel "Petrol/Motor Spirit" (MS) sales.

Key measures include extending the Pradhan Mantri JI-VAN Yojana to 2028-2029 for advanced biofuels, diversifying feedstocks, reducing taxes (GST) on ethanol to 5%, and ensuring fair procurement prices. Policy reforms facilitate ethanol movement across states, with an interest subvention scheme and Oil Marketing Companies' proactive procurement aim to boost production capacity and market stability[38].

Similarly, the Biodiesel Purchase Policy allows direct sale of biodiesel for blending with diesel and has facilitated biodiesel production using used cooking oil, aligning with the goal of a 5% biodiesel blend by 2030[39].

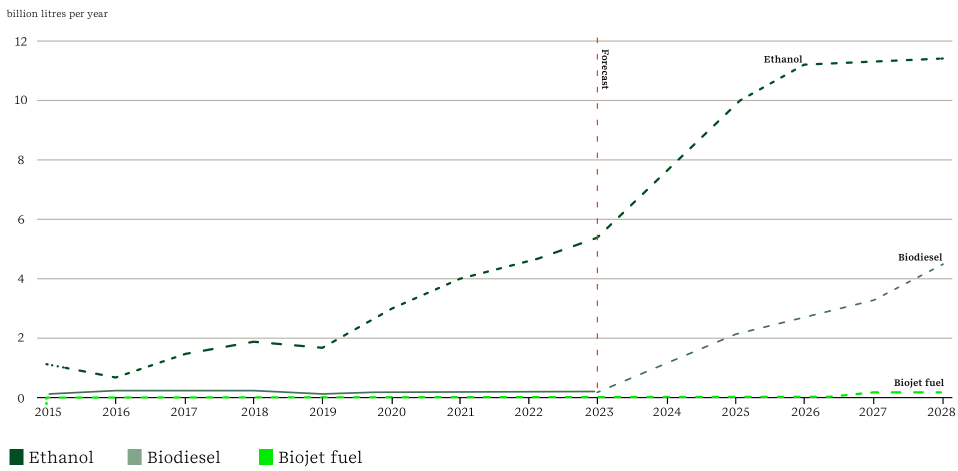
Despite these advancements, challenges persist. India's biofuels sector faces feedstock constraints and logistical bottlenecks, while inconsistent policy implementation hampers the scaling up of production[41]. Several technological challenges for the development of bioethanol in India also needs to be addressed, including:

- **Higher cost of production compared to first generation ethanol:** The cost of ethanol production from lignocellulosic biomass is higher than first-generation ethanol and there may be requirement of subsidy for economic viability and competitive ethanol pricing.

- **Commercial availability of lignin boiler:** Lignin is recommended to be used as fuel in boilers. Its commercial availability needs to be ascertained.

- **The availability of biomass** round the year depends on proper pre planning and is essential to build an ecosystem that ensures biomass supply. The supply of secondary fuel for use in boilers should also be addressed.

**Figure 8:** Projected biofuel consumption in India 2015-2028[40]




5

# Low-Carbon Hydrogen

5.1

## Description

There are two main methods for producing hydrogen:

- **Steam Methane Reforming (SMR):** SMR is a widely used method of commercial hydrogen production. It separates hydrogen atoms from carbon atoms in methane (CH4). High-temperature steam reacts with methane to produce hydrogen, carbon monoxide, and a relatively small amount of $CO_2$[42].

- **Electrolysis of Water:** Electrolysis is a process that splits hydrogen from water using an electric current. This reaction takes place in an electrolyzer.

Low carbon hydrogen is hydrogen that is made in a way that creates little to no GHG emissions. It is classified based on the production method, which determines its carbon intensity:

- **Green Hydrogen** is produced through the electrolysis of water. It has near zero emissions as renewable energy is used but is costly from the use of electrolyzers and renewable energy.

- **Blue Hydrogen** is produced from natural gas through SMR or Autothermal Reforming (ATR), coupled with CCUS. It reduces GHG emissions by capturing 60–95% of the $CO_2$ emitted during production[43].

- **Turquoise Hydrogen** is produced through methane pyrolysis, which splits methane into hydrogen and solid carbon.

<u>Green hydrogen definition in India</u>

The Ministry of New and Renewable Energy (MNRE) has defined green hydrogen based on the carbon emissions associated with its production. According to the newly established standard, hydrogen produced through electrolysis or biomass conversion must have a well-to-gate emission of no more than 2 kg of $CO_2$ equivalent per kg of hydrogen produced[44]. This includes emissions from water treatment, electrolysis, gas purification, drying, and compression of hydrogen.

The Bureau of Energy Efficiency (BEE) is the designated authority for the accreditation of agencies responsible for monitoring, verifying, and certifying green hydrogen production. These agencies will ensure compliance with green hydrogen standards through measurement, reporting, and onsite verification processes. The establishment of such standards is a key part of India's efforts to become a global hub for green hydrogen production.

5.2

## Market Dynamics

The green hydrogen market in India is currently nascent, with significant growth potential. The Indian government has been proactive in supporting this sector, with the NGHM aiming to make India a hub for the production, use, and export of green hydrogen. In 2022, India consumed approximately 6 million tonnes (MMT) of hydrogen, mostly from grey hydrogen sources[45]. .= Demand is primarily from industries such as fertilizers, refineries, steel, and chemicals, which collectively consume significant quantities of hydrogen.

The transition of heavy industrial sectors from grey to green hydrogen is crucial to achieve decarbonization targets[46]. The NGHM aims to position India as a global hub for green hydrogen production and export.

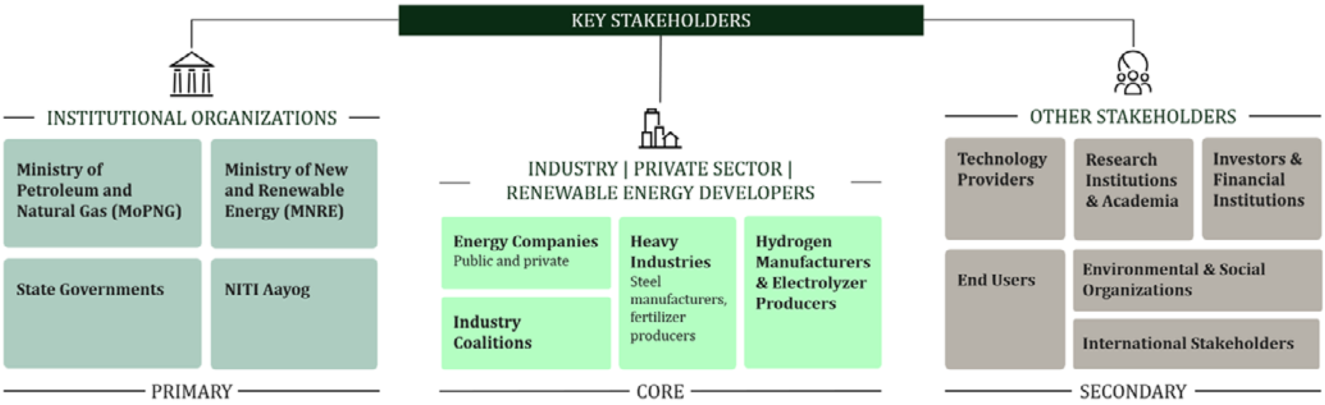
Currently, green hydrogen production in India costs between \$3 and \$6.5 per kg, significantly higher than grey hydrogen at approximately \$1 per kg. Government incentives, such as subsidies and tax benefits, are also pivotal in bridging the cost gap to achieve commercial viability that necessitate a reduction in production costs to \$1-\$2 per kg[47].

While there is considerable momentum in the green hydrogen market in India, the success of this transition depends on reducing production costs, scaling up electrolyser manufacturing, overcoming infrastructure challenges, and securing long-term financing. These elements, along with supportive government policies, will determine the pace and extent to which green hydrogen can contribute to India's energy transition and decarbonization efforts.

## Key stakeholders involved in green hydrogen:

Key stakeholders involved in the that are active and/or may play a critical role in the development of the fuel in India are shown below.

**Figure 9:** Stakeholders landscape for low carbon hydrogen in India




## Hydrogen potential clusters and competitive landscape

The regional distribution of green hydrogen demand in India is expected to be shaped by the industrial hubs across the country. Presently, Gujarat leads with 30% of the nation's industrial hydrogen consumption, followed by Uttar Pradesh at 17%, Maharashtra at 8%, Rajasthan at 7%, and Madhya Pradesh at 6%. As the adoption of green hydrogen accelerates, states with significant steel production such as Jharkhand, Chhattisgarh, Odisha, and Karnataka are anticipated to become key consumers. Meanwhile, its demand in mobility applications is projected to be geographically widespread, reflecting a decentralized pattern across India[48].

In terms of the competitive landscape, key industry players include both international and domestic firms involved in hydrogen production and electrolyzer technology. Domestic players like ReNew Power, Adani Green Energy, and Tata Power are increasingly involved in green hydrogen projects, alongside multinational companies such as Shell and Siemens. Despite this, India's lack of domestic electrolyser manufacturing capacity remains a barrier to rapid scale-up.

The table below shows a non-exhaustive list of projects from Indian conglomerates:

**Table 11:** List of green hydrogen production plant projects[49]

| Project Name | Developer | Capacity | Location | Cost |
|---|---|---|---|---|
| JSW Energy's Green Hydrogen Project for Steel Production | JSW Energy | 3,800 MTPA | Vijayanagar, Karnataka | NA |
| Green Hydrogen Hub | RIL and L&T | 1.4 MTPA hydrogen, 7 MTPA ammonia | Kandla, Gujarat | USD 12 Billion |
| Green Hydrogen Project by ACME | ACME Group and Karnataka Government | 1.2 MTPA | Karnataka | USD 6.24 Billion |
| Green Hydrogen Ecosystem | Adani and TotalEnergies | 1 MTPA | Mainly in Gujarat [50], including Khavda district of Gujarat's Kachch | USD 50 Billion |
| Green Hydrogen Plant by INOXAP | INOX Air Products | 190 MTPA | Chittorgarh, Rajasthan | NA |

| | | | | |
|---|---|---|---|---|
| Green Hydrogen Projects by Ohmium and Tata Projects | Ohmium and Tata Projects | NA | Doddaballapura, Karnataka | NA |
| Green Hydrogen plant by CIAL and BPCL | Ohmium and Tata Projects | NA | Doddaballapura, Karnataka [51] | |

On the other hand, large oil and gas (including BPSL, HSCL, MRPL, NML) and fertilizers companies are launching large tenders in 2025 for green hydrogen (for supply of up to 45kTPA) and green ammonia (740 kTPA) from 2025 onwards with long-term supply agreements for up to 25 years.

5.3

## Technical Considerations

As India aims to become a global leader in green hydrogen, several technical considerations must be addressed to enable its large-scale adoption.

- **Renewable Energy Integration:** India's significant renewable energy capacity, particularly in solar and wind, forms the backbone of green hydrogen production.
- **Water Availability and Management:** Electrolysis relies on water, making its availability a critical factor for green hydrogen projects. India faces challenges of freshwater scarcity, especially in regions identified as potential hubs for hydrogen production[52].
- **Electrolyzer Technology:** The choice and deployment of electrolyzer technology plays a significant role in scaling green hydrogen. While commercially available alkaline and Proton Exchange Membrane (PEM) electrolyzers are viable, advanced options like Solid Oxide Electrolyzers (SOEC) offer higher efficiency and may be more suitable for large-scale applications. Localization of electrolyzer manufacturing is equally critical to reducing costs and minimizing reliance on imports, aligning with India's broader "Make in India" initiative[53].
- **Cost of Production:** Green hydrogen production costs in India is higher than the global target of $1-2 per kilogram[54]. Cost reductions can be achieved by leveraging renewable energy subsidies, such as waivers on inter-state transmission fees and open access for renewable energy producers.
- **Storage and Transportation:** Hydrogen's low density presents challenges for storage and transportation. Solutions such as compression, liquefaction, or conversion to carriers like ammonia or methanol are being explored to address storage needs.

To address these technical challenges, a collaborative approach involving policymakers, industries, and research institutions is required. Investments in renewable energy infrastructure, technological advancements, and robust policy frameworks will be essential to position India as a global leader in green hydrogen production. With strategic planning and execution, the fuel can play a transformative role in achieving India's decarbonization goals.

5.4

## Policies

The National Green Hydrogen Mission (NGHM), led by the Ministry of New and Renewable Energy (MNRE) is the main policy supporting the development of green hydrogen in India. It is a Government of India (GOI) program that aims to incentivize the commercial production of green hydrogen and make India a net exporter of the fuel. The Mission will facilitate demand creation, production, utilization and export of Green Hydrogen. The present section follows up on the description given in Section 3.2.

<u>NGHM aims to create demand by:</u>

- **Exports:** Mission will facilitate export opportunities through supportive policies and strategic partnerships.
- **Domestic Demand:** The GOI will specify a minimum share of consumption of green hydrogen or its derivative products such as green ammonia, green methanol etc. by designated consumers as energy or feedstock. The year wise trajectory of such minimum share of consumption will be decided by the Empowered Group (EG).
- **Competitive Bidding:** Demand aggregation and procurement of green hydrogen and green ammonia through the competitive bidding route will be undertaken.

- **Certification framework:** MNRE will also develop a suitable regulatory framework for certification of green hydrogen and its derivatives as having been produced from renewable energy sources.

Strategic Interventions:

In the initial stage, two distinct financial incentive mechanisms are proposed with an outlay of INR 7.4 billion (or approximately USD 90 million) up to 2029-2030[55]:

- Incentive for manufacturing of electrolyzers;
- Incentive for production of green hydrogen.

Upon market and technology development, specific incentive schemes and programs will continue to evolve as the NGHM progresses.

To ensure quality and performance of equipment, participants bidding for the procurement of green hydrogen and its derivatives requires the project to utilize equipment approved by the GOI as per specified quality and performance criteria.

Pilot Projects

Targeted industries for pilot projects include long range heavy mobility, port and shipping, steel, and biomass to hydrogen, while other target areas include decentralized energy applications, hydrogen production from biomass, hydrogen storage technologies, etc. Budget outlays are provided below:

- Outlay of INR 4.55 billion (or USD 55 million) up to 2029-2030 for low carbon steel projects
- Outlay INR 4.96 billion (or USD 60 million) up to 2025-2026 for mobility pilot projects
- Outlay of INR 1.15 billion (or USD 14 million) up to 2025-2026 for shipping pilot projects

Green Hydrogen Hubs

The NGHM will identify and develop regions capable of supporting large scale production and/or utilization of hydrogen as green hydrogen hubs. The development of necessary infrastructure for such hubs will be supported under the Mission. It is planned to set up at least two such green hydrogen hubs in the initial phase with an outlay of INR 4 billion (or USD 48 million) up to 2025-2026 for hubs and other projects[56].

Additional features of the NGHM include:

- **Enabling Policy Framework:** To facilitate delivery of renewable energy for green hydrogen production, various policy provisions including inter-alia waiver of Interstate transmission charges for renewable energy used for green hydrogen production; facilitating renewable energy banking; and time bound grant of open access and connectivity, will be extended for green hydrogen projects.
- **Infrastructure Development:** The NGHM will support the development of supply chains that can efficiently transport and distribute hydrogen. This includes the use of pipelines, tankers, intermediate storage facilities, and last leg distribution networks for export as well as domestic consumption.
- **Mission Governance Structure:** An EG chaired by the Cabinet Secretary and comprising Secretaries of Government of India and experts from the industry will guide the Mission. An Advisory Group chaired by the PSA and comprising experts will advise the EG on scientific and technology matters. A Mission Secretariat headquartered in MNRE will undertake the program implementation.
- **Mission Outlay:** The initial outlay for the Mission will be INR 197.4 billion (~USD 2.2 billion), including an outlay of INR 7.4 billion (~USD 90 million) for the Strategic Interventions for Green Hydrogen Transition (SIGHT) program, INR 14.7 billion (~USD 169 million) for pilot projects, INR 4 billion for R&D (~USD 46 million), and INR 3.9 billion (~USD 44 million) towards other Mission components. MNRE will formulate schemes guidelines for implementation of the respective components.
- **Regulations and Standards:** The Mission will coordinate the various efforts for regulations and standards development in line with the industry requirements for emerging technologies. Work has commenced on establishing a framework of regulations and standards to facilitate growth of the sector and enable harmonization and engagement with international norms.
- **Research and Development:** A public-private partnership framework for R&D (Strategic Hydrogen Innovation Partnership – SHIP) will be facilitated under the Mission.

Skill Development

- Public Awareness, Stakeholder Outreach and International Cooperation

### Financing options

Various financing mechanisms may support initiatives for green hydrogen in India:

- **The SIGHT program,** as per the NGHM framework, offers substantial financial support for both electrolyzer manufacturing and green hydrogen production, which directly facilitates green ammonia production. Producers benefit from subsidies during the initial three years of production, reducing upfront capital investment risks. To address price volatility, contracts for difference (CFD) agreements ensure a minimum price for green hydrogen or ammonia, encouraging private sector investments in low-carbon ammonia projects[57]. The subsidies for green hydrogen production are applicable for three years starting with Rs50/kg (~0.58 USD) on the first year, Rs40/kg (~0.56 USD) on the second year and in third year Rs30/kg (~0.35 USD).

Additional subsidies include Capital Subsidy, State Transmissions charges waiver, electricity charges waiver.

5.5

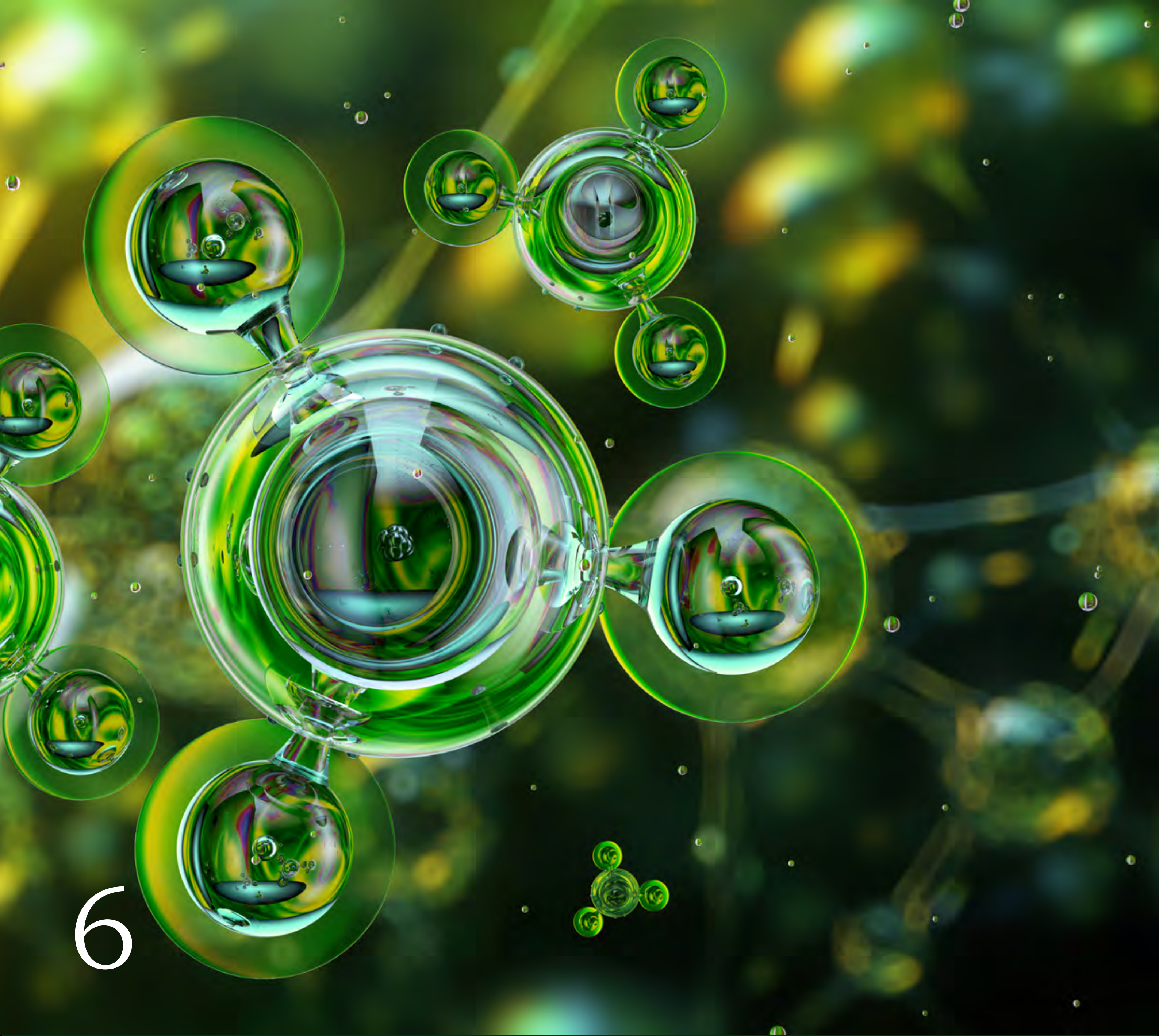
## Conclusion

India's green hydrogen market is expected to grow, driven by government initiatives and industry demand. Currently, its production costs between $3 and $6.5 per kg, which can be reduced through technological advancements and government incentives. This is imperative for green hydrogen to become commercially viable in India, as it is currently more expensive than grey hydrogen. It must fall to around $1 per kg to compete (not including potential carbon taxes).

This presents a major challenge for scaling up production, and requires advancements in electrolyzer technology, which plays a crucial role in green hydrogen production. As of now, the global electrolyzer manufacturing capacity is limited, with projections indicating a need for 65 GW of electrolyzer capacity in India by 2030 to meet domestic green hydrogen production targets[58].

India's abundant solar resources provide a competitive advantage, but challenges include high initial capital requirements and supply chain issues. India's green hydrogen market faces capital costs and infrastructure issues, requiring multilateral financing, green bonds, and government policies to reduce production costs and secure long-term financing. To facilitate investments options for project development, investors may explore the SIGHT Program.

As of 2025, the main driver to ensure the success of the National Green Hydrogen Mission is to guarantee the demand, which is currently stimulated by large tenders from public corporations such as IOCL or fertilizer companies. Indeed, the main focus of green hydrogen utilization is currently from large industries for conventional use of hydrogen (chemical, refineries, steel) and is yet to be viable and developed for energy purposes.



6

# Low-Carbon Ammonia

6.1

## Definition

Ammonia (NH3) is a vital component of modern industry, serving as a feedstock for fertilizers, plastics, rubber, fibers, explosives, and other products. However, ammonia production is responsible for nearly 2% of global $CO_2$ emissions, primarily due to the hydrogen extraction process from natural gas or coal[59].

These emissions can be significantly reduced or eliminated using low-carbon technology, which include:

- **Carbon Capture, Utilization and Storage (CCUS):** Capturing $CO_2$ emissions during production and storing it underground or utilizing it in durable products.
- **Electrolysis:** Producing hydrogen by splitting water using electricity generated from zero-carbon sources, such as renewables.
- **Ammonia is classified as "green"** when its production process is entirely renewable and free of carbon emissions (excluding embodied emissions from systems).

6.2

## Market Dynamics

India's current ammonia consumption is approximately 18.3 million tonnes annually, with over 90% used in fertilizer production (urea accounts for 80% of this consumption). Fertilizer manufacturers often operate captive ammonia production facilities (grey ammonia) to meet their internal needs, with excess production sold to traders or other consumers[60]. Traders aggregate demand from smaller consumers, enabling cost-effective supply and providing logistics support. The domestic merchant market accounts for only 2–3% of ammonia demand, with imports—mainly from regions with inexpensive natural gas like Qatar, Saudi Arabia, and Egypt—covering about 15%.

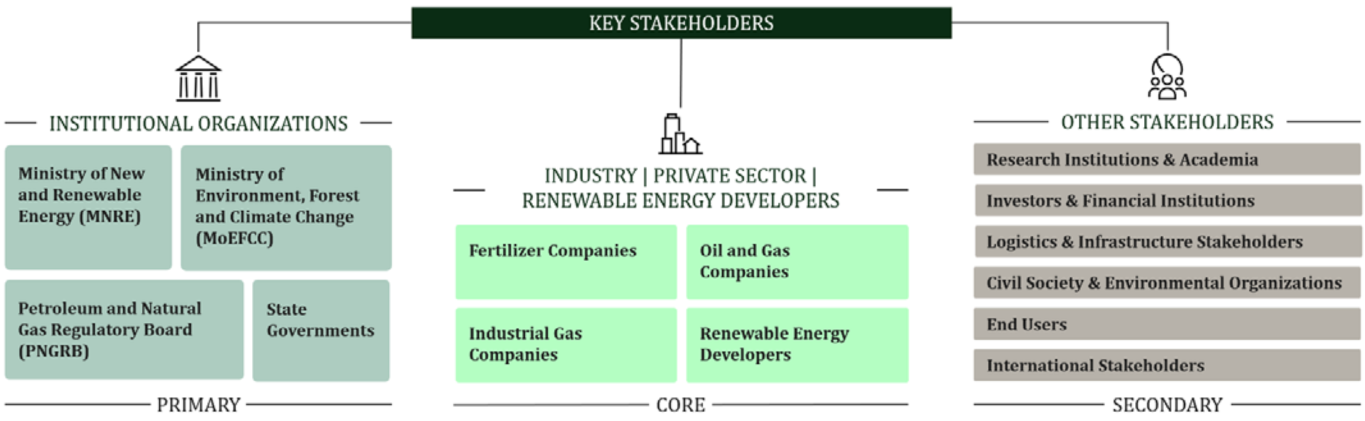
Green ammonia demand in India is expected to experience modest growth, primarily driven by the fertilizer sector, with additional but limited use in marine fuels, power generation, and hydrogen transport. Overall ammonia demand from fertilizer sector is projected to reach 18 million tonnes by 2025 and approximately 20 million tonnes by 2040, with green ammonia accounting for up to 20% of this by 2040 (~4 million tonnes). India's fertilizer sector is highly subsidized, with the government absorbing any price increases to prevent the burden from falling on consumers. Existing urea plants could transition to using 10–20% green ammonia with minimal capital investment, but this would increase annual subsidy requirements by INR 60-70 billion (USD 800 million). For other fertilizers like DAP, which can potentially use 100% green ammonia, the subsidy impact would be even higher.

The adoption of green ammonia in marine fuels and power generation is likely to remain limited due to cost challenges and competition from cheaper renewable energy alternatives.

Key stakeholders involved in green ammonia:

Key stakeholders involved in the that are active and/or may play a critical role in the development of green ammonia in India are shown below.

Figure 10: Stakeholders landscape for low carbon ammonia in India




Cost of green ammonia production

The cost-competitiveness of low carbon ammonia relies on primary production cost factors, like natural gas and clean electricity prices, both of which are volatile. Modern natural gas-based ammonia plants achieve production costs as low as USD 160/tonne, benefiting from economies of scale. However, these costs heavily depend on natural gas prices, which account for over half of the levelized cost of ammonia production. Since 2021, surging natural gas prices have driven global ammonia prices from USD 200–300/tonne to over USD 1,000/tonne in regions like Europe, the Middle East, and the United States (U.S.)[61].

In India, the production cost of grey ammonia is USD 640–660 per tonne at a delivered natural gas price of USD 12/MMBTU, with natural gas contributing 60–65% of total costs. The current pricing structure for natural gas ensures some insulation for fertilizer manufacturers from global price volatility. Green ammonia, however, remains significantly more expensive at USD 900–950 per tonne, largely due to the cost of renewable electricity (USD 60/MWh).

For green ammonia, production costs in major hubs primarily depend on the levelized cost of renewable electricity and government subsidies for hydrogen production.

The Council on Energy, Environment and Water published an analysis estimating the incremental cost of 10% blending green ammonia for fertilizer production from 8 to 17% (based on a production 28.3 MTPA and a levelized cost of 700USD/tonne)[62].

For blue ammonia, high capital requirements and long plant lifespans (up to 50 years) further hinder the evolution of the global ammonia production infrastructure. For example, building an 875 kt/year SMR-based ammonia plant involves approximately USD 1.68 billion in capital investment. Adding a CCUS retrofit increases costs by USD 335 million—roughly 20% of the initial investment. Emerging technologies, such as smaller reformers or oxygen-blown autothermal reformers (ATRs), could reduce these costs over time.

Additionally, blue ammonia production, like grey ammonia, relies on centralized facilities, incurring transportation costs of about USD 52/tonne via pipeline, USD 100/tonne via truck, or USD 140/tonne via railway for 1,600 km. In contrast, green ammonia, due to its modular production potential, offers opportunities for distributed production, reducing transportation costs.

**Table 13:** Levelized cost of energy for low-carbon ammonia in India[63]

| CAPEX (USD/tonne) | LOCE (US Cents/kWh) at 75% Utilization | Subsidy Support offered |
|---|---|---|
| 800 to up to 2240 (based on level of subsidies) | 5 – 5.5 | Total USD 2.4 billion subsidy announced |

Current initiatives for green ammonia in India[64]

**Table 14:** Examples of on-going projects for low-carbon ammonia in India

| Developer | Projects description |
|---|---|
| Uniper and GreenKo | Uniper, German Utility Company, signed a contract with GreenKo Group to source green ammonia from India. The agreement is for 250,000 tonnes per year of green ammonia from Greenko's Kakinada facility in Andhra Pradesh. The project is set to become a significant green ammonia production and export facility, with plans to expand its capacity to 1 million tonnes per year by 2027. |
| ACME and IHI Corporation | ACME Group, an Indian renewable energy company, and IHI Corporation, a Japanese heavy industry group, signed an offtake term sheet for the supply of 0.4 MMTPA of green ammonia from ACME's project in Odisha, India to Japan. The project represents a partnership across the value chain, from production to logistics and supply to Japanese customers. |
| ReNew and JERA | ReNew Power, an Indian renewable energy company, partnered with JERA, a Japanese utility, to jointly develop a green ammonia project in India. The project is expected to have a production capacity of 100,000 tonnes of green ammonia annually by 2030, with JERA having the right to offtake the ammonia for Japan. |
| Yara and ACME | Yara, a Norwegian crop nutrition company, and ACME Cleantech, signed a binding agreement for the supply of 100,000 tonnes per annum of renewable ammonia from ACME's project in Oman. Yara is actively expanding the market for renewable ammonia to help decarbonize. |
| AM Green | India's AM Green has partnered with Dubai-based global port and logistics firm DP World to develop infrastructure to export 1 million tonne per annum (MTPA) each of green ammonia and methanol. AM Green, which is targeting green fuel production capacity of 5 MTPA by 2030, has already committed to a 1 MTPA green ammonia plant in Kakinada in the southern state of Andhra Pradesh[65]. |

6.3

## Technical Considerations

The most common method of producing green ammonia involves generating hydrogen through water electrolysis and separating nitrogen from the air, both powered by renewable energy sources (e.g., solar, wind, or hydro). These components are then fed into the Haber-Bosch process, where nitrogen and hydrogen react at high pressure and temperature in the presence of a catalyst to form ammonia.

In contrast, conventional ammonia production relies on steam methane reforming (SMR) to produce hydrogen, followed by the Haber-Bosch process as can be seen in the figure below. This conventional approach results in significant $CO_2$ emissions, with SMR contributing approximately 90% of the total emissions from ammonia production[66].

Opportunities and challenges of low carbon ammonia

Low carbon ammonia has significant potential to decarbonize key sectors, including agriculture, shipping, and energy storage. However, its widespread adoption hinges on overcoming challenges related to costs, safety, and infrastructure. Innovations in renewable energy, carbon capture, and ammonia handling technologies will be crucial to shaping its role in a sustainable future.

The main opportunities and challenges are summarized as follows:

**Table 14:** Opportunities and challenges of low carbon ammonia

| Opportunities | Challenges |
| --- | --- |
| **Decarbonization Potential:** Low-carbon ammonia significantly reduces emissions.<br><br>Traditional ammonia production via the Haber-Bosch process emits about 1.8 tonnes of $CO_2$ per tonne of ammonia[67].<br><br>• **Efficient Energy Carrier:** It acts as a hydrogen carrier, enabling hydrogen storage and global shipping as ammonia, which can be reconverted to hydrogen at the destination.<br><br>• Fertilizer Decarbonization<br><br>• Maritime Fuel Applications | **Energy-Intensive Production:** Green ammonia production requires substantial renewable electricity—around 10-12 MWh per tonne of ammonia[68]. Insufficient renewable capacity could strain energy supplies.<br><br>**High Costs:** Green ammonia production is currently double to triple the price of conventional ammonia production, due to high renewable electricity and electrolyzer costs.<br><br>• **Energy Losses in Hydrogen Conversion:** Using ammonia as a hydrogen carrier involves energy-intensive cracking processes, with efficiency losses of 10–30%. Hydrogen leakage further diminishes climate benefits.<br><br>• **Toxicity and Safety Risks:** Ammonia is toxic and corrosive, posing risks during production, storage, transportation, and use. Leak management and safety protocols add operational complexity.<br><br>• **Competing Uses for Green Hydrogen:** Green hydrogen, a key input for green ammonia, has competing applications in sectors like fuel cells, industrial processes, and steel production, creating potential supply bottlenecks. |

Low carbon ammonia offers alternatives for decarbonizing essential industries, with its success dependent upon overcoming these economic, technical, and market challenges. A concerted focus on scaling renewable energy, developing efficient CCUS, and incentivizing adoption through policy frameworks is key to unlocking its full potential.

6.4

## Policies

The key policy supporting the development of low carbon ammonia is the NGHM, that includes specific sections related to ammonia production.

As described in section 5.3., India's NGHM aims to establish the country as a global leader in the production, use, and export of green hydrogen and its derivatives, such as green ammonia and green methanol.

Complementing the Mission, the upcoming Green Ammonia Policy focuses on hydrogen and ammonia production using renewable power and grid connectivity. Key provisions include[69]:

- **Renewable Power Access:** Manufacturers can purchase renewable energy or set up their own renewable generation units.
- **Interstate Waivers:** Waiver of interstate transmission charges for 25 years for projects commissioned by 30th June 2025.
- **Priority Grid Access:** Grid connectivity for manufacturers and renewable plants will be expedited.
- **Banking Renewable Power:** Manufacturers can bank unconsumed renewable energy for up to 30 days for later use.
- **Support for Ports:** Ports will provide land for ammonia storage bunkers to facilitate exports and shipping use.
- **Single-Window Clearance:** A portal will simplify approvals and statutory clearances for manufacturers.

Additional policies

Additional policies and initiatives have been developed to support the development of ammonia in India, including:

**Strategic Interventions for Green Hydrogen Transition (SIGHT):** The **SIGHT** Program, managed by the Solar Energy Corporation of India (SECI), incentivizes renewable ammonia production via competitive bidding[70]. Highlights include:

- **Annual Subsidy Allocation:** A total of 550,000 tonnes of ammonia production per year will be subsidized for three years from 2027.
- **Incentive Structure:** Subsidies of $106/tonne in year one and $85/tonne in years two and three[71].

**Green Hydrogen Standards:** Producers must meet the national carbon intensity standards established in 2023.

**Support for Green Shipping:** The Ministry of Ports, Shipping, and Waterways has revised its incentive program to encourage green fuel adoption. Key measures include:

**Funding for Vessels:** Up to 30% financial assistance for vessels using green fuels such as ammonia or hydrogen[72].

**Industry Growth:** Over the past four years, 88 alternatively-fuelled vessels have been ordered, with 69 already delivered, signalling a shift toward sustainable maritime operations.

Ministry of New and Renewable Energy (MNRE) will develop a suitable regulatory framework for certification of green hydrogen and its derivatives as having been produced from renewable energy sources.

### Financing options

Targeting green hydrogen, which is the main feedstock for green ammonia, the SIGHT programme provides significant financial backing for electrolyzer manufacturing and green hydrogen production, which directly supports green ammonia production. Producers can access subsidies for the first three years of production, reducing upfront capital investment risks[73].

Indian developers can also leverage green bonds and access funding from multilateral development banks like the Asian Development Bank and World Bank for projects aligned with climate goals.

6.5

## Conclusion

Guidance for prioritization of the use of ammonia will be critical as India is still relying on fertilizer imports.

All low carbon ammonia types face market reluctance to pay a premium for a lower carbon footprint. This makes policy interventions, such as subsidies and incentives, crucial for scaling demand and bridging the cost gap with grey ammonia.

The use of green ammonia for non-fertilizer applications is still limited and lacking a framework and/or standards at the national level. In upcoming years, green ammonia is anticipated to be a focus on the reduction of fertilizer imports and to lower the carbon footprint of the local sector. Its potential is dependent of the development of the green hydrogen supply chain in India, for which costs of renewable energy and electrolyzers will play a major role.

The maritime industry's efforts to meet the International Maritime Organization (IMO) ambitious targets for GHG reduction, by at least 20% by 2030 and by 70% by 2040 with a goal of net zero by 2050, should also lead the developments for incorporating green ammonia as an alternative fuel.

7

# Low-Carbon Methanol

7.1

## Description

Methanol ($CH_3OH$) is a liquid chemical used in a variety of applications, including plastics, paints, cosmetics, and fuels. It is mainly produced from synthesis gas (syngas), a mixture of hydrogen, carbon monoxide, and carbon dioxide, which can be derived from diverse feedstocks using various technologies. It is a versatile fuel suitable for internal combustion engines, hybrid vehicles, fuel cell vehicles, and marine vessels. As a liquid at ambient temperature and pressure, methanol is easy to store, transport, and distribute. It is compatible with existing distribution infrastructure and can be blended with conventional fuels, without requiring extensive infrastructure upgrades, enhancing its adoption potential. Additionally, it serves as a feedstock for producing chemicals and materials, allowing industries to reduce their reliance on fossil fuels and move toward a more sustainable production model when procured from low carbon sources.

### Low carbon methanol definition

The production and use of low carbon methanol in India is largely guided by global standards and certifications. However, the country is developing its own frameworks for low carbon fuels as part of the Methanol Economy Program, spearheaded by NITI Aayog[74]. These national frameworks are expected to align with international standards such as the International Sustainability and Carbon Certification (ISCC) and Product Carbon Footprint Standards (IMPCA) to ensure compatibility with global markets. These certifications help establish transparency and credibility in emission reductions, while also facilitating alignment with global regulatory frameworks, like the Carbon Border Adjustment Mechanism (CBAM).

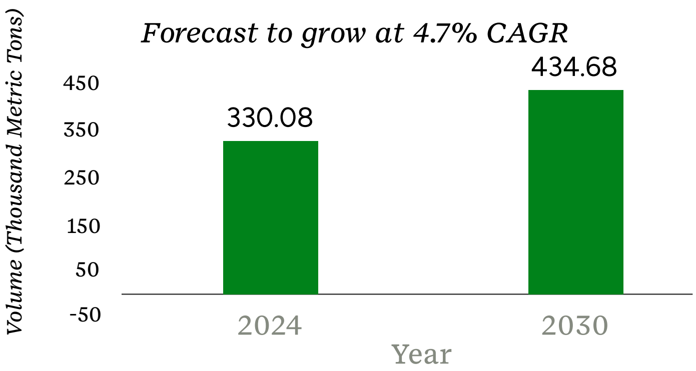
7.2

## Description

### Methanol production

India currently has an installed methanol production capacity of 2 million tonnes (MT) per annum. The Indian methanol market reached a total volume of 330 thousand metric tonnes in 2024 and is projected to grow to 435,000 metric tonnes by 2030, reflecting a compound annual growth rate (CAGR) of 4.73% during the forecast period.

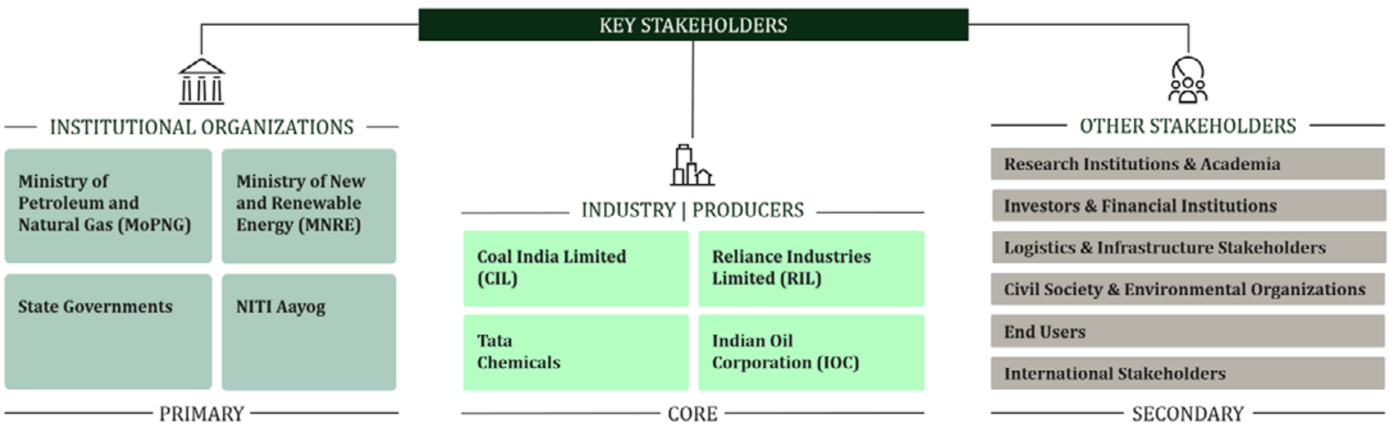
**Figure 11:** Indian methanol market[75]




Key stakeholders involved in low carbon methanol

Key stakeholders involved in the that are active and/or may play a critical role in the development of low carbon methanol in India are shown below.

**Figure 12:** Stakeholders landscape for low carbon methanol in India



Current trends and dynamics in India

Historically, India has relied on methanol imports to meet its domestic demand, but the country is now focusing on self-sufficiency and reducing its dependence on imports. The government has introduced various policies and incentives to boost domestic methanol production and attract investments in the sector. India's expanding chemical sector offers significant opportunities for methanol use.

As per a plan outlined by NITI Aayog, based on feedstock availability, the country has the potential to produce up to 20 MT of methanol annually, leveraging resources such as Indian high-ash coal, stranded gas, and biomass (with proven coal reserves of 125 billion tonnes and up 700 million tonnes of biomass)[76]. According to NITI Aayog, India's methanol economy is expected to generate around five million jobs across methanol production, application, and distribution sectors.

In this context, India is planning to expand its methanol production capacity with several key projects. These include the establishment of five high-ash coal-based methanol plants, five dimethyl ether (DME) production plants, and one large-scale natural gas-based methanol plant in collaboration with international partners.

The National Green Hydrogen Mission is also indirectly supporting the production of e-methanol by lowering the cost of hydrogen[77]. These policies aim to strike a balance between enhancing energy security and promoting environmental sustainability. With strong government support and growing international collaborations, methanol is poised to play a significant role in India's transition to a cleaner and more sustainable energy future.

At least five projects of e-methanol production have been identified in India[78]

**Table 17:** List of low-carbon methanol production projects

| Name | Developer | Location | Description | Status |
|---|---|---|---|---|
| NTPC Vindhyachal | NTPC | Vindhyacha, Uttar Pradesh | 3Kt capacity using $CO_2 + H_2$ (renewable) | Operational – Start 2024 |
| Thermax $CO_2$-to-Methanol | Thermax Limited | Pune, Maharashtra | $CO_2 + H_2$ (non-renewable) – Capacity unknown | Feasibility stage<br><br>Expected start in 2027 |
| NTPC – GACL | NTPC | Vadodara, Gujarat | 26Kt capacity using $CO_2 + H_2$ (renewable) | Feasibility stage<br><br>Expected start in 2029 |
| ReNew E-fuels Rayagada | ReNew | Rayagada, Odisha | 300Kt capacity using $CO_2 + H_2$ (renewable) | Feasibility stage<br><br>Expected start in 2029 |
| ReNew E-fuels Malkangiri | ReNew | Malkangiri, Odisha | 500Kt capacity using $CO_2 + H_2$ (renewable) | Feasibility stage<br><br>Expected start in 2030 |

### Costs

The production cost of e-methanol is significantly higher than conventional coal-based methanol, costing 2–4 times more. E-methanol prices range between IDR 35,000 to IDR 80,000 per tonne (USD 400–1,200 per tonne), driven primarily by the cost of renewable hydrogen and $CO_2$ capture. In contrast, fossil fuel-based methanol is priced at approximately IDR 10,000 to IDR 15,000 per tonne (USD 150–200 per tonne). Factors influencing the cost include renewable electricity prices, capital expenditure for electrolyzers and methanol synthesis plants, and the infrastructure required for $CO_2$ and methanol storage and transportation[79].

India's low-cost renewable electricity offers a competitive advantage for hydrogen production, although round-the-clock (RTC) electricity is essential for methanol synthesis. Access to concentrated $CO_2$ sources, such as those from cement plants, is available, but transportation infrastructure remains a challenge. Locating methanol plants near industrial hubs where $CO_2$ is abundant can help mitigate these costs. Scaling production facilities and improving electrolyzer efficiencies, along with leveraging economies of scale, could reduce costs by 30–50% by 2050[80].

Additionally, policies such as carbon taxes and green hydrogen subsidies could further improve cost-competitiveness.

### Barriers to Adoption

Despite its potential, several barriers hinder the large-scale adoption of low carbon methanol. Renewable hydrogen remains expensive, contributing significantly to production costs. While the technology for methanol synthesis from $CO_2$ and hydrogen is proven, scaling up production requires significant capital investment and policy support. Ensuring a stable, cost-effective supply of renewable energy and sustainable $CO_2$ sources is essential. Additionally, market reluctance to pay a "green premium" for low-carbon methanol further complicates adoption.

### Financing Options & Incentives

The financing options for low-carbon methanol align with those commonly used for other renewable energy projects, including Green Bonds, Concessional Loans, and investments from Private Equity and Venture Capital. Key government initiatives such as the Methanol Economy Program, the National Green Hydrogen Mission, and the Government of India's (GOI) policy to add over 50 GW of renewable energy annually until 2028 will play a crucial role in supporting and enabling the production of low-carbon methanol[81].

Additionally, the introduction of future carbon markets, such as the Carbon Credits Trading Scheme (CCTS), will provide financial incentives for producing low-carbon methanol by increasing the cost of conventional alternatives, making renewable methanol more competitive.

Infrastructure development is critical for scaling up methanol production. Investments in $CO_2$ capture, transport pipelines, and renewable energy supply chains will be essential. Government support for upgrading port facilities to store and transport methanol is another key enabler for the adoption of low-carbon methanol. Public-Private Partnerships (PPPs) involving government bodies, industries, and international organizations will be vital for securing the funding needed to implement large-scale methanol projects.

7.3

## Technical Considerations

The technical feasibility of low-carbon methanol production in India depends on several key factors, including the availability of feedstocks, integration with existing infrastructure, production technologies, and the scalability of operations. To reduce the carbon footprint of methanol production, several methods have been developed.

### Methanol production

Low carbon methanol can be categorized into two main types:

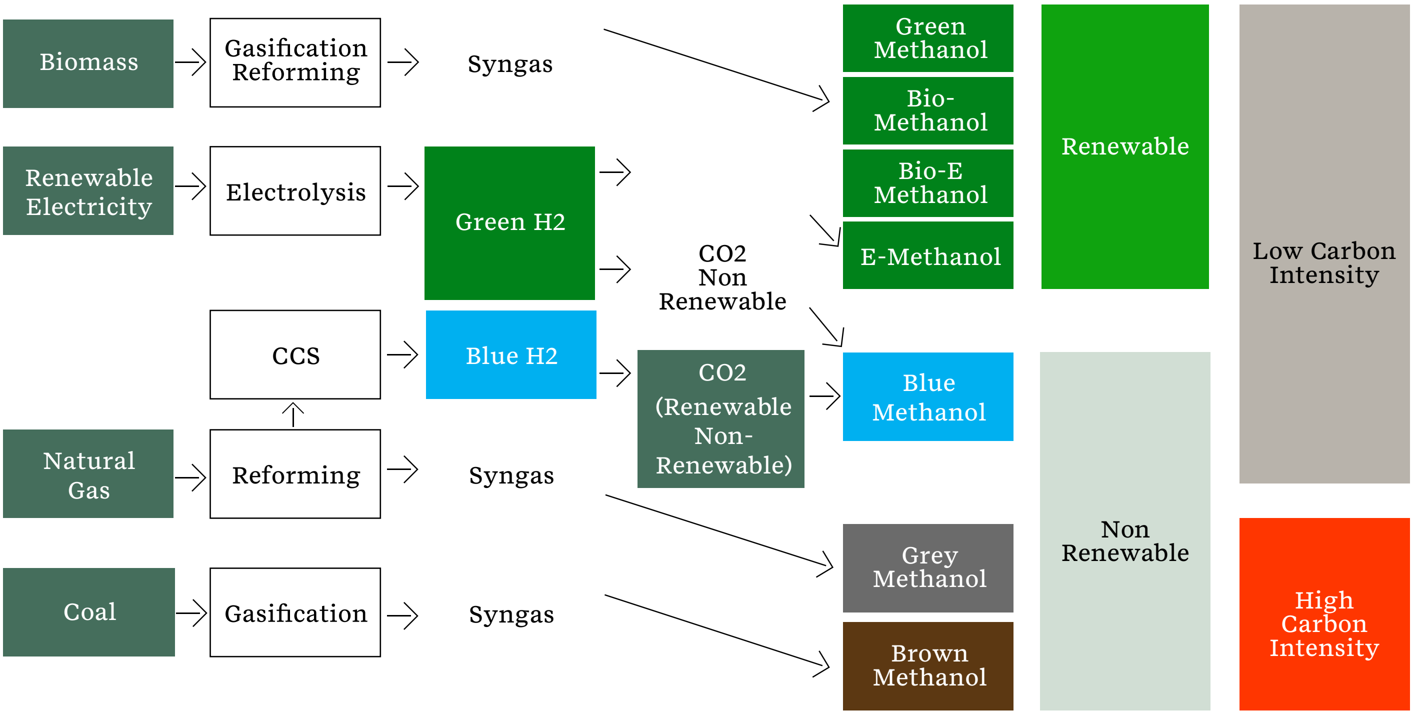
- Bio-methanol is produced from sustainable biomass sources such as agricultural residues, municipal solid waste (MSW), biogas, and byproducts from industries like pulp and paper. With over 700 million tonnes of biomass generated annually, a significant portion remains underutilized. Technologies for converting agricultural residues into syngas and methanol are commercially viable, and the gasification of biomass is already being deployed in India, with companies leading advancements in fluidized bed gasification.

- E-methanol is synthesized by combining green hydrogen, produced through water electrolysis (using renewable energy), with captured $CO_2$. Another approach is integrating $CO_2$ from external processes into the methanol synthesis loop, which helps minimize emissions.

These production methods provide significant environmental benefits, including a reduction in $CO_2$ emissions by 60–95%, nitrogen oxide emissions by 60–80%, and near-complete elimination of sulfur oxides and particulate matter[82]. The use of renewable feedstocks further reduces carbon emissions associated with methanol production and combustion, while also supporting a circular economy using waste streams as raw materials. The selection of the pathway and feedstock depends on factors such as availability, cost, sustainability goals, and technological maturity.

These pathways underscore the potential of low carbon methanol as a key contributor to global decarbonization efforts, enabling industries and nations to reduce their carbon footprint while leveraging existing infrastructure.

**Figure 13:** Methanol production pathways[83]




<u>Comparison of bio-ethanol and bio-methanol feedstocks, applications and performances.</u>

Bio-ethanol and bio-methanol utilization may overlap due to their similar characteristics:

**Table 15:** Existing challenges for low-carbon methanol development in India

| Challenges | Description |
| --- | --- |
| Feedstock & Production | • Agricultural residues high in lignin, such as rice husks, wheat straw, and sugarcane bagasse, are generally more advantageous for bio-methanol production. These residues are more compatible with thermochemical processes like gasification, which can efficiently convert them into syngas for methanol synthesis.<br>• Methanol synthesis and ethanol fermentation can be processed from lignocellulosic biomass. Comparing two pathways, a study estimated that the bio-methanol production process was preferable to the bio-ethanol process in terms of thermal efficiency, carbon conversion and environmental burden, except electrical energy consumption[84]. |

| Challenges | Description |
| --- | --- |
| Utilization | • When biofuels are employed in internal combustion engines, bio-methanol has greater potential for gasoline substitution, but the difference in expected $CO_2$ reduction is rather small due to higher power consumption in methanol production.<br>• Bio-ethanol has traditionally been prioritized as it is the most compatible biofuel with traditional gasoline engines due to lower corrosivity. In both cases, lower blending ratios of bioethanol (up to E10) or bio-methanol (up to M10) are more feasible for traditional ICEs. However, higher blends necessitate specific vehicle modifications (especially for methanol) to handle the corrosive nature and different combustion characteristics of these biofuels.<br>• M15 (15% methanol blended with gasoline) is not easily compatible with traditional ICE cars in India without significant modifications. The corrosive nature of methanol, its lower energy density, and the need for material compatibility make it unsuitable for general use in vehicles that are not designed for methanol. If India was to move toward larger-scale use of methanol blends like M15, there is a need for regulations, incentives, and an infrastructure overhaul (fuel stations, vehicle modifications) to make the transition feasible. In the absence of these, the use of bio-ethanol (like E10 or E20) is currently more viable and compatible with the existing vehicle fleet in India. |
| Policies driving specific fuel production/blends | • India's bio-ethanol policies, including the National Bio-Energy Policy and the Ethanol Blending Program (EBP), aim to achieve 20% ethanol blending in petrol (E20) by 2025. This has created a strong demand for ethanol feedstocks, supported by subsidies and incentives that particularly favor production from sugarcane molasses and grain-based sources.<br>• In contrast, the Methanol Economy Program is focused on reducing crude oil imports by promoting methanol as a fuel for transportation and industry. However, policies for methanol blending are still at early stages, with limited direct support for methanol production from biomass. As a result, robust policy backing for ethanol skews biomass utilization toward ethanol production, reducing the availability of biomass for methanol and other green fuels. |
| Integration with existing infrastructure | • Methanol, in liquid form at room temperature, is compatible with India's existing fuel storage, transport, and distribution systems. Retrofitting existing methanol plants to accommodate bio- or e-methanol synthesis is technically feasible and cost-effective. However, significant upgrades to port infrastructure and pipeline networks are necessary to support large-scale imports, exports, and domestic logistics. |

7.2

## Policies

India has implemented a variety of policies to foster the production and utilization of low carbon methanol as part of its overarching strategy for decarbonization and energy transition. These initiatives are designed to reduce dependence on imported fossil fuels, decrease GHG emissions, and capitalize on domestic resources such as coal, agricultural residues, and captured $CO_2$. Below are three key policies driving the adoption of low-carbon methanol in India.

**Table 16:** Existing policy landscape for low carbon methanol in India[85]

| Existing Policies | Description |
|---|---|
| National Green Hydrogen Mission (NGHM) | Refer to Section 5.3 for details about the NGHM that aims to increase investments into green hydrogen that can further be used to produce e-methanol. |
| Methanol Blending | The Ministry of Road Transport and Highways (MoRTH) has set official blending standards for methanol, including M15, M85, and M100, to integrate methanol with conventional fuels. The standards also include guidelines for blending Dimethyl Ether (DME) with LPG to reduce household fuel costs. These methanol blends are expected to reduce urban air pollution and cut GHG emissions by up to 20% when compared to traditional fuels. |
| Methanol Economy Program by Niti Aayog | This initiative was launched to reduce India's oil imports and curb greenhouse gas emissions by promoting methanol as a green fuel across various sectors, including transportation, industry, and cooking.<br><br>Key features of the NITI Aayog's Methanol Economy plan include:<br><br>• **Large-scale Methanol Production:** Using Indian high-ash coal and indigenous technologies, methanol production can be scaled up at a cost of around INR 19 per litre, with $CO_2$ capture technology ensuring that coal use aligns with environmental goals and India's COP21 commitments.<br><br>• **Alternative Feedstocks:** Biomass, stranded gas, and municipal solid waste (MSW) will contribute to approximately 40% of methanol production.<br><br>• **Diversified Applications:** Methanol and DME will be used in transportation (rail, road, marine, and defence), industrial boilers, diesel gensets, power generation, and mobile towers.<br><br>• **Blending with gasoline:** The program advocates for the blending of methanol with gasoline (15% blend), which can decrease oil imports by 15% and mitigate emissions of particulate matter, nitrogen oxides (NOx), and sulfur oxides (SOx)<br><br>• **Domestic Use:** Methanol and DME will also be used for domestic cooking, with a blending program for LPG.<br><br>• **Fuel Cell Applications:** Methanol will be utilized in fuel cells for marine, genset, and transportation uses. |

| Existing Policies | Description |
| --- | --- |
| Methanol Economy Program by Niti Aayog | • **Fuel Cell Applications:** Methanol will be utilized in fuel cells for marine, genset, and transportation uses.<br>As part of its roadmap, NITI Aayog aims to replace 10% of crude oil imports by 2030 with methanol, requiring approximately 30 MT of methanol. Methanol and its derivative, DME (dimethyl ether), are significantly cheaper than petrol and diesel, and by 2030, India could potentially reduce its fuel bill by 30%. |

7.5

## Conclusion

India is developing its own framework for low-carbon fuels, including methanol, as part of the Methanol Economy Program, under the leadership of NITI Aayog.

Commercially established methanol synthesis technologies and India's NGHM support e-methanol development. The Indian methanol market is expected to grow by 4.73% by 2030, driven by government initiatives to promote it as a cleaner transportation fuel. The integration of green methanol with existing infrastructure is feasible and cost-effective, but significant upgrades to port infrastructure and pipeline networks are needed for large-scale imports, exports, and domestic logistics.

Nevertheless, low-carbon methanol is facing direct competition with conventional methanol production with Niti Aayog encouraging production from all potential pathways including from coal-sources. Conversely, bio-methanol feedstocks and applications overlap with bio-ethanol.

From a short-term perspective, bio-ethanol may be preferred as it is a ready substitute for gasoline for conventional vehicles. From a long-term perspective, bio-methanol has greater potential for gasoline substitution and $CO_2$ mitigation. As renewable electricity becomes cheaper and green hydrogen technology advances, the e-route can contribute to increase the development of low carbon methanol without competing with bio-ethanol in terms of feedstock.

# 8

# Sustainable Aviation Fuels

8.1

## Description

Sustainable Aviation Fuels (SAFs) are liquid fuels with the same properties as conventional jet fuels that originate from renewable energy resources, either bioenergy or renewable electricity. Their compatibility with existing aircraft technology and refueling infrastructure makes them so-called “drop-in-fuels”.

They can be produced from several sources, including waste fats, oils and grease, municipal solid waste, agricultural and forestry residues, wet wastes, as well as non-food crops cultivated on marginal land. They can also be produced synthetically via a process that captures carbon directly from the air.

SAFs can be considered ‘sustainable’, when their feedstocks do not compete with food crops or output, nor require incremental resource usage such as water or land clearing, and more broadly, do not promote environmental challenges such as deforestation, soil productivity loss or biodiversity loss.

8.2

## Global Dynamic

According to IATA, to achieve net zero by 2050 in the aviation sector, SAF will contribute 65% share towards reduction in emissions needed by aviation to reach net-zero in 2050.

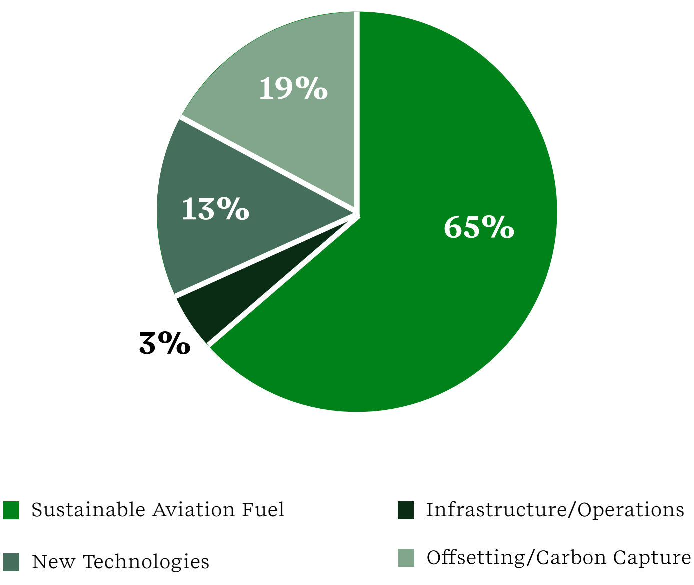



**Figure 14:** Expected contribution from GHG mitigation opportunities for aviation sector decarbonization (IATA)

Globally, countries are taking ambitious blending mandates. For example, the European Union (EU) has laid a detailed roadmap until 2050 for using bio-SAF and synthetic SAF. Additionally, the EU’s regulations also specify feedstock acceptable for SAF production.

The obligation for aviation fuel suppliers to ensure that all fuel made available to aircraft operators at EU airports contains **a minimum share of SAF from 2025 and, from 2030, a minimum share of synthetic fuels,** with both shares increasing progressively until 2050. Fuel suppliers will have to incorporate 2% SAF in 2025, 6% in 2030 and 70% in 2050. From 2030, 1.2% of fuels must also be synthetic fuels, rising to 35% in 2050.

SAF production increased to 600 million liters (~0.47 million tonnes) in 2023 and is estimated to reach 1,900 million liters (~1.5 million tonnes) in 2024 globally. Most of the existing facilities today are based on the HEFA technology pathway.

<u>Production costs depending on the technologies</u>[86]:


**Figure 15:** Future projections for the average selling price of HEFA, FT, ATJ, AND E-JET Pathways

| Existing Policies | HEFA | FT | AtJ | E-jet |
|---|---|---|---|---|
| CAPEX range (%) | 22 to 40% | 54 to 81% | 45 to 75% | 5 to 20% |
| OPEX range (%) | 8 to 10% | 12 to 21% | 2 to 14% | 5 to 15% |
| CAPEX range (%) | 51 to 69% | 0 to 32% | 20 to 44% | 70 to 85% |

**Table 19:** CAPEX, OPEX, AND Feedstock range of contribution to the production costs

Key stakeholders involved in Sustainable Aviation Fuels (SAFs) in India

Key stakeholders involved in the that are active and/or may play a critical role in the development of Sustainable Aviation Fuels (SAFs) in India are shown below.

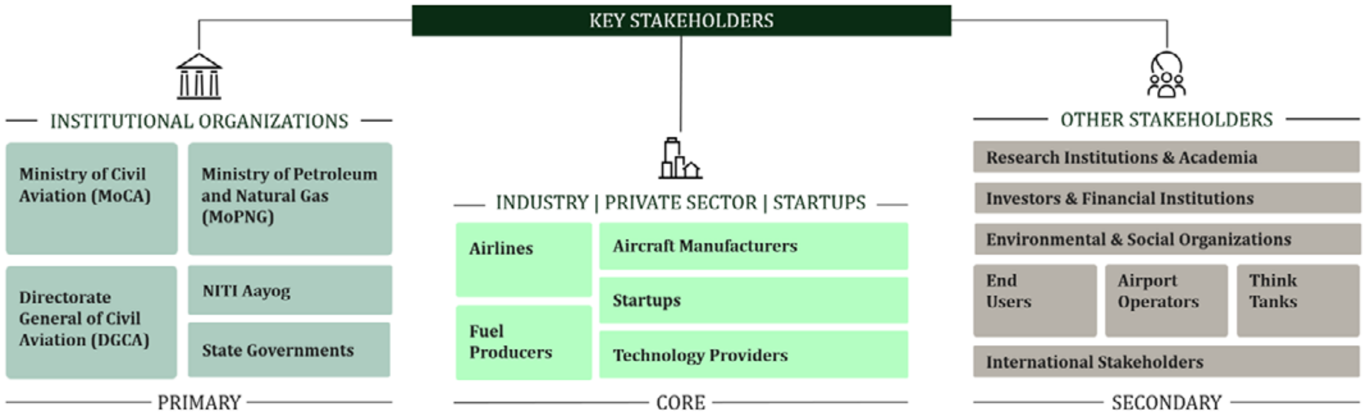



**Figure 15:** Stakeholders landscape for SAFs in India

### Dynamic in India

India's aviation industry has experienced significant growth in the past 10 years. India's aviation sector is forecast to grow at ~11%over the next few years due to infrastructure development, aircraft capacity addition, increasing Tier 2/3 connectivity and evolving passenger preferences for air travel due to which, the severity of aviation emissions is estimated to increase. The domestic air passengers have more than doubled in the past decade, with Indian airlines significantly expanding their fleets. On the other hand, the number of operational airports in the country has doubled from 74 in 2014 to 157 in 2024 and the aim is to increase this number to 350-400 by 2047.

- Aligning with CORSIA requirements, India has set indicative SAF blending targets for international flights by 1% by 2027 and 2% by 2028. Below are existing initiatives from India's stakeholders in the SAF market:

- Indian state-controlled refiner India Oil Corporation plans to achieve at least 1% sustainable aviation fuel (SAF) blending in jet fuel by July-September 2025, ahead of the government's aim of 2027.

- IOCAL is also collaborating with LanzaJet[87] which has developed a patent for SAF production with Alcohol-to-Jet (ATJ) technology.

- In India, multiple airline operators – Indigo, Vistara, AirAsia and SpiceJet– have undertaken test flights with SAF blends as high as 25%.

- To promote SAF, Indian Oil Marketing companies are setting up plants at three locations in the state of Karnataka, Maharashtra and Haryana. India is also pursuing innovative consortium partnerships to promote SAF.

- In addition to liquid biofuel, Sustainable Alternative Towards Affordable Transportation (SATAT)" was launched on 1st October 2018 to promote biogas as well. Oil and Gas Marketing Companies (OGMCs such as IOCL, HPCL, BPCL, GAIL and IGL) are inviting expression of interests from potential entrepreneurs to procure CBG from their projects.

As specific initiatives, the Indian Institute of Petroleum under the Council of Scientific & Industrial Research (CSIR, CSIR-IIP) has established a pilot plant for SAF production at Dehradun for flight tests by the Indian Air Force. The maiden biofuel flight in the country by SpiceJet was also fueled by the CSIR-IIP production facility (Tripathi, 2022). Recently, CSIR-IIP, SpiceJet, and Boeing have joined hands to explore opportunities for the use of SAF in the Indian aviation industry. CSIR-IIP is also currently awaiting ASTM certification for the commercial production of SAF at a capacity of 15,000 liters per day (approximately 3,200 tonnes annually).

Current Jet fuel and projected SAF consumption

The annual jet fuels consumption in India can be seen on the following page[88]. As per the Petroleum Planning and Analysis cell, percentage of jet fuels used by international aviation represented 23-27% of the consumption.

**Table 20:** Jet fuel consumption in India

| Existing Policies | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 |
|---|---|---|---|---|---|---|
| CAPEX range (%) | 8.1 (projection based on data from Apr to Dec.) | 4.3 | 5.0 | 6.9 | 8.2 | 9.6 (projection based on data from Jan to Sept.) |
| Jet fuel consumption by international aviation MMT/yr (%) | | | | | 2.0 (24%) | 2.6 (27%) |

**Table 21:** Projected SAF demand by 2030 based on corsia requirements

| Projected SAF demand[89] | 2027 | 2028 | 2030 |
|---|---|---|---|
| Blending requirement | 1% | 2% | 5% |
| SAF demand at constant consumption from 2024's levels | 0.026 MMT/yr<br>34 million liters | 0.052 MMT/yr<br>68 million liters | 0.130 MMT/yr<br>170 million liters |
| SAF demand with a 11% yearly increase from 2024 levels | 0.035 MMT/yr<br>46 million liters | 0.079 MMT/yr<br>103 million liters | 0.242 MMT/yr<br>319 million liters |

8.3

## Technical Considerations

Each SAF variety works with different technologies, cost profiles, carbon abatement profiles, environmental impact, and of course, feedstock. Main pathways for producing SAF can be simplified as follows:

Bio-based SAF:

There are currently five internationally approved processes through which SAFs can be produced. Each of these pathways has its benefits, such as the availability of feedstock, cost of the feedstock, carbon reduction or cost of processing. While some may be more suitable than others in certain areas of the world, all pathways have the potential to help the aviation sector significantly reduce its carbon footprint. Hydro processed Fatty Acid Esters and Free Fatty Acid (HEFA) production is currently the most commonly used pathway.

**Table 22:** Main SAF production pathways

| Production Pathway | TRL | Max. Blend | Feedstock |
|---|---|---|---|
| Hydro processed Fatty Acid Esters and Free Fatty Acid (HEFA) | 9 | 50% | Oil-bearing biomass, such as algae, jatropha and camelina |
| Fischer-Tropsch Synthetic Paraffinic Kerosene (FT-SPK)<br><br>Fischer-Tropsch Synthetic Paraffinic Kerosene (FT-SPK/A) | 7-8 | 50% | Renewable biomass such as municipal solid waste, agricultural wastes and forestry residues, wood and energy crops |
| Hydro processing of Fermented Sugars - Synthetic<br><br>Iso-Paraffinic kerosene (HFS-SIP) | 5-7 | 10% | Made through the microbial conversion of sugars to hydrocarbon |
| Alcohol-to-Jet Synthetic Paraffinic Kerosene (ATJ-SPK) | 5-7 | 30% for isobutanol and 50% for ethanol | Alcohol from agricultural waste products, such as stover, grasses, forestry slash and crop straws |
| Catalytic hydro thermolysis synthetic jet fuel (CHJ) | 6 | 50% | Made from triglyceride-based feedstocks such as plant oils, waste oils, algal oils, soybean oil, jatropha oil, camelina oil, carinata oil and tung oil |

**Synthetic SAF:**

Electricity generated from renewable sources, carbon dioxide recovered from industrial emissions, and green hydrogen created by the electrolysis of water are all combined to create hydrocarbon-based e-fuels. By mixing airborne nitrogen that has been separated with green hydrogen using the Haber-Bosch process, e-ammonia is produced without the need for $CO_2$. Methanation for e-methane, methanol synthesis for e-methanol, reverse water-gas shift (RWGS) reaction to create syngas, followed by Fischer-Tropsch synthesis to make e-FT fuels are often documented synthesis procedures for the generation of hydrocarbon-based e-fuels.

The current state of e-fuel production faces difficulties, necessitating further work before it can be used commercially. The overall Technology Readiness Level (TRL) for e-fuels such as SAF (e-jet, e-methanol for jet) is evaluated between five to eight depending on $CO_2$ source.

The production costs for e-fuels are currently more expensive than fossil fuels. Their production processes are more energy consuming due to the synthesis steps involved, converting at best half of the energy in the electricity into liquid or gaseous fuels. The energy losses from manufacturing are high due to the many processes involved. This this might be justified where electrical propulsion is not practical and renewable electricity is cheap and plentiful. Innovation in each process stage has the potential to reduce these costs in the future to enable production and scale-up.

8.4

## Policies

The main policy/framework in place to support the development is the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) led by the International Civil Aviation Organization (ICAO) globally and the Directorate General of Civil Aviation (DGCA) responsible for implementing and ensuring compliance with CORSIA guidelines in India. DGCA adopted guidelines for environmental protection developed by ICAO (including CORSIA) on 24th July 2023[90].

The scheme requests indicative blending targets of 1% by 2027, 2% by 2028 and 5% by 2030 of Sustainable Aviation Fuel in Traditional Aviation Fuel for international flights.

8.5

## Conclusion

SAFs are liquid aviation fuels derived from renewable energy sources, such as bioenergy or electricity. The International Civil Aviation Organization (ICAO) develops the framework for SAF development through CORSIA, which aims to reduce $CO_2$ emissions by up to 80%. SAFs can be produced through bio-based and synthetized pathways, each offering unique benefits like feedstock availability, cost, and carbon reduction, assuming sustainability criteria are met. Despite higher production costs and energy losses, innovation in each process stage could reduce costs and enable commercialization.

Among the challenges to be tackled for increased development and adoption of SAF, the following elements can be noted:

- **Production Cost:** While normal jet fuel cost is around 200-300 dollar per tonne, SAF production costs are around 1,000-1,500 dollars per tonne depending on the technology.
- **Technology and feedstock:** Production pathway is mostly HEFA technology, with Used Cooking Oil (UCO) as one of the main feedstocks. Due to limitation of feedstock availability SAF producers needs to transition from HEFA to other technology pathways such as Power-To-Liquid, with feedstock with limited competition with other usages such as road transportation.
- **Regulations and Incentives:** Promote specific incentives for reducing costs of SAF against conventional fuels such as capital investment subsidies for SAF production or flexible fiscal between fuels and/or with penalties for companies not adopting SAF.

Despite these challenges, India is aligning with the IACO-CORSIA roadmap aiming to 1% SAF in jet fuel for international flights by 2027, with this percentage doubling to 2% by 2028 and 5% by 2030. To achieve these targets, the country will require approximately 140 million liters of SAF annually.

Key players include Indian Oil Corporation that aims to achieve at least 1% SAF blending in jet fuel by July-September 2025.

A recent report by Deloitte highlights India's significant potential in sustainable aviation fuel (SAF) production, projecting that the country could generate 8-10 million tonnes of SAF annually by 2040[91].

9

# Opportunities and Challenges Summary

9.1

## Definition

As described from Sections 2 to 8, the technologies, policy landscape and market are emergent for green fuels and multiples challenges are yet to be overcome for these fuels to take a significant market share compared to conventional fuels. Collaboration with international stakeholders, including private sector can therefore support India in the development of these green fuels, leveraging on the opportunities provided by the local institutions and businesses.

The following table is developed on a Strengths-Weaknesses-Opportunities-Threats (SWOT) approach and summarizes key considerations to have before engaging in green fuels activities development for Danish businesses in India.

**Table 23:** SWOT Analysis for green fuels development for Danish businesses in India

| Strengths | Weaknesses |
|---|---|
| • **Advanced technologies:** Danish companies possess advanced technology in renewable energy and green fuel production, such as electrolysis and Power-to-X solutions.<br>• **Successful case studies:** Various companies have successfully implemented large-scale renewable energy projects, including offshore wind farms and green hydrogen production.<br>• **Market Leadership:** Danish companies are leaders in the green energy sector but also maritime (Maersk) or solutions for agriculture sectors, with a strong presence in Europe and growing influence globally.<br>• **Existing presence in India:** Several Danish companies already have a long-term presence in the country, having built commercial relationships with local companies, developed market share and with their own production capacities.<br>• **Bilateral Support:** The Green Fuels Alliance India (GFAI) is part of the Green Strategic Partnership signed in 2020 between India and Denmark, reflecting strong political commitment from both nations towards sustainable energy collaboration. | • **Market Competition:** Danish companies face competition from other global players, especially in emerging markets like India.<br>• **Limitation in real case projects on green energy which are mainly limited to European context:** Most successful projects and case studies are based in Europe, with limited data on projects in India or other regions.<br>• **Challenges in maturity of infrastructure, technologies, regulation in India**<br>• Danish companies have advanced technologies however there will be challenges in implementation in India is the market is still developing hence the infrastructure and regulatory is still inadequate to support the development of green fuels.<br>• Some fuels and feedstocks, such as ammonia are hindered by the need for specialized infrastructure, including pipelines, storage tanks, and maritime bunkering facilities, which differ significantly from existing systems.<br>• **The availability of feedstock:** India has a significant potential for biofuel feedstocks, including crop residues, used cooking oil, and municipal solid waste. However, the industry is still scaling up, and there are challenges related to cost and supply chain management. |

## Strengths

## Weaknesses

- Conversely, carbon capture is still embryotic in India, limiting as of now possibilities for e-fuels.
- Market Access to International Company: International companies can access the Indian market, but they often need to partner with local stakeholders or create joint ventures (JVs) to navigate regulatory and market challenges.

## Opportunities

- **Political Stability:** India's political landscape has been relatively stable and the commitment of the government for GFAI is a good sign for international companies to start considering India as a potential green fuel development hub.
- **Multiple financial mechanisms:** Both domestic financing and international and multilateral instruments available to support important capital investments across fuels.
- **Demand rise in India's energy and chemical sectors:** Rising energy demand, expanding chemical sector, and focus on sustainability position low-carbon methanol as a versatile, clean-burning solution for fuel, feedstock, and power generation.
- **National Policy incentives:** India has policy incentives for most green fuels, including the National Green Hydrogen Mission (which also includes Green Ammonia), Biofuels Policy, SAF blending targets and the Methanol Economy Programme. These provide opportunities and a broader access to stakeholders willing to expand.
- **India's Growing Aviation Sector:** India's doubling of airports and domestic air passengers over the past decade, alongside 11% projected aviation growth, and blending targets for international flights, highlights a strong demand trajectory for SAF adoption.

## Threats

- **Supply Chain Constraints:** The decentralized production of second-generation feedstocks, such as agricultural residues, increases logistical complexity and costs for collection, transportation, and storage, particularly in rural areas.
- **Regulatory Inconsistencies Across States:** Different states prioritize varied crops and feedstock types, creating regulatory fragmentation and complicating nationwide deployment of advanced green fuel projects.
- **Global Competition:** Other international players, including those from the US, are aggressively entering the Indian green fuel market, intensifying competition for market share
- **Infrastructure Gaps:** India lacks sufficient infrastructure for scaling up sustainable aviation fuel (SAF), ammonia pipelines, and renewable hydrogen storage, posing logistical challenges
- Policy Gaps and Misalignment: While India's biofuel policies support second-generation technologies development, specific incentives and infrastructure for feedstock management and processing are still inadequate, creating barriers to scaling.

## Opportunities

- **State-driven opportunities:** India offers diverse opportunities for green fuels, with Gujarat, Maharashtra, and Tamil Nadu leading in green hydrogen, e-methanol, and ammonia production, while Uttar Pradesh, Madhya Pradesh, and Punjab stand out for biofuel and SAF production due to abundant agricultural residues and second-generation feedstock availability.

- **Advancements in Carbon Capture Utilization and Storage (CCUS):** Policies incentivizing CCUS enable cost reductions for producing green fuels like methanol and ammonia, positioning India as a hub for advanced decarbonization solutions.

- **Expanding Infrastructure and Industry Synergies:** India's rising energy demand and industrial growth, particularly in the chemical and transport sectors, drive demand for low-carbon methanol, hydrogen, and other green fuels

## Threats

- **Environmental Risks:** Over-reliance on agricultural residues could lead to soil degradation if crop residues are removed without replenishing nutrients, drawing criticism and potential regulatory action.

- **Competing Uses:** Agricultural residues often serve existing purposes, such as animal feed or soil conditioning. Diverting them to biofuel production could lead to conflicts with local communities or other industries.

- **Limited Awareness of advanced fuels:** Limited awareness and trust in advanced green fuels among policymakers, industries, and end-users in India hinder adoption, investment, and policy focus, creating significant market entry barriers for emerging technologies.

- **Regulatory Challenges:** Differences in regulatory frameworks between India and Denmark could pose challenges in implementing joint projects under the GFAI.

# 10

# Conclusion

India is a fast-growing market with a constantly developing policy yet politically stable landscape. Coupled with available financing mechanisms that support capital-intensive structure and its government's commitments, the country holds multiple facets that enable opportunities in the green fuels market for private companies.

In this context, private developers are expected to play a more significant role in green fuels development based on the policies developed by national authorities. It is therefore pertinent to continue exploring opportunities to increase the support for green fuels, particularly in terms of financing. Certain policies have set financing instruments expected to facilitate projects profitability and implementation such as the Pradhan Mantri Ji-Van Yojana and SIGHT programs. Additional financing options including debt-based or multilateral financing can also be explored in Appendix C. Important tenders are commercial plants development are already occurring for supporting green fuels production to replace conventional fuels consumption locally and to drive the demand particularly from strategic industries.

With growing interest from international partners, like Denmark under the India-Denmark Green Strategic Partnership, there is an increased emphasis on understanding India's green fuel sector, addressing existing challenges, and capitalizing on emerging opportunities.

Danish companies can benefit from their progress in the development of advanced technologies, with successful case studies and market leadership in various sectors such as Maersk in the maritime sector. Its presence in India with existing or future partnerships with local companies should be leveraged to facilitate opportunities in the development of green fuels in the country.

Denmark may face market competition, including for real case projects which are limited to only European countries, as well as challenges in the maturity of infrastructure, technologies, regulation in India, and the availability of feedstock and market access to international companies. This can be seen as hurdles to overcome by companies to successfully implement projects or to gain trust from locally implanted companies.

**Way forward:**

Based on the findings from the Green Fuels Baseline Market Study & Roadmap, it is recommended to proceed with the following actions:

1. **Monitor green fuels-related announcements from national and local institutions:** Stay informed about announcements from institutional agencies and ministries regarding updates to the policies, regulations and call for applications and projects for financing support.

2. **Screen local investors and developers:** Conduct a thorough screening of potential developers to identify suitable candidates for collaboration.

3. **Engage relevant stakeholders:** Initiate engagement with relevant stakeholders as outlined in Section 3 and Appendix A for each different fuel.

4. **Update technical and E&S reviews:** Perform and/or update the technical and environmental and social screenings based on any new information that is collected.

5. **Explore partnerships:** Discuss partnership opportunities with selected developers to support the development or upgrading of targeted green fuels projects, with the aim of securing additional financing.

# Acronyms

| | |
|---|---|
| ATR | Autothermal Reforming |
| BECCS | Bioenergy with Carbon Capture and Storage |
| CAGR | Compound Annual Growth Rate |
| CBAM | Carbon Border Adjustment Mechanism |
| CBG | Compressed biogas |
| CCTS | Carbon Credits Trading Scheme |
| CCUS | Carbon Capture, Utilization, and Storage |
| CNG | Compressed Natural Gas |
| $CO_2$ | Carbon dioxide |
| CORSIA | Carbon Offsetting and Reduction Scheme for International Aviation |
| DME | Dimethyl Ether |
| EBP | Ethanol Blended Petrol |
| EOR | Enhanced Oil Recovery |
| FT | Fischer-Tropsch |
| GBA | Global Biofuels Alliance |
| GFAI | Green Fuels Alliance India |
| GHG | Greenhouse Gases |
| $H_2$ | Hydrogen |
| HEFA | Hydro processed Fatty Acid Esters and Free Fatty Acid |
| ICAO | International Civil Aviation Organization |
| IEA | International Energy Agency |
| LCAF | Low Carbon Aviation Fuels |
| LCOE | Levelized Cost of Energy |
| LNG | Liquefied Natural Gas |
| LPG | Liquefied Petroleum Gas |
| MeOH | Methanol |
| MMT | Million Metric Tonnes |
| MNRE | Ministry of New and Renewable Energy |
| MONPG | Ministry of Petroleum and Natural Gas |
| MORTH | Ministry of Road Transport and Highways |
| MTBE | Methyl tert-butyl ether |
| MTOE | Million-tonne equivalent oil |
| MTPA | Million tonne per annum |
| NPB | National Policy on Biofuels |
| NDC | Nationally Determined Contribution |
| NGHM | National Green Hydrogen Mission |
| NH3 | Ammonia |
| NITI Aayog | National Institution for Transforming India Aayog |
| NZE | Net Zero Emissions |
| OEM | Original Equipment Manufacturer |
| OMC | Oil Manufacturers Companies |
| PPP | Public-Private Partnerships |
| PtG | Power-to-Gas |
| PtL | Power-to-Liquid |
| PtX | Power-to-X |
| RE | Renewable Energy |
| REC | Renewable Energy Certificates |
| SAF | Sustainable Aviation Fuels |
| SATAT | Sustainable Alternatives Towards Affordable Transportation |
| SIGHT | Strategic Intervention of for Green Hydrogen Transition |
| SMR | Steam Methane Reforming |
| VGF | Viability Gap Funding |

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91 India's sustainable aviation fuel potential

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