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ADVANCED REFINING AND FUTURE FUELS: INDIA 2047

Petroleum Planning & Analysis Cell
(Ministry of Petroleum & Natural Gas, Government of India)
2nd Floor, Core-8, SCOPE Complex, 7
Institutional Area, Lodhi Road, New
Delhi - 110003, India www.ppac.gov.in
Email: ppac-mopng@ppac.gov.in
(only for PPAC Journal related communication)

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Editorial

With the urgent need for global net-zero CO_2 emissions to halt global warming, there is a focus on reducing fossil fuels. Oil, with 31.7% being the largest part of world energy, is obviously at the heart of the discourse. But the world knows that oil cannot be eliminated totally because today it touches our lives in more ways than just fuel. Our cars do not just run on petrol and diesel but are largely made of plastic polymers, which come from petrochemicals. Our kitchens rely on LPG for cooking, and most of the white goods around us are made of petrochemicals. Oil is also a building block of heart valves, medicines, and many products that are termed necessities today.

This makes it difficult to reduce dependence on oil for long times. As a result, we see that refining capacities have gone up by 10% in about the last ten years. Today world has 104.523 mbpd refining capacity. Over 1k bpd of refining capacity has been added during 2024 alone. In such a "dependent scenario," it becomes important that refineries become advanced and consume minimal energy and produce fuels which have minimal emissions. In this backdrop, PPAC decided to bring out its Independence Day edition of the PPAC Journal on the theme of Advanced Refining & Future Fuels: India 2047.

India is the 4th largest refiner in the world, with 23 refineries of 5.2 mbpd capacity, and is a net exporter of the refined products. However, the demand for fuels is expected to rise.

According to various estimates, India's primary energy demand is poised to grow at an average rate of ~3% per annum until 2050, compared with the average global growth rate of <1% per annum. India also aspires to remain a net exporter. To meet this demand, the country is planning to add capacity. One 9 MMTPA refinery is rising in the desert of Rajasthan. Another similar capacity refinery is coming up at the site of an earlier old small refinery at Cauvery Basin. Many other existing refineries are undertaking expansion-cum-modernization projects. These green and brown additions total up to 55.55 MMTPA and take the country's refining capacity to 309.5 MMTPA by 2030. Two more refineries have been announced recently to keep pace with the demand.

The critical part of these additions is that these refineries need to be very advanced in nature with higher complexity so that they can process various crude oils into valuable products, especially fuels and petrochemicals. While refineries in the initial days in the 19th century were just to make kerosene, the modern refineries make a vast range of products, including petrochemicals. There is greater emphasis on making refining itself and its products sustainable to meet the larger goal of net zero. In this context, refineries need to reconfigure to be more flexible for product slate in line with market demands. Refineries also need to be advanced in terms of integrating petrochemicals. To make the refineries sustainable, there is enhanced focus on processes like residue upgradation & catalytic cracking, biofuels, and green hydrogen.

A simple refinery configuration in the 1950s had crude oil distillation, naphtha/kerosene/ATF treatment, and catalytic reforming for upgrading naphtha to petrol, with no secondary processing, low energy recoveries, and high sulphur FO as internal fuel. In later periods, the configurations were modified to include units, viz., continuous catalytic reforming, hydrocracker, and hydro-treating/hydro-desulphurisation facilities to generate low-sulphur fuels. Newer refineries in India have been built with state-of-the-art technology; the existing refineries, including vintage refineries, have also been continually expanded and modernized.

The 23 articles in this edition speak loud and clear about the resolve of the Indian oil industry to meet the demand of petroleum products in the country and also to take Indian refining to the next level of highest complexities and sustainability.

We are thankful for the overwhelming response from the experts and organizations. Their taking out time to write for this journal not only reiterates the commitment of India towards the vision of Atmanirbhar Bharat.

We acknowledge the sincere support of Shri Brijesh Kumar, Advisor, CHT for assisting PPAC in reviewing articles.

We would like to add that views expressed in the articles are those of the writers in their personal/official capacities, and PPAC has only provided a platform for knowledge sharing. PPAC/MoPNG are not responsible for any errors, omissions, discrepancies, and disputes arising out of these articles. PPAC/MoPNG are also in no way endorsing any of the organizations that have contributed to the journal.

Suggestions and feedback from the readers are invited for improvement of the PPAC Journal. We also invite articles for our next issue, which will be on the theme of “Ensuring Energy Security: The Role of Energy Policies of States.”

Dr Pankaj Sharma, Editor
Addional Director, PPAC

Message from

Director General

"Innovation is not merely a word or an event. It's an ongoing process. You can innovate only when you understand a problem and try to find out its solution. We must go to the root of the problem and find out-of-the-box solutions... In the era where knowledge is power, innovation is the driver of growth." — Hon'ble Prime Minister Shri Narendra Modi.

As India charts its path towards **Viksit Bharat 2047**, technological advancements in the oil and gas sector are poised to play a pivotal role in driving energy security, economic resilience, and industrial transformation. From the digitalization of operations to the adoption of clean and advanced refining technologies, the sector stands at the forefront of enabling a sustainable, efficient, and future-ready energy ecosystem.

The **Petroleum Planning & Analysis Cell (PPAC),** an attached office of the **Ministry of Petroleum & Natural Gas**, continues to uphold its mandate of collecting, analyzing, and disseminating vital data for the oil and gas sector. Through its periodical reports and research, PPAC has remained a trusted repository of sectoral insights. Aligned with India's vision for a sustainable and self-reliant energy future, PPAC has been proactively supporting the development and adoption of advanced refining technologies and future fuels. These efforts aim to modernize the energy sector, reduce environmental impact, and drive innovation in line with the country's long-term energy transition goals.

The **4th edition of the PPAC Journal**, released as a special **Independence Day edition,** highlights the ongoing efforts in **Advanced Refining** and **Future Fuels** that are shaping India's energy journey in alignment with the vision of Viksit Bharat 2047. This edition provides a platform for domain experts to share insights, best practices, and innovative solutions contributing to a sustainable and responsible energy future.

Advanced refining technologies are central to India's pursuit of a cleaner and self-reliant energy economy. These innovations not only enhance efficiency and fuel quality but also significantly reduce emissions. Through the integration of cutting-edge digital solutions, residue upgradation, and crude-to-chemical conversion, India's refining infrastructure is being modernized to meet evolving energy demands while minimizing environmental impact.

Future fuels—such as green hydrogen, synthetic fuels, and cleaner derivatives from integrated refinery and petrochemical complexes—are emerging as game-changers in India's energy transition. By enabling the domestic production of low-carbon, high-efficiency alternatives, these fuels reduce import dependence, support decarbonization goals, and lay the groundwork for new industrial value chains. These efforts are aligned with India's **Net Zero 2070** commitment and the broader vision of Atmanirbhar Bharat.

India's refining sector is being rapidly transformed through targeted investments in refinery upgrades, digital transformation using AI, IoT, and predictive maintenance, and the integration of carbon capture and energy efficiency measures under national schemes such as PAT. The focus on indigenous R&D, academic collaboration, and public-private partnerships is creating a globally competitive, technologically advanced, and sustainable refining ecosystem.

The success of this transformation rests on key strategies:

i. Modernizing refinery infrastructure through advanced technologies.

ii. Promoting R&D in future fuels.

iii. Fostering public-private investment and clean fuel infrastructure.

iv. Strengthening policies that enable energy transition.

v. Building a digitally skilled and future-ready workforce.

vi. Integrating refining and petrochemicals for enhanced value addition.

vii. Encouraging international collaboration for technology and innovation.

India's proactive efforts in embracing and developing advanced refining technologies and future fuels underscore its commitment to building a cleaner, more self-reliant, and energy-secure future. These advancements are not only improving operational efficiency and environmental performance but also positioning India as a hub of innovation and responsible industrial leadership. I am confident that this edition of the journal will offer valuable insights into the transformative role of advanced refining and future fuels in India's energy landscape, while inspiring greater collaboration and investment across the value chain.

I extend my sincere appreciation to all contributors and the editorial board of PPAC for their dedication in bringing this edition to life.

Inspired by the words of our Hon'ble Prime Minister during India Energy Week 2025, that *"India is driving not only its growth but also the growth of the world, with the energy sector playing a significant role,"* let us collectively reaffirm our commitment to building a sustainable future. The oil and gas industry continues to play a critical role in powering India's development— driving technological innovation, enabling the transition to cleaner fuels, and laying the foundation for Viksit Bharat 2047 and a more sustainable, inclusive world.

P. Manoj Kumar
Director General
Petroleum Planning & Analysis Cell (PPAC)
Ministry of Petroleum & Natural Gas
Govt. Of India

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Digboi (IndianOil); Estd.-1901

1 Barrels of Change: Tracing India's Refining Evolution

Shri K Vikrant Rao, Asst. Director (Supply);
Shri Priyanshu Raparia, Asst. Director (D&ES);
Shri Deepak Trivedi, Addl. Director (D&ES)

Petroleum Planning and Analysis Cell, MoPNG

1. Introduction

India's refining journey is approaching its sesquicentenary; it has evolved from batch process to continuous process in its initial years. From processing merely ~0.5 MMT of crude oil at the time of independence, India has grown to a network of 23 refineries with an annual crude throughput exceeding 260 MMT, placing the country among the top global refining nations and a significant exporter of clean petroleum products. These were a result of both brownfield and greenfield expansion projects.

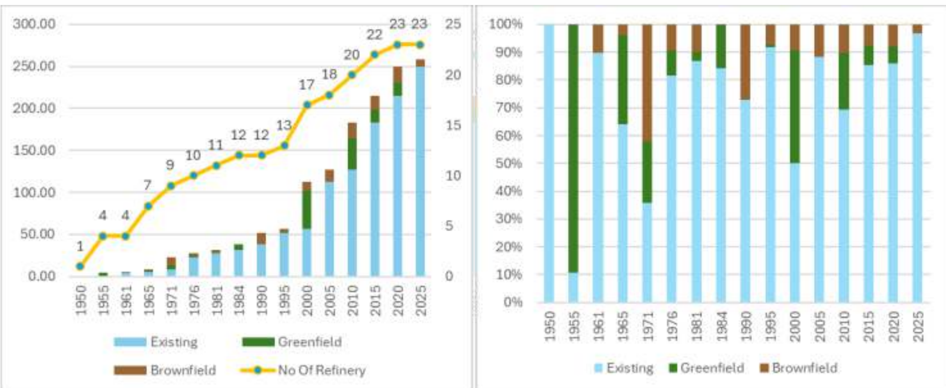


Figure 1: Greenfield and Brownfield Capacity Expansion of Indian Refineries

Over the last few decades, Indian refiners have continuously reconfigured and expanded their facilities; the factors were driven by evolution of automobile industry, domestic and commercial electrification, GDP growth, development of alternate fuel, and tightening environmental policies. Indian refineries have evolved from simple configurations involving crude distillation, catalytic reforming, and hydrotreating to complex refineries incorporating vacuum distillation or flashers, catalytic crackers, alkylation units, and gas processing systems. Ultimately this progression has culminated in the establishment of very complex refineries equipped with delayed coking units, residue upgradation technologies, and integrated petrochemical production capabilities.

2. Laying the Foundations: Historical Development up to 1980s

The origins of India's oil refining trace back to the late 19th century. In 1866, the Calcutta-based firm McKillop, Stewart & Co. began systematic drilling in Upper Assam and struck oil at Makum near Margherita. In 1890, the Assam Railways and Trading Company (AR&T Co.) discovered a significant oilfield, which was named the Digboi oilfield. In 1893, AR&T Co. established a modest refinery at Margherita to process crude from Makum and Digboi.

By 1901, the Digboi Refinery was operational. In 1923, the entire plant was rebuilt. By the 1930s, the site had added several new units, such as an Edeleanu Plant for treating kerosene with sulphur dioxide, a Dubbs Plant for cracking, and a Bitumen Plant. In the 1950s, lube oil and gasoline extraction plants were also set up.

Post-Independence, government and legacy private firms (American & European) laid a seed on the west coast, where Burmah-Shell (now BPC Mumbai-1955) and Esso (now HPC Mumbai-1954) commissioned their Bombay plants in the 1950s and installed some of Asia's earliest catalytic crackers, setting a benchmark for high-octane motor spirit. Similarly on the east coast, nested between the Bay of Bengal and the Eastern Ghats, Caltex Oil Refining (India) Ltd. established Visakhapatnam Refinery (1957).

During the 1960s, the focus of nation-building efforts expanded to include the eastern and southern regions of the country. Guwahati Refinery (1962), established in the Northeast with Romanian collaboration, became India's first public sector refinery-a greenfield venture that included a pilot delayed Coker unit. Kochi Refinery (1963) opened a vital supply corridor to the southern region, while Barauni Refinery (1964), developed with Soviet assistance, served the Indo-Gangetic plain with lubricant and calcined coke production. The multi-train Gujarat Refinery at Koyali (1965–68) quickly rose to become the nation's largest refining complex, incorporating Crude Distillation Units (CDUs), Vacuum Distillation Units (VDUs), and Vis breaking capacity. This initial developmental phase culminated with Haldia (1975) on the Hooghly and Bongaigaon (1979) in the Northeast, further fuelling the eastern seaboard. The era saw continuous debottlenecking, larger furnaces, vacuum distillation, Vis breaking, and LPG recovery at all sites.

During this formative period, the country reached 12 refineries with a crude processing capacity of 31 MMT. The product slates were centred on kerosene (illumination), furnace oil for industry, and limited motor spirit.

3. Conversion and Diversification: The 1980s and 1990s Transition

The 1980s and 1990s marked a period of transformation for India's refining sector. Earlier refineries were designed to process light, sweet indigenous crude, but rising demand created the need for enhancement in refining capacity. This led to the establishment of new refineries and the reconfiguration of existing ones to handle heavier, sour grades. The share of indigenous crude in the total crude basket peaked at 65% during the 1980s before gradually declining as product demand continued to rise. During 2024, the LS:HS crude processing ratio was approximately 21:79.

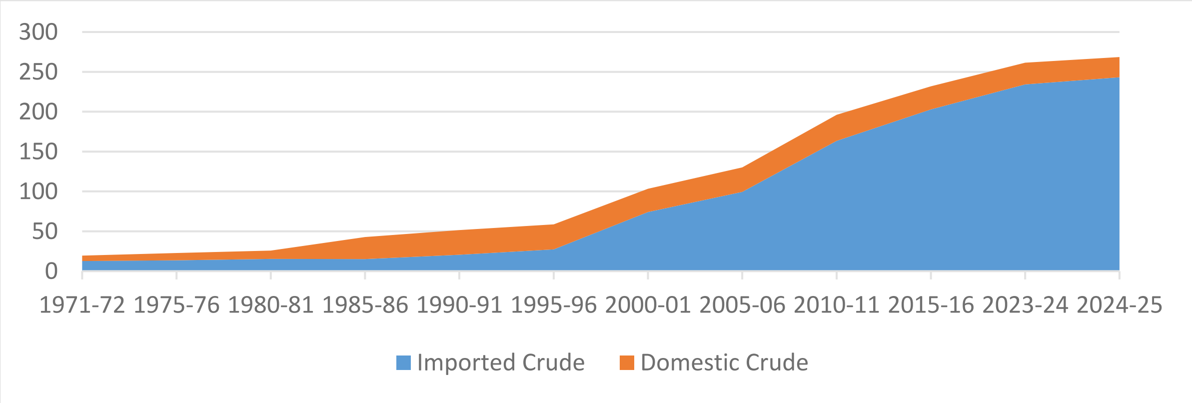


Figure 2: Processing of Imported and Domestic Crude

This growing dependence on heavier, sour imported crude made residue management a major challenge. To address this, refiners progressively installed and increased capacities of units such as Vacuum Distillation, Vis Breakers, Propane De-Asphalting, Bitumen Blowing, and Delayed Cokers to convert heavy residues into lighter products and other products.

Refiners increased producing products like 80/100 Bitumen, Carbon black feedstock, Paraffin Wax, Slack Wax in this era.

The 1980s also saw the start of Lube base oil and specialty solvent capacities (Hexane, SBP) at select sites, while aromatics recovery emerged at Koyali and elsewhere to serve petrochemical chains. These moved diversified revenue streams and created operational flexibility.

In 1993–94, Gujarat Refinery commissioned the country's first hydrocracker unit to convert heavier ends of crude oil into high-value products. This was followed in 1999 by the commissioning of India's first Diesel Hydrodesulphurization (DHDS) unit to reduce sulphur content in diesel.

4. The Configuration Wave of 2000s–2020s: Rise of Very Complex and Integrated Refinery-Petrochemical Hubs

During this phase, several high-complexity, high-conversion refineries were established with private participation and joint ventures-such as RIL Jamnagar (DTA and SEZ), Essar Vadinar (now Nayara Energy), Bharat Oman Refineries Ltd., Bina (now BPCL), and HPCL-Mittal Energy Limited (HMEL), Bhatinda. These refineries incorporated advanced technologies, including integrated multi-train Delayed Cokers, Residue Gasification units for hydrogen and power generation, multi-stage Claus units with Tail Gas Treating Units (TGTUs), and sulphur recovery complexes. Their design and configuration enabled the production of Bharat Stage (BS) Grade at par with Euro-grade fuels, while allowing for the export of surplus distillates, indicating India's capability to build world-class refining infrastructure.

PSU refiners built new Greenfield refineries like Paradip and ran massive brownfield projects like the expansion of Vizag, Kochi, Numaligarh, etc. Indian refineries had now transitioned from simple and complex configurations to the category of very complex refineries.

Earlier, the refineries and petrochemical complexes used to be distinct. Refineries primarily used to supply feed stocks like naphtha, chemicals, and off-gases to petrochemical plants, yielding valuable building blocks like ethylene, etc. However, with the anticipated surge in petrochemical demand in the coming decades, a new trend emerged: both brownfield and greenfield refineries began integrating petrochemical capacities within their complexes. This strategic shift led to the development of integrated refinery-petrochemical complexes at key locations such as Paradip, Panipat, Jamnagar, Bhatinda, and Kochi.

5. Fuel Quality as a Catalyst: Policy-Driven Refinery Transformation

India's most significant refinery reconfigurations were driven by clean-air and public health imperatives, which translated into phased fuel-quality mandates over time.

5.1 From Leaded to Unleaded Petrol

Metro air-quality actions during the 1990s introduced low-lead petrol and unleaded grades in Delhi, Mumbai, Kolkata, and Chennai, with nationwide low-lead by 1997 and a national unleaded mandate effective in 2000. Leaded petrol was ordinary gasoline dosed with the anti-knock additive Tetra-Ethyl Lead (TEL), which raised octane and left a protective lead-oxide film on exhaust-valve seats. It was phased out because of its toxic nature. Lead limits tightened from 0.56 g/L in the 1980s to 0.15 g/L in 1994 and were eliminated nationwide by April 2000. Removing TEL required refiners to generate higher octane blending components; hence, processes like platforming/catalytic reformers, isomerization (e.g., n-C5/C6 to iso-paraffins), and the blending process of MTBE/TAME etherification were introduced.

5.2 Bharat Stage Roadmaps: Auto Fuel Policy 2003 to Auto Fuel Vision 2025

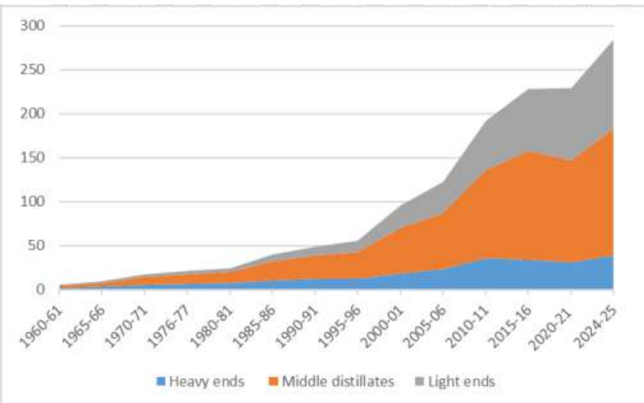
Fuel specifications based on environmental considerations were notified by the Ministry of Environment & Forests in April 1996. Further, based on the Supreme Court order of April 1999, the Ministry of Surface Transport (MoST) notified Bharat Stage-I (BIS 2000) and Bharat Stage-II vehicle emission norms broadly equivalent to Euro I and Euro II for introduction in all of India and the NCR, respectively. In line with the Auto Fuel Policy (2003), starting from 2005, fuel conforming to BS III norms was introduced in 13 major cities. The Auto Fuel Vision & Policy 2025 review (2014) recommended skipping BS-V, and, in a landmark 2016 decision, the government leapfrogged directly to BS-VI 10-ppm fuels for the entire nation on 1 April 2020.

Bharat Stage	BS I (BIS 2000)	BS II	BS III	BS IV	BS VI
MS Sulfur max (ppm)	≈1 000 ppm (0.1 wt%)	500 ppm (0.05 wt %)	150 ppm	50 ppm	10 ppm
RON† min	88	88	91	91	91
Benzene vol % max	n/a	3	1	1	1
HSD Sulfur max (ppm)	2 500 ppm (0.25 wt %)	500 ppm	350 ppm	50 ppm	10 ppm
Cetane No. min	48	48	51	51	51
Density @15°C kg m^{-3}	820-860	820-845	820-845	820-845	820-845

To meet the BIS specification, Indian refineries re-engineered both gasoline and diesel value chains. For Motor Spirit (MS), Benzene, Olefin, and Aromatic caps were taken care of by the isomerization units. Dedicated FCC-gasoline desulphurization units, Naphtha Hydrotreaters and alkylation ensured high RON and low sulphur fuel. For high-speed diesel (HSD) upgradation processes, like Diesel Hydro-Desulphurisers (DHDS), high-severity DHDTs, VGO hydrotreaters, and once-through or recycle hydrocrackers, were installed.

6. Evolving Product Slate: Trends and Shifts from 1960 to 2025

The product slate of a refinery is the reflection of both the advancement of technology and consumer behavior. The change in product slate shows that refiners have been equipped with more conversion capacities, which can mold the hydrocarbon structure as per the demand. This was achieved with the diversification of secondary units. It is evident that residue upgradation progressively diverted heavier bottoms to upgradation. Therefore, the Light: Middle: Heavy ratio flipped from 1: 2.5: 2 in the 1960s to roughly 2.4: 3.7: 1 in 2024.



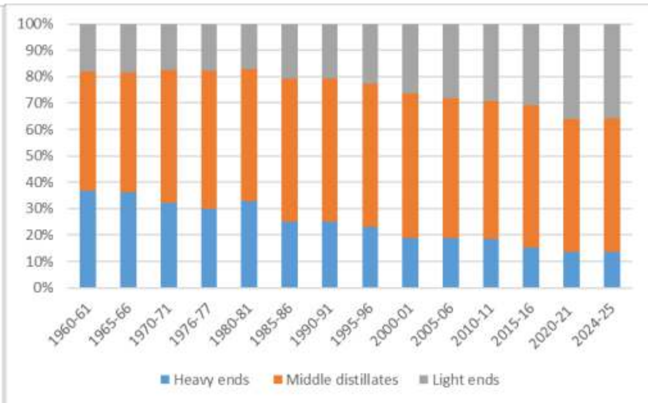


Figure 3 : Gradual change in Light, Middle & Heavy Distillate

6.1 Lights Ends

Light distillates-such as LPG, gasoline, and naphtha-have low boiling points, typically ranging from 70°C to 200°C, are highly volatile, and are primarily used as fuels and chemical feedstocks. They are the finished products in both gaseous and liquid states. Its production has ballooned from ~1 MMT in the 1960s to ~101 MMT in 2024. As for the percentage composition of the refined products, it has jumped from 17% to 37%.

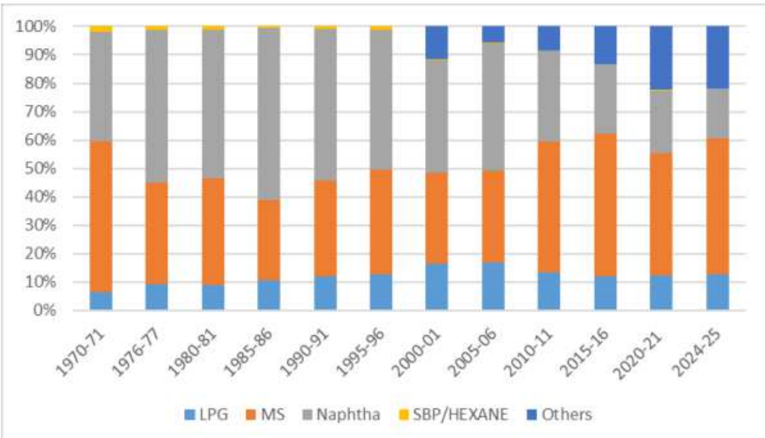


Figure 4 : Evolution of Light Distillates

Refinery-sourced LPG was negligible in 1960s (~0.008 MMT) but reached ~12.8 MMT 2024. As a share of crude processing, it increased from 0.4% to 5%, this was made possible by enhanced gas recovery from secondary processing units driven by strong policy push through household clean cooking programmes. The consumption of LPG has increased from 0.2 MMT in late 60s to 31 MMT in 2024.

Motor Spirit output grew from ~1.3 MMT in the mid-1960s to ~48 MMT in 2024. The MS Story is linked with the rapid urbanization and rise in sales of light vehicles.

The growth of MS and Naphtha went hand in hand, making most of the lighter distillates. In fact, until the start of the millennium, the percentage share of naphtha production was greater than MS. However, with the consistent increase in demand for MS from the 80s and with policy factors, Refinery started installing Reformers and Hydrotreaters to convert straight-run naphtha into high-octane, low-aromatic, and low-sulphur Motor Gasoline. This is reflected in production as well, as the MS production during the 1960s was 1.2 MMT, which had risen to 3.3 MMT in 1990, and from there it has exponentially grown to 48 MMT in 2024. Whereas the Naphtha Production was ~1.4 MMT in 60s has grown to 18 MMT in 2024.

Also, with the increase in the petrochemical demand, refiners started consuming the naphtha cut by converting it into petrochemical products, thereby increasing the production of other lighter products.

6.2 Middle Distillates Remain the Workhorse-But Composition Shifts

Middle distillates (like kerosene and diesel) have intermediate boiling points, typically around 200-350°C, and are used as fuel for various applications. They are usually in a liquid state. Their production has increased from 2.6 MMTPA in the 1960s to 142 MMT in 2024. As for the percentage composition of the refined products, it has steadily increased from 42% to 54%, thanks to hydrocrackers and hydrotreaters. Within this pool, HSD expanded from ~1.6 MMT to ~118 MMT, increasing its percentage share from 20% to 42% in the crude mix.

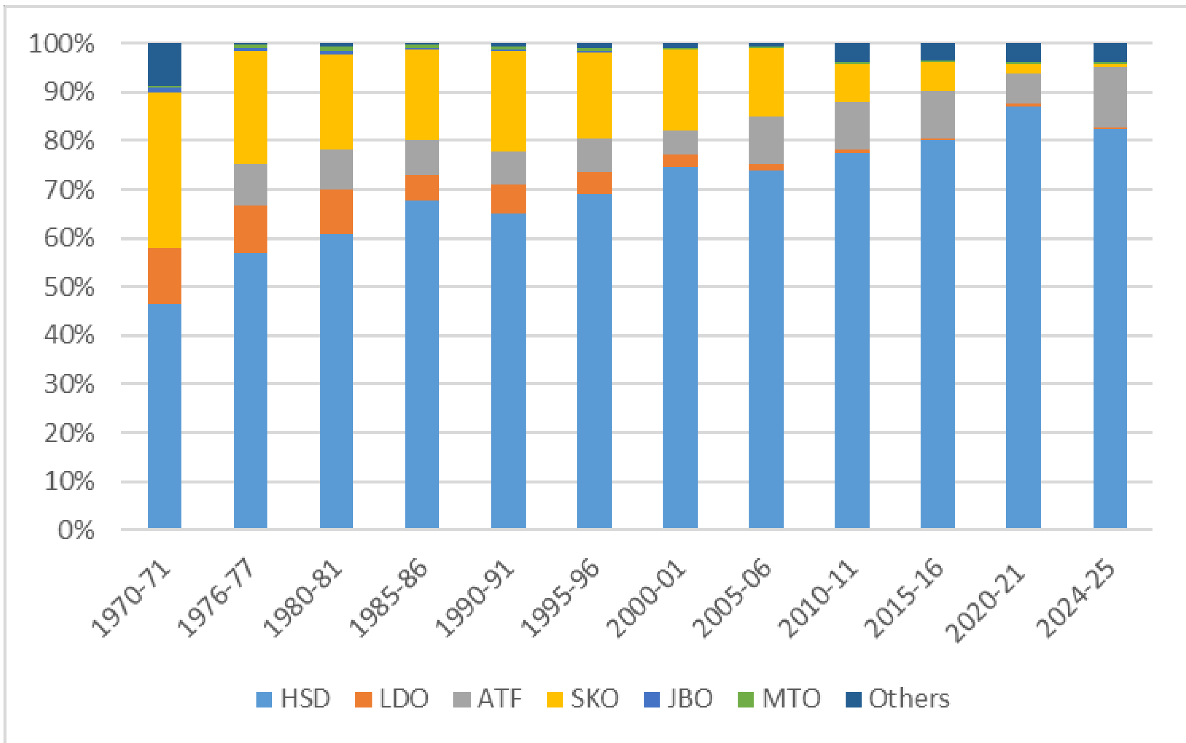


Figure 5: Evolution of Middle Distillates

India's growth story is reflected in the diesel economy, the nation-linking highways fuelling the commerce, the tractors and harvesters supporting the agrarian growth, and the heavy equipment depicting the industrial growth. In a striking reversal of the 1990s-when nearly one-third of India's diesel demand was met through imports-diesel is now the very product that accounts for nearly one-third of the exports from India's surplus refineries.

Conversely, Superior Kerosene Oil (SKO), once the dominant household fuel, both for cooking and illumination, ~1.6 MMT in 1960s, peaking to ~9 MMT in mid 2000s, to finally declining to less than 1 MMT in 2024, as government-led initiatives like LPG expansion (PAHAL, PMUY) and rural electrification steadily eroded kerosene demand. Kerosene once accounted for as much as 15% of the total crude processed, but its share has since dropped sharply to just 0.04%. Refiners installed units like Kero Hydro Desulphurization (KHDS) to reduce the sulphur content and finally transform it into near cuts of HSD and ATF.

ATF production has increased from less than 0.1 MMT in 1960s to ~18 MMT in 2024.In the percentage terms it is 6 % of the total production has seen a steady growth, gradually with the growth in the Domestic and International Aviation sector.

Light diesel oil (LDO) is a distillate fuel that is lighter and less dense than heavy oils, but it is denser and more viscous than high-speed diesel (HSD). It is mainly used in Industrial Boilers, Furnaces and Marine & Locomotive. During 1960s its production was around 0.8 MMT, that was 7% of the total production at that time, Its production quantity remained more or less consistent with peaking in early 2000s to approx. 1.5 MMT, However, due to the environmental concerns as well as availability of alternate fuels, its share in the production has dropped to less than 0.2%, and in terms of quantity it has dropped up to 0.7 MMT.

6.3 Heavy Ends

These fractions have the highest boiling points, typically above 350°C. They include heavier fuel oils and residues. They are characterized by low volatility and may require heating to flow.

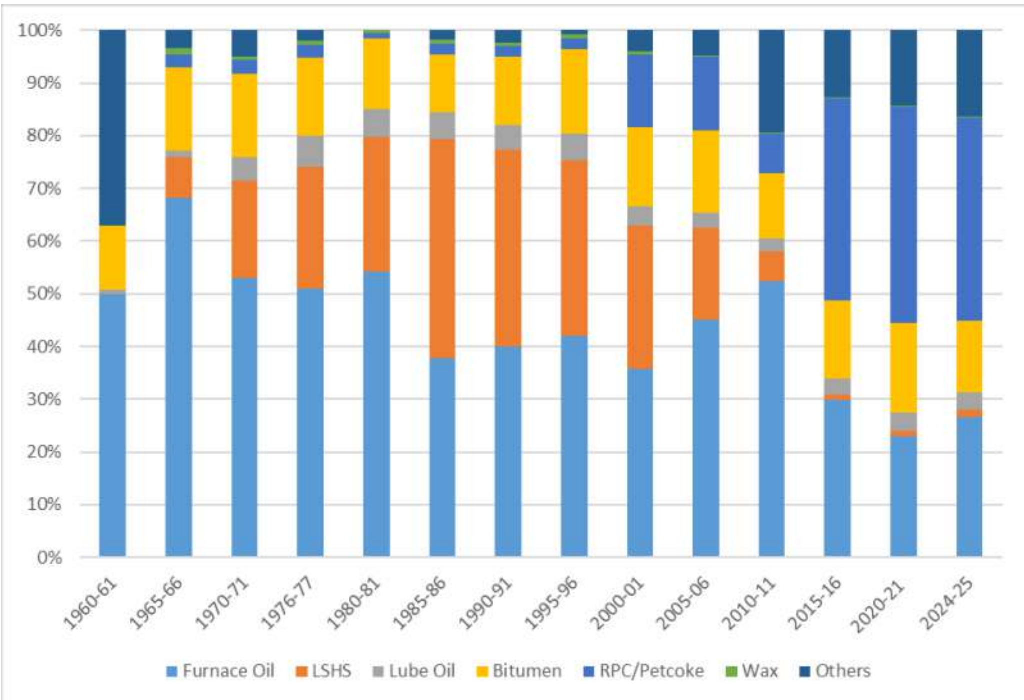


Figure 6 : Evolution of Heavy Ends

Recalling India's Forgotten Twin Refineries

Shri Kumar Biswas, Former Joint Director (Operations), OCC, PPAC

Abdul Karim Abdul Shakur Jamal was born in 1862 in the vibrant State of Jamnagar Gujarat (which in future emerged as biggest centre of Refining in India). His family, driven by ambition and opportunity, migrated to Burma which was then part of British India. Karim's sharp mind and adventurous spirit propelled him onto a path of remarkable entrepreneurship. Seeing big opportunities in petroleum business, Abdul Karim Abdul Shakur Jamal established Jamal's Oil Company Limited.

In 1909, A.S. Jamal Brothers & Company signed an agreement with Steel Brothers & Company of Great Britain and the Indo-Burma Petroleum Company was born under the Indian Companies Act of 1882 in Yangoon. This bold venture grew out of Jamal's Oil Company, which by then already operated two oil wells in the fabled region of Yenangyaung, named after the water-smelly creeks that gave it a unique identity.

Recognizing the demand and potential, the company established a refinery at Seikkyi, perched on the banks of the Rangoon River, with a capacity of 2,000 barrels per day. The refinery produced kerosene oil and paraffin wax, lighting the homes and fueling the industries across the region. As the second oil well began producing more crude, the company expanded further, erecting another refinery to meet growing demand.

In 1910, Jamal's vision extended a storahe land at Budge Budge, in Kolkata. By 1912, a storage terminal was operational there, and the company embarked on an ambitious expansion of its marketing infrastructure, establishing new terminals in Bombay (now Mumbai) and Chittagong (now in Bangladesh). Kerosene was packaged in tins and loaded aboard ships, linking Seikkyi, Budge Budge, Bombay, and Chittagong in a seamless distribution network.

The acquisition of the ship S.S. Shwedagon in 1912 further cemented the company's logistical capabilities, providing vital riverine transport. By 1919, Indo-Burma Petroleum Company stood as a fully vertically integrated enterprise, owning oil wells, refineries, ship, storage terminals, and an extensive distribution network. This impressive feat was a testament to Jamal's entrepreneurial foresight and unyielding spirit.

The years ahead were not without challenge and the company faced stiff competition from multinational giants such as Burmah Shell, Standard Oil, and Caltex, navigating the complex dynamics of a rapidly changing global oil market. Then came the dark clouds of World War II. Amidst this turmoil, Field Marshal Sir William Slim of British Army ordered the complete destruction of the oilfields and refinery at Seikkyi. on April 15, 1942 to prevent the powerful Japanese military from capturing vital petroleum assets.

Following the end of World War II, the company shifted its headquarters from Yangon to Kolkata (then Calcutta). In 1972, the Government of India assumed complete control from of IBP, transforming it into a public sector enterprise. In 2002, IOC acquired full ownership of IBP, and by 2007, the company was formally merged into its parent organization.

Acknowledgement: 'A Phoenix Revived: The IBP Story (1909-1992)' by Chamapaka Basu

Heavy Ends saw a consistent decrease in the percentage of crude processing; it depleted from ~40% in the 1960s to 14% in 2024. This was due to India's fuel consumption pattern moving toward transportation fuels-MS (Petrol), HSD (Diesel), and ATF (Aviation Turbine Fuel)-which are lighter fractions. Refineries responded by upgrading configurations to extract more light and middle distillates from the same barrel of crude. Environmental regulations and a shift to cleaner power generation fuels (natural gas, renewables) reduced demand for FO and LSHS in industrial boilers and utilities. Refineries installed Delayed Cokers, Hydrocrackers, Catalytic Crackers to convert heavy residues into valuable lighter products.

Furnace oil (FO) served as a primary fuel for industrial heating, power generation, and marine applications, while LSHS emerged as a lower-sulphur alternative, especially in sectors like textiles and chemicals. Due to environmental regulations and the availability of cleaner alternatives like Natural Gas, the production has been impacted. FO production was 2.7 MMT in the 1960s (27 % of the Total Production) and it topped double digits in 2005-2015 but then fell to 9.7 MMT in 2024(less than 1 % of the Total Production).

Meanwhile, the Petcoke production, which was 0.1 MMT in the 1960s and remained below 0.5 MMT until the early 2000s, has suddenly risen to 15 MMT due to domestic demand as well as refiners installing and increasing the existing capacities of Coker units, to increase the conversion of Heavier ends.

In line with the stringent environment guidelines, refiners gradually increased the capacity of their Sulphur Recovery units and installed Tail Gas Treating Units to capture the sulphur content of the finished product and convert it into solid/molten sulphur. At present the Sulphur Production is around 2.3 MMT in 2024.

Industrialization and highway build programmes expanded demand for Bitumen (~0.4 MMT 1960 ➜ ~5.3 MMT 2024) and supported regional lube base-oil and wax capacity at multiple refineries. Government sector overviews highlight the contribution of these specialty products to downstream manufacturing value chains.

7. Conclusion

Hydrocarbons have influenced human life for millennia, but-like any transformative technology-their purpose and impact have evolved dramatically over the past two centuries. From lighting homes with kerosene lamps in the past, to now fueling power plants with natural gas, hydrocarbons have continually adapted to human needs. They propel automobiles, power aircrafts, and drive maritime transport. Beyond mobility, hydrocarbons have played a critical role in powering our industries thereby resulting in reshaping our everyday lives-from the clothes we wear, the cups we drink from, and the pens we write with to the keyboards we use to type. Their presence extends far beyond energy, deeply embedding themselves into the very fabric of modern living.

Refineries are the result and reflection of how chemistry and engineering have evolved. The consumption behaviour has changed again and again in the past; along with it, the refining configurations have also changed. So, by looking at the past, we can say one thing for certain: in the future also, the Indian refineries will adapt as per the drastically changing consumer behaviour. Research labs and Licensors will come up with new technology, and India's refiners will keep upgrading, innovating, and finding ways to meet the country's needs-driving us steadily towards Viksit Bharat 2047.

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Guwahati (IndianOil); Estd. -1962

2 Designing and Operating Greenfield Refineries: Key Lessons for Emerging Economies

Mr. Daniel Evans, Vice President,
Global Head of Fuels and Refining Research
S&P Global Commodity Insights

Introduction: The Evolution of Refineries

Refineries are designed and built to operate for many decades. The Digboi refinery in Assam, which began operations in 1901, is the world's oldest continuously operating refinery and has survived two world wars, India's independence, and seen India regain its position as one of the world's largest economies. The extent of change in the refining industry over the 124 years since the Digboi refinery began operations is difficult to overstate. Global oil demand, on a total liquids basis, has grown to exceed 100 million b/d, and the size and complexity of the refining industry has increased tremendously to meet that demand. India's largest refinery, the Jamnagar complex, is more than one hundred times the size of Digboi, and with Greenfield refineries costing billions of dollars, anticipating how the industry might evolve in the coming decades is a critical part of the process of designing new assets.

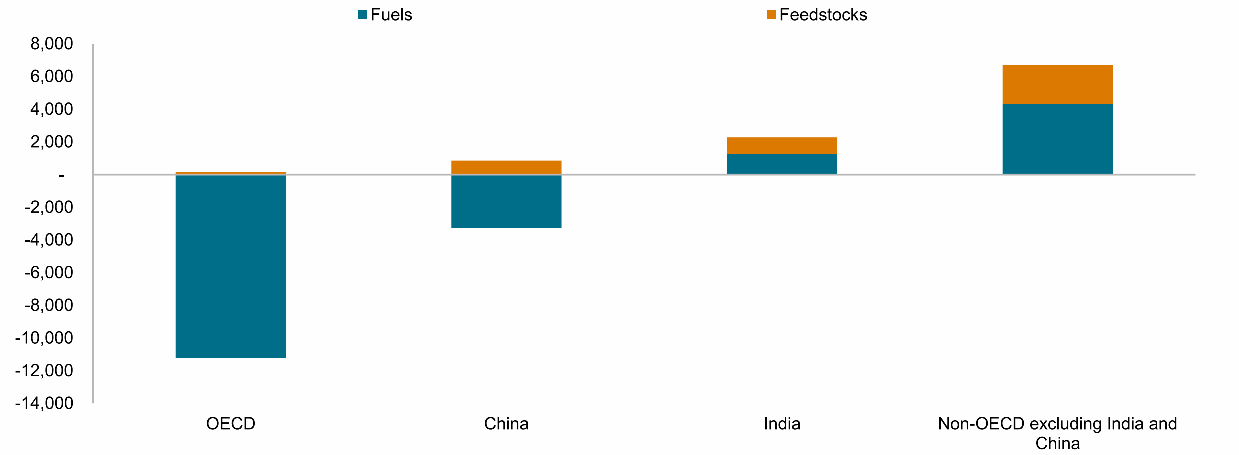
S&P Global Commodity Insights anticipates a future where refining remains an essential part of the energy landscape, especially in emerging markets. However, the refinery of the future will be quite different from the refineries of the past. The refinery of the future will be larger, more complex, and more integrated into petrochemicals. It will also be greener, processing more low-carbon feedstocks, producing more low-carbon fuels and chemicals and have a significantly lower carbon footprint. This article discusses how the industry is changing and presents what Commodity Insights considers some of the key factors to be considered in the design process.

Industry Transformation: Adapting to New Demands

With few exceptions, such as direct use in power generation, crude oil cannot be consumed directly. It cannot be used to power a car, truck, or plane. Refining has been, and will remain, critical to convert crude oil into products that consumers can use. To that extent, understanding how consumption patterns might change is critical to configuring the refinery of the future. We believe three macro trends are changing oil demand structurally.

- Firstly, refined product demand is shifting from mature economies to emerging economies. Today, OECD markets and China account for 62% of demand. In the period to 2047, refined product demand in these markets will contract by almost 16 million b/d, driving several waves of capacity rationalization. At the same time, demand for refined products in the non-OECD markets will increase by more than 6 million b/d. This shift is driven not just by the pace of the energy transition in China, Europe, and the US, which will see oil lose market share to electric vehicles, but also by shrinking populations and slowing economies. By contrast, emerging market demand will be supported by booming populations and economic growth which is set to outpace the global average. This means that while there will be pressure to close assets in markets where demand is shrinking, there will be a continued need to add capacity in the emerging markets where demand will grow in the decades to come.
- Secondly, oil demand is shifting from fuels to chemicals. Demand for oil in transportation is set to peak globally and begin declining as electric vehicles and lower carbon molecules gain market share from oil. Globally, we expect demand for gasoline and gasoil to decline by 11 million b/d between 2025 and 2047. By contrast, we do not foresee peak polymer demand on the horizon and expect ethane, LPG and naphtha demand to increase by 4.5 million b/d from 2025 to 2047. In many emerging markets, including India, we project increases in both fuel and feedstock demand meaning that although refineries will need to produce more transportation fuels going forward, they will also need to either produce more petrochemical feedstocks or be more deeply integrated into petrochemicals.
- Thirdly, a focus on emissions reduction is generating more demand for less carbon-intensive molecules. The share of renewable fuels in the road, aviation and marine fuels is set to increase. Our expectation is that demand for both biofuels and synthetic low carbon fuels will increase in the period to 2047, with biofuels demand increasing from 3 million b/d in 2025 to close to 5 million b/d in 2047, and the low carbon synthetic fuels market will start to evolve, particularly in the aviation sector.

Change in fuels and feedstock demand from 2025 to 2047 (thousand b/d)



As of Jun. 19, 2025.
Fuels includes motor gasoline, jet fuel and gasoil/diesel. Feedstocks includes ethane, LPG and naphtha.
Source: S&P Global Commodity Insights

Although the pace of change remains uncertain, refiners must consider these structural shifts when designing future assets. This involves building capacity in regions where demand is growing, configuring assets to produce more chemicals or chemical feedstocks and less fuels than before, and considering how to process lower carbon feedstocks, produce lower carbon fuels and chemicals and reduce emissions at the site.

Strategic Design Considerations for Future Refineries

While there is no recipe for success, we believe considering the five factors below has always helped create resilience and they remain relevant today. In addition, there are some new factors to consider that are discussed in the subsequent section.

1. **Acknowledge the need to keep investing:** We project that global refined products demand in 2047 will be 81 million b/d, some 10 million b/d lower than demand in 2025. While upstream decline rates imply a need to keep investing to find, develop, and produce the oil that will be needed in the future, this outlook seems to imply that the world needs little more Greenfield refining capacity. That ignores the fact that current capacity is in the wrong place, is often poorly configured to meet the structure of future demand and is aging and inefficient. For emerging markets, the need to invest is particularly acute. With demand in many emerging markets set to buck the global trend and grow for the foreseeable future, relying on imports from older refineries outside of the region may prove a risky strategy, particularly in a context where structurally weaker assets are likely to close. So, while a peak oil demand scenario presents a challenge when building investment cases, we believe investing with conviction will be required.

2. **Do the basics well:** While the refining industry is set to undergo significant change, doing the basics well will remain important. This means building refineries in the right place, adopting best-in-class technologies, and striving for top-tier efficiency will remain as important in the future as they have in the past.

3. **Build for the future, not for now:** As discussed in the introduction, demand is changing structurally. A refinery being designed now would be expected to begin operations in the early 2030s and payback the investment through the 2030s and 2040s. During that period, the global, regional, and

local demand profile is expected to shift dramatically. Therefore, the design needs to consider expectations of future demand.

4. **Expect change:** The history of refining is ripe with examples of projects that were built with one expectation of the market only to see it change. The expectation that the European dieselization trend was set to continue saw European refiners invest in adding hydrocracker capacity whilst Middle Eastern NOCs built distillate maximizing capacity targeting the European market. The subsequent "dieselgate" scandal has seen European consumers shun diesel-powered cars in favor of gasoline and hybrid models, leaving refiners scrambling to shift yields. Similarly, the expectation that crude slates would become heavier and sourer led to a wave of deep conversion investments, but the shale revolution has seen the global crude slate get sweeter and lighter than expected. These lessons should remind us that operational flexibility is critical. Building a refinery that is tied to a single crude grade or laser-focused on maximizing a single product slate should be shunned in favor of building in flexibility that enables the refinery to adapt to unexpected future shifts in the market.

5. **Keep your options open:** A good design should also keep future options open. In other words, it needs to have strategic flexibility in addition to the operational flexibility described in point four above. Whether that means having the space to expand the site or the ability to shift crude import or product offtake logistics, as has been the case for many European refiners following the ban on processing Russian crude, considering what might impact your business in the future is essential.

Addressing Emission Challenges in Refinery Design

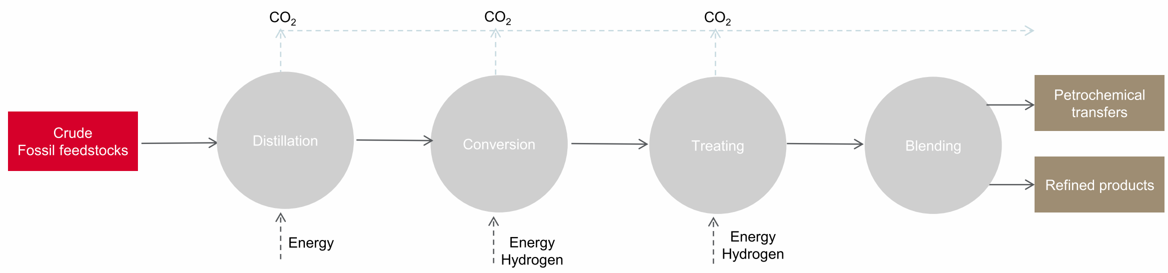
While considering the five factors above remains important, the energy transition presents specific challenges that must also be addressed, chief amongst them, the need to limit emissions and the need to meet the increasing demand for low carbon fuels and chemicals.

1. **Need to limit greenhouse gas emissions:** It is likely that going forward, the cost of emitting is not only going to become more expensive but will become a more important driver of both profitability and access to market as mechanisms aimed at containing emissions such as emissions trading systems (ETS) or carbon border adjustment mechanisms (CBAM) become more commonplace. Containing emissions will become increasingly important for stakeholders including government, shareholders, and consumers. With that in mind, a focus on reducing emissions is already a critical part of design. This means maximizing energy efficiency, limiting the carbon intensity of inputs such as power and hydrogen by considering lower carbon intensity or renewable options, and taking the carbon intensity of feedstocks into account.

2. **Need to produce low CI fuels:** A further emission-related challenge is the need to increase the volume of low carbon intensity fuels. We believe low carbon intensity molecules including biofuels and synthetic fuels will account for 7% of demand in 2047 versus just 4% today and that this could be higher if ambitious policy targets are achieved. For example, in one of Commodity Insight's net-zero scenarios, low carbon molecules could account for almost a quarter of total transportation fuel demand. Integrating the production of these fuels into the refinery process requires consideration of new feedstocks and how to co-process them alongside fossil feedstocks.

   The schematics below highlight some key aspects of the transition in refining we believe will be necessary to ensure long-term competitiveness. Figure 1 shows a typical current configuration, crude oil goes in, energy and hydrogen are used to convert the crude oil into fuels and chemicals, with CO2 produced as a by-product.

Figure 1: The refinery as a fossil-fuel machine



Data compiled June 19, 2025
Source: S&P Global Commodity Insights
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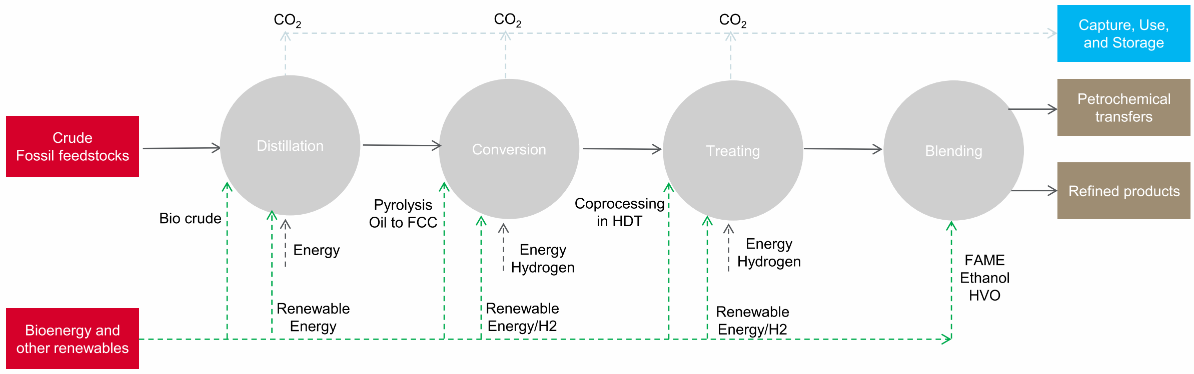
Figure 2 illustrates the transition to the refinery of the future. Fossil fuels are supplemented by bio or renewable feedstocks which can be co-processed at multiple stages in the refining process or blended to make finished products at the end of the production process. Energy and hydrogen inputs, which often today use fossil sources, are replaced, fully or partially by renewable sources such as wind or solar power, or hydrogen produced via electrolysis powered by renewable energy. Even waste heat can be recovered and put to good use across avenues like district heating networks. Finally, the CO2 produced can be captured and stored or used. This ambitious blueprint now needs to be integrated into the design process to ensure that the Digboi of the future is fit for the next 100 years.

Figure 2: The refinery of the future, at the heart of a low-carbon manufacturing hub



Data compiled June 19, 2025
Source: S&P Global Commodity Insights
FCC = fluid catalytic cracker, HDT = hydrotreater, FAME = fatty acid methyl ester, HVO = hydrogenated vegetable oils, H2 = hydrogen
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Conclusion: Navigating the Future of Refining

In conclusion, doing the basics right still matters. Good design should take into account how the market is likely to change. But designers should also be humble, things will change in unpredictable and unforeseen ways, so flexibility and optionality need to be built in. That said, the transition towards a lower carbon future is underway and gathering steam. A responsible design needs to consider how a refinery can be relevant for the lower carbon decades to come. That means taking into consideration the large plot space required for investments of the future like CCS and the need for substations and cable trenches to enable future investments in electrification on process units.

Barauni (IndianOil); Estd. -1964

3 Indian Refineries: Journey of Improvement, Expansion and Future Outlook

Shri Manish Agarwal, Joint Director;
Shri Kishore Kumar Bhimwal, Additional Director
Centre for High Technology (CHT)

1. Introduction

India is the third-largest energy consumer globally and the fourth-largest refiner after the US, China, and Russia. The Indian refining sector has evolved significantly over the past few decades—from a modest beginning in the 1950s to becoming a global refining hub today. With a refining capacity of over 258.1 million metric tonnes per annum (MMTPA) as of 2025, India not only meets domestic demand but also exports refined petroleum products to other countries.

India is a third-largest consumer of crude oil globally, heavily relies on imports to meet its oil demands. The country imports approximately 80% of its total oil consumption, primarily from the Middle East, with countries like Iraq and Saudi Arabia being the top suppliers. The import of crude oil plays a significant role in India's economy, influencing various sectors such as transportation, manufacturing, and power generation. However, the high dependency on imports also exposes the country to global price fluctuations and supply disruptions, prompting the government to explore alternative energy sources and increase domestic production. Please note that while I strive to provide accurate information, it's always best to refer to the latest data and research for the most up-to-date facts.

India, known for its vibrant economy, plays a significant role in the global petroleum market. The country imports a substantial amount of crude oil to meet its energy demands. The imported crude oil is then refined into various petroleum products such as gasoline, diesel, and jet fuel. On the other hand, India exports a considerable amount of petroleum products. The country's sophisticated refineries produce high-quality petroleum products that are in demand worldwide. This trade of petroleum products significantly contributes to India's economy. However, the country's dependency on oil imports also exposes it to global oil price fluctuations, which can impact the economy. Therefore, India is continuously exploring ways to increase domestic oil production and reduce its dependency on oil imports.

This article captures the journey of Indian refineries—highlighting their improvements in efficiency and capacity, expansion strategies, and future plans in alignment with energy transition goals and Atmanirbhar Bharat (self-reliant India) vision.

2. Historical Evolution and Modernization

India's first refinery was set up in 1901 at Digboi, Assam. Post-independence, the government took the initiative to establish public sector refining companies, leading to the formation of Indian Oil Corporation (IOC), Bharat Petroleum Corporation Limited (BPCL), Hindustan Petroleum Corporation Limited (HPCL), and others. Until the late 1990s, refineries were mainly focused on catering to domestic consumption with limited technological sophistication.

Table:1 Evolution of Indian Refineries

Refinery	Year of Establishment	Capacity, MMTPA
	Public Sector	
Digboi (IndianOil)	1901	0.65
Guwahati (IndianOil)	1962	1.20
Barauni (IndianOil)	1964	6.00
Koyali (IndianOil)	1965	13.70
Haldia (IndianOil)	1975	8.00
Mathura (IndianOil)	1982	8.00
Panipat (IndianOil)	1998	15.00
Bongaigaon (IndianOil)	1974	2.70
Paradip (IndianOil)	2016	15.00
Manali (CPCL IndianOil)	1965	10.50
Nariman (CPCL IndianOil)	1993	0.00*
Mumbai (HPCL ONGC)	1954	9.50
Visakh (HPCL ONGC)	1957	15.0
Mangalore (MRPL ONGC)	1996	15.00
Tatipaka (ONGC)	2001	0.07
Mumbai (BPCL)	1955	12.00
Kochi (BPCL)	1963	15.50
Bina (BPCL)	2011	7.80
Numaligarh (NRL OIL)	1999	3.00
	Joint Ventures	
Bhatinda (HMEL)	2012	11.30
	Private Sector	
Jamnagar (RIL- DTA)	1999	33.00
Jamnagar (RIL- SEZ)	2008	35.20
Nayara Energy Ltd. (NEL)	2006	20.0

Indian refineries have indeed undergone significant transformations in recent years, driven by a combination of factors including increasing domestic demand, a focus on cleaner fuels, and the need to reduce reliance on crude oil import. This includes capacity expansions, modernization efforts, a growing emphasis on petrochemical production and production of cleaner fuels from BS II to BS VI.

The supply of BS-IV quality fuel across the entire country was completed in phases by April 1, 2017. The Government decided to leapfrog directly from BS-IV to BS-VI emission norms nationwide starting April 1, 2020. Considering the rise in pollution levels in Delhi, BS-VI was implemented in NCT Delhi from April 1, 2018, followed by major parts of NCR from April 1, 2019.

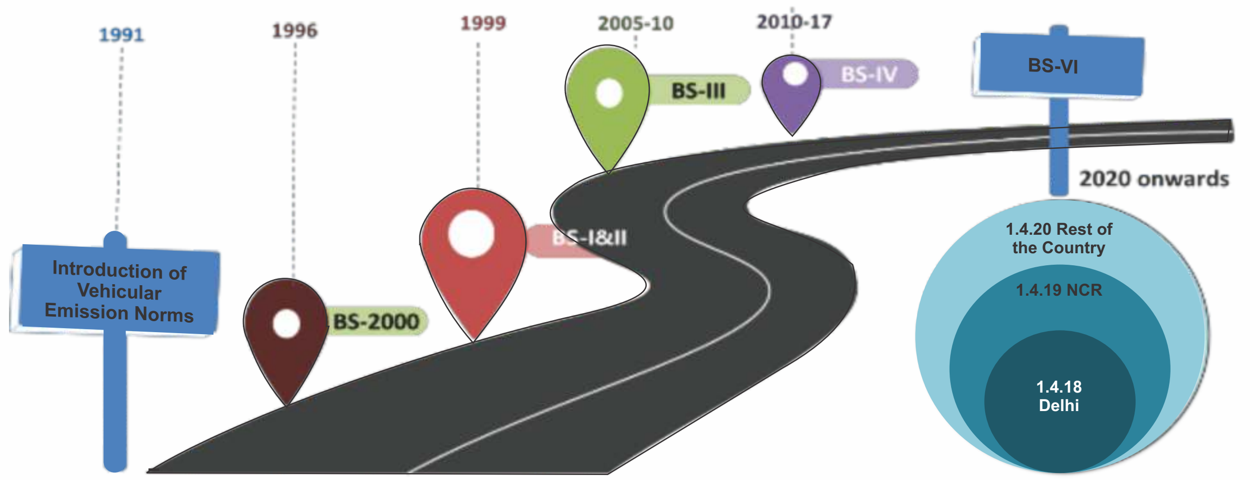
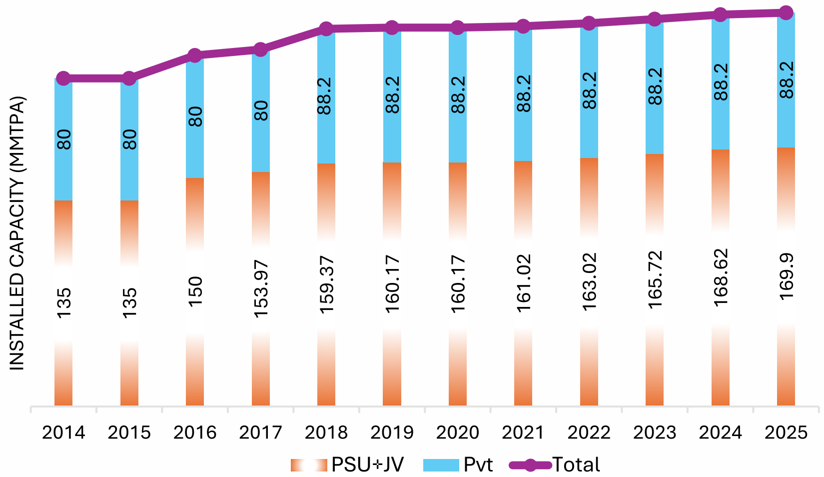


Figure 1 : Indian Fuel Quality Improvement Journey

3. Current Capacity and Operational Excellence

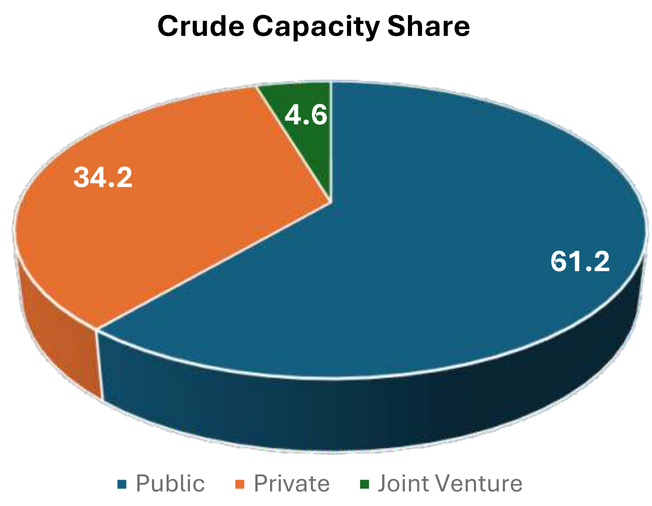
3.1 Refining Capacity & Refinery Crude Throughput

Indian refining industry has done well in establishing itself as a major player globally. India, which is the fourth largest refiner in the world and second largest refiner in Asia after China, has emerged as a refining hub with refining capacity exceeding demand. The graphical representation of the Indian refining capacity addition over the years shown in Graph 1. The Indian refining capacity has been increased to 258.1 MMTPA from 215 MMTPA in 2014.



Graph 1 : Growth of Indian Refineries Capacity

As of April 2025, India operates 23 refineries (19 public, 4 private/joint ventures) with a cumulative capacity of 258.1 MMTPA. In FY 2024-25, crude oil processed reached 267.28 MMT, reflecting capacity utilization at 103.5% against the design capacity.



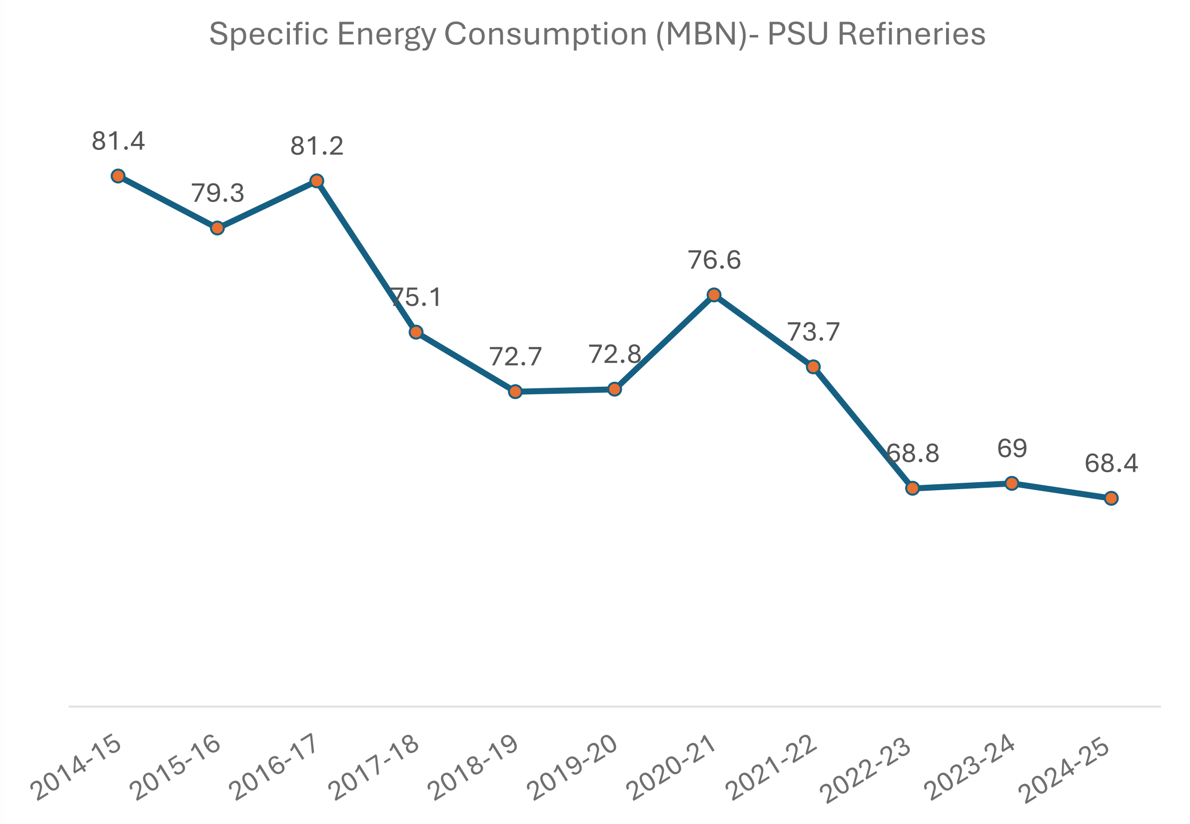
Graph 2 : % sharing of Refining capacity

3.2 Performance Benchmarks and Global Competitiveness

Indian PSU refiners have made significant strides in energy efficiency and operational benchmark by adoption of Solomon Energy Intensity Index (EII) and MBN (Million BTU per barrel of throughput) as performance indicators. Energy Efficiency as First Green Fuel, Indian refineries are on the path of gradual energy efficiency improvement. Over the past decade, MBN improved from 81.4 to 68.4 as shown in Graph 3, despite peaks during BS-VI implementation and the COVID-19 period.

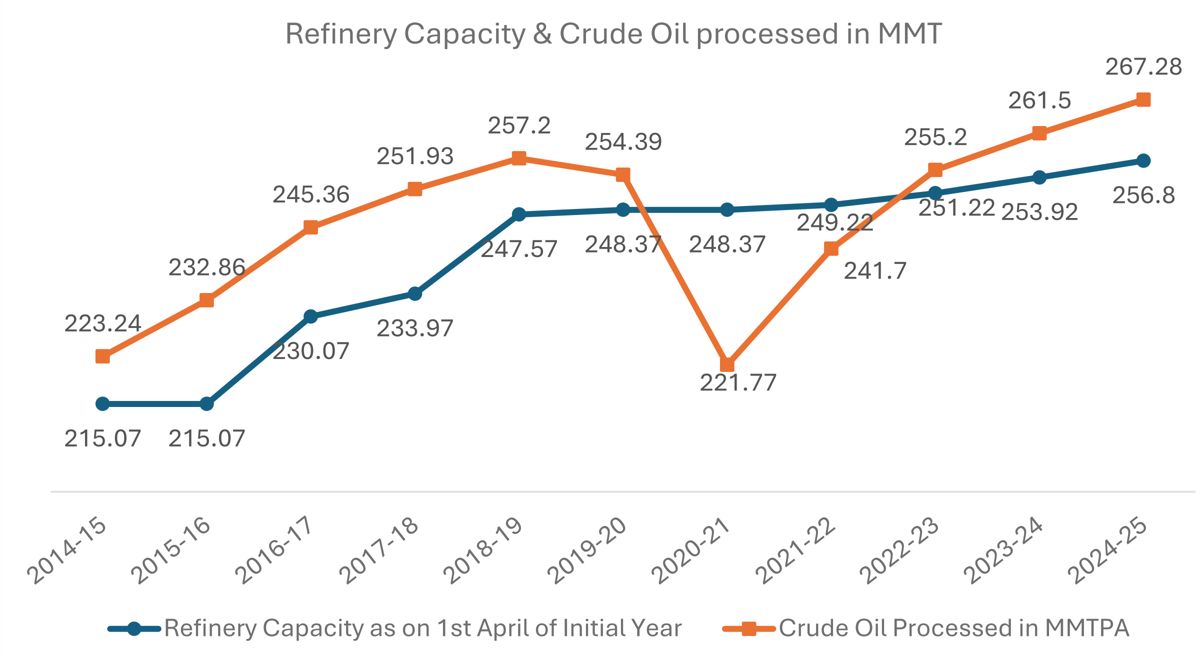
PSU refineries have been benchmarked by CHT regularly through M/s Solomon Associates (SA), USA since 2010. PSU refineries have improved their EII in last 10 years, EII has reduced by 19% during the period 2010 to 2022 and have been reducing EII at 3 times the rate of global average, however, significant scope still exists in areas like:

- Reliance on steam power should be shifted to Electric power. 1% reduction in Steam System Size equals ≈0.9 EII improvement.
- Cooling Towers in Indian PSU refineries accounted for more than 30 EII equivalent of heat rejection to the air
- Rationalization of the number of storage tanks should be followed.



Graph 3 : Improvement in Specific Energy Consumption

Indian PSU refineries above 3 MMTPA capacity have set their targets to come in quartile -1 of Energy Intensity index (EII) of Solomon performance by 2030 under Mission Q-1.



Graph 4: Refining Capacity & Refinery Crude Throughput

3.3 Integration with Petrochemicals and Diversification

The energy transition will reduce demand for oil products but increase opportunities to capture the growing demand for petrochemicals. While total global demand for transportation fuels is expected to peak in the next one to two decades, demand for petrochemical feedstocks (ethane, LPG, naphtha) will continue to grow. With rising petrochemical demand and flattening gasoline/diesel growth, Indian refiners are increasingly integrating refining with petrochemical production:

- **IOC Paradip:** Petrochemical complex with PX, PTA, and MEG units.
- **BPCL Kochi:** Propylene derivatives petrochemical project (PDPP).
- **HMEL Bhatinda:** Commissioning of dual feed cracker and polypropylene units.
- **RIL Jamnagar:** World's largest integrated refining and petrochemical complex.

Such integration enhances value addition, hedges against fuel demand uncertainty, and supports "Make in India" goals.

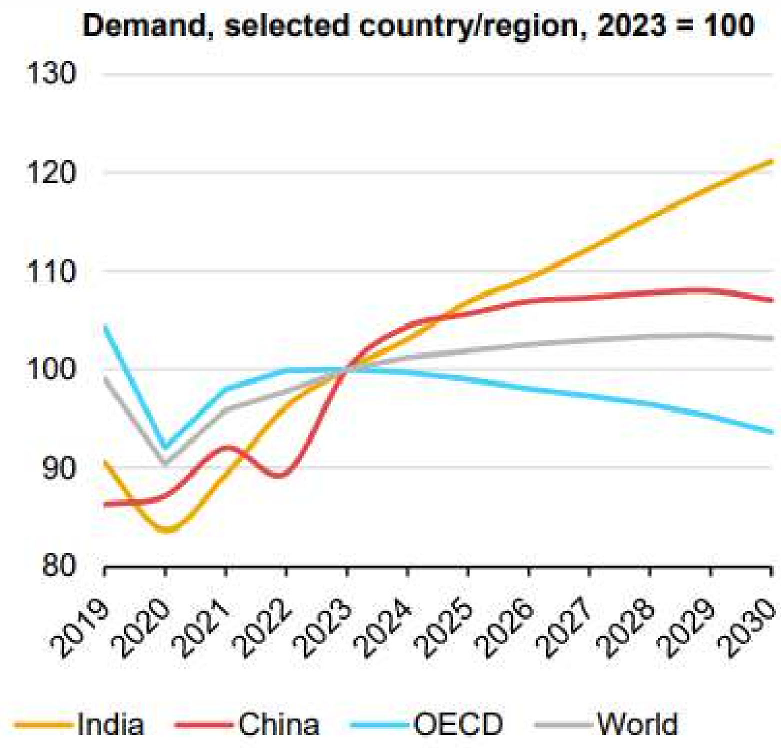
4. Expansion and Future Outlook

According to OPEC, global oil demand is expected to increase by almost 18 mb/d, rising from 102.2 mb/d in 2023 to 120.1 mb/d in 2050, bolstered by robust growth in petrochemicals, road transport, and aviation sectors. While dependence on oil is set to reduce in the long-term, it remains critical to the energy mix, and supply disruptions can still cause significant economic issues. Emission reduction is crucial for the industry, and driving investments, advancing alliances, and optimising supply chains will be necessary to foster a resilient ecosystem that meets demand.

India has emerged as one of the largest refining hubs in the world, with a total refining capacity of approximately 258.1 million metric tonnes per annum (MMTPA) or 5.16 million barrels per day as of 2025. The country's refining sector plays a critical role in meeting domestic demand for petroleum products and also supports its status as a significant exporter of refined petroleum products.

To meet growing energy demand and enhance self-reliance, India is expanding its refining capacity. By 2030, India aims to raise its capacity to over 309.5 MMTPA or 6.2 Million barrels per day. Grass route Projects like the HPCL Rajasthan Refinery Limited (HRRL), CPCL-Nagapattinam restructuring and expansion of existing refineries contribute to this target.

As per IEA report the country is on track to post an increase in oil demand of almost 1.2 mb/d by (2030), accounting for more than one-third of the projected 3.2 mb/d global gains and country is self-sufficient in the refining capacity for its domestic consumption as shown in Graph -6



Graph 6: Oil Demand Projections

List of Green Field and Expansion of Existing Refineries

Table 2: Incremental Capacity in MMT by 2030

Refineries	Location	Capacity
HRRL	Barmer, Rajasthan	9.0
BPCL	Bina, Madhya Pradesh	3.2
BPCL	Mumbai, Maharashtra	4.0
BPCL	Kochi, Kerala	2.5
IOCL	Digboi, Assam	0.35
IOCL	Koyali, Gujarat	4.3
IOCL	Barauni, Bihar	3.0
IOCL	Panipat, Haryana	10.0
CBRPL	Nagapattinam	9.0
NRL	Numaligarh, Assam	6.0

Regarding Indian Refinery Capacity Expansion, there is a visibility of around 330 MMTPA till the year 2037. Beyond that, the capacity expansion will depend upon the global demand-supply scenario, export position and biofuels blending in addition to any other factor emerging in due course of time.

5. Future of Refineries:

Refineries that embrace **flexibility, innovation, integration, and sustainability** will be better positioned to remain competitive in a decarbonizing global economy. Following factors that may influence the future of petroleum refining, including product demand, crude supply, environmental regulations, and new technology development

Decline in Gasoline & Diesel: The growing adoption of electric vehicles (EVs), stricter fuel efficiency norms, and urban air quality mandates are expected to curtail demand for transportation fuels like gasoline and diesel, especially in developed markets.

Growth in Petrochemicals Demand: Petrochemicals demand is driven by the rising global consumption of plastics, packaging, and chemicals—especially in Asia and other developing regions. The feedstock for petrochemicals shall be optimised to become low cost producer of petrochemicals. This needs careful consideration to include alternate feed stocks like ethane, propane in addition to surplus refinery feed stocks & technologies such as COTC.

Jet Fuel and Marine Fuels: While aviation fuel demand is recovering post-pandemic, it may eventually face pressure from decarbonization efforts. Similarly, marine fuels are evolving in response to IMO sulfur caps and the drive for low-carbon shipping solutions.

Regional Imbalances: The trajectory of fuel demand will vary significantly across regions. Developed nations may experience declining demand, while countries such as India, Southeast Asia, and parts of Africa are expected to drive consumption growth in the near to mid-term.

Carbon Emission Targets: Global and national commitments to net-zero goals are pushing refineries to reduce **Scope 1 and 2 emissions** (from operations) and indirectly Scope 3 emissions (from product use).

Carbon Pricing & ESG: Introduction of carbon pricing, emissions trading systems, and investor-driven **ESG (Environmental, Social, Governance)** metrics are adding financial and reputational dimensions to regulatory compliance.

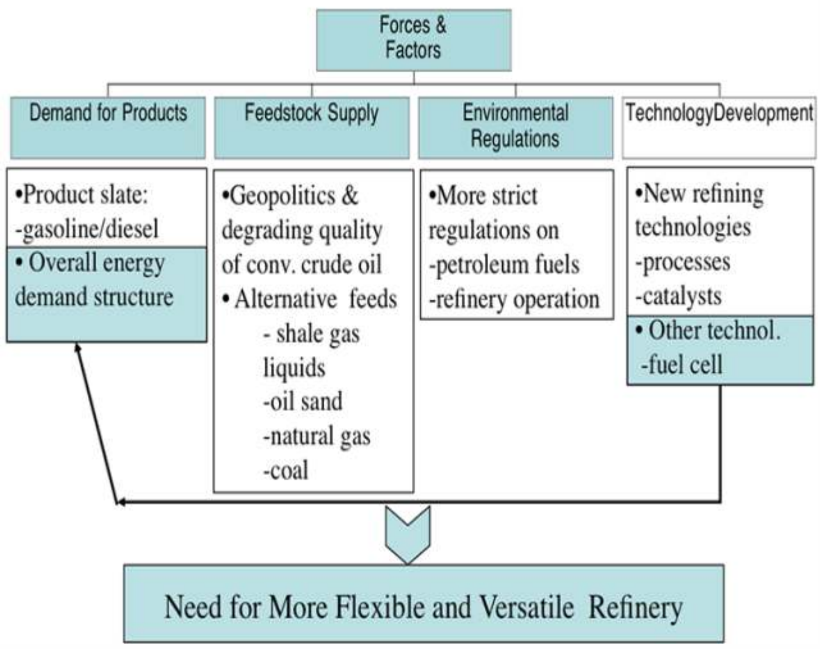


Figure 2 : Future Trends in Petroleum Refining

6. Future Challenges

6.1 Climate change

Staying profitable and taking advantage of new possibilities that come with the shift to cleaner energy—will be crucial and challenging for companies to survive.

Climate change will add the challenges in other ways. Higher temperatures could further restrict refinery capacity—especially during hot months, when traditional cooling towers become less effective. Meanwhile, shifting weather patterns may reduce water levels in sources that refineries rely on.

Indian refineries, many of which are situated in coastal or flood-prone regions, must also brace for the physical impacts of climate change. These facilities face increased risks from a higher frequency of extreme weather events, such as cyclones, intense monsoons, and heatwaves, along with the long-term threat of rising sea levels.

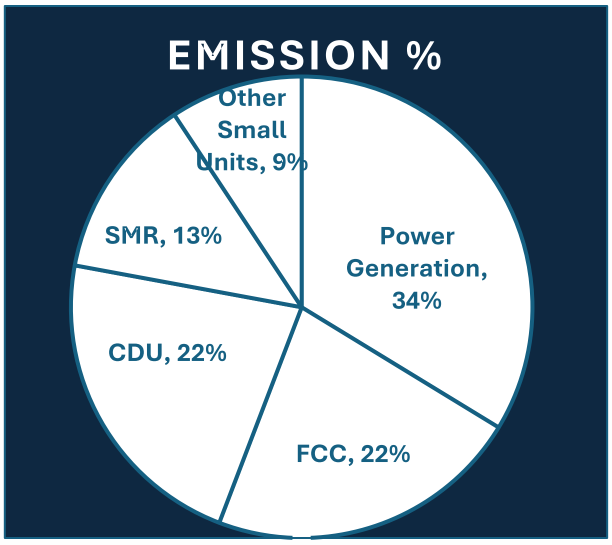
The devastating floods in regions like Chennai (2015) and Kerala (2018) serve as stark reminders of the critical need for robust climate resilience measures. Refineries that had not adequately prepared for such events faced prolonged shutdowns, incurring significant costs for repairing damaged electrical systems, critical infrastructure, and machinery. These disruptions can also severely impact the national energy supply chain, given India's significant reliance on refined petroleum products for its growing economy.

In contrast, those that had invested in strengthening their infrastructure, for example, by raising and reinforcing protective barriers, improving drainage systems, upgrading cooling systems to cope with higher ambient temperatures, and implementing robust early warning systems—were able to resume operations much quicker once external conditions normalized. This not only minimized their financial losses but also enabled them to contribute to recovery efforts in affected communities, highlighting the socio-economic imperative of climate resilience.

6.2 The Low-Emissions Refinery of the Future

India is the 3rd largest emitter of CO2 in the world after China and the US, with estimated annual emissions of about 2.8 gigatonne per annum (gtpa). The Government of India has committed to reducing CO2 emissions by 50% by 2050 and reaching net zero by 2070.

The main emission sources in larger conversion refineries are, in order of importance, the power station (29% of total emissions in an average refinery), fluid catalytic cracking unit (19%), atmospheric distillation units (19%), and steam methane reformer for hydrogen production (11%), Smaller units such as heaters, boilers, and gas turbines are also commonly powered by fuel gases, fuel oil, or natural gas. These heterogeneous emission point sources have a relatively low CO2 concentration (around 8%vol).

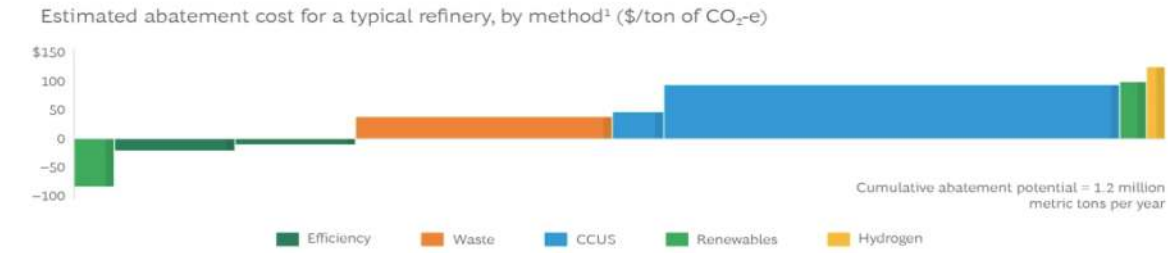


Graph 7: Typical Emission sources from a refinery

Many refinery operators have announced ambitious goals for reducing their carbon emissions, but achieving those goals won't be easy. As Exhibit 3 shows, abating a refinery's Scope 1 and 2 emissions will require actions across multiple levers. The price will be high, with considerable portions of refineries' emissions costing close to or exceeding $100 per ton of CO2-e to abate. And abatement efforts will depend in part on a variety of technologies that have yet to become practical at scale. Various oil PSUs have set target for achieving operational Net Zero (Scope1 & scope 2) as shown in Table 3.

Table:3 Net Zero Targets year by OMCs

OMCs	NetZero Target Year
ONGC	2038
OIL	2040
IOCL	2046
HPCL	2040
BPCL	2040
CPCL	2046
MRPL	2038
NRL	2038
EIL	2035
GAIL	2035



Source: BCG analysis.

Note: CO_2-e = CO_2 equivalent. CCUS = carbon capture, utilization, and storage.

[1]Totals shown are based on the cumulative emissions, in CO_2-e, produced by the average refinery each year. Some methods may have different abatement costs depending on how easily they are implemented and/or the specific technologies involved. Costs also vary by asset and location.

Figure:3 Estimated abatement cost for a typical Refinery

For reducing Scope 2 emissions, the primary approaches include improving efficiency and buying sustainable renewable energy whenever possible. However, for refiners targeting Scope 1 emissions, the emphasis should shift toward developing and implementing strategies that lower the emissions intensity of refineries—that is, the amount of carbon dioxide equivalent (CO2-e) emitted per unit of energy produced. Accordingly, the following techniques and technologies that refineries may consider:

6.2.1 Renewables

Refineries have potential to reduce their emissions by integrating renewable energy sources into their operations. This allows them to energizes their facilities sustainably and even feed surplus energy back into the national grid. The extent of carbon dioxide equivalent (CO2-e) abatement achieved hinges on the specific refinery setup and its capacity to store generated energy. While energy storage technology is advancing rapidly, high costs currently remain a key challenge for widespread adoption. Further investment in efficient, affordable storage solutions is crucial for maximizing the environmental benefits of renewable integration in the refining sector.

6.2.2 Electrifying Heat-Heavy Processes: A keyway to cut carbon is by replacing heaters and steam-powered equipment that use fossil fuels with electric alternatives. Electric heating technologies, like induction and resistance heating, offer precise temperature control and fast heat delivery, leading to much higher energy efficiencies (up to 95-99% for electric heating compared to typical 25-40% for fuel-powered combustion systems). This shift, especially for small fossil-fired heaters and steam-driven turbines (which can be replaced by very efficient electric motors with variable speed drives, offering 90-95% efficiency), reduces direct burning emissions, lowers maintenance costs due to fewer moving parts, and allows for easy integration with renewable electricity sources. While only 5-10% of a refinery's total energy use is currently electrical, this offers a significant chance to reduce emissions by using low-carbon electricity.

6.2.3 Fuel Switching

Beyond current strategies, an additional approach to both mitigate greenhouse gas (GHG) emissions and reduce operational costs involves transitioning to alternative fuel sources. These include biomass, synthetic gas derived from biomass, biogas generated from various organic sources like municipal solid waste and sewage sludge, and biomethane, which is produced by upgrading biogas. The economic viability and overall cost-effectiveness of utilizing these fuels are critically dependent on the availability of the required feedstocks and their geographical proximity to refineries.

6.2.4 Green Hydrogen

Refineries can further reduce emissions by transitioning from producing hydrogen through steam methane reforming to generating green hydrogen using fully renewable energy sources. The cost of producing green hydrogen is currently 60-65% dependent on electricity prices, which remain too high for widespread commercial adoption. However, as additional green hydrogen projects are launched nationwide under the Green Hydrogen Mission, the cost of renewable power is expected to decline further.

Under the Strategic Intervention for Green Hydrogen Transition (SIGHT)-2B program, the MoPNG has allocated a substantial 200 KTPA of green hydrogen procurement capacity to refineries on a built-own-operate basis by 2030. This ambitious target translates to an impressive 2.2 million tonnes of CO2 equivalent emissions averted annually. The SIGHT program is structured with two distinct financial incentive mechanisms: one to support domestic manufacturing of electrolysers and another to encourage the production of Green Hydrogen. Demonstrating proactive implementation, Oil Marketing Companies (OMCs) have already released tenders for 42 KTPA of green hydrogen, with tenders from IOCL and HPCL successfully awarded, and other tenders in various stages of the awarding process.

6.2.5 Carbon Capture, Utilization, and Storage (CCUS)

For any complex refinery, there are multiple CO2 emission sources such as Hydrogen Generation Unit (HGU), Power Plant/ Co-Gen Plant (PP/CGP), Fluid Catalytic Cracking (FCC), Crude Distillation Unit (CDU) / Vacuum Distillation Unit (VDU) as well as heaters and boilers. Amongst these, the HGUs generate the most concentrated gas streams in terms of CO2 (20-70 vol%), followed by CDU/VDU (10-12 vol.%), FCC (8-16 vol.%) and PP / CGP (4-8 vol%). The majority of CO2 emissions in a typical refinery is contributed by the hydrogen generation unit, FCC, boilers, and process heaters. For refineries to achieve their net-zero emissions targets, it's crucial to adopt and develop economically viable technologies for capturing, storing, and utilizing the CO2 released from refinery operation like grey Hydrogen production from SMR. Refiners are already familiar with pre-combustion and post-combustion carbon capture technologies. The main hurdle here is the economics, which largely depend on the volume and concentration of CO2 being captured.

Ultimately, the economic benefit of carbon capture hinges on our ability to store and re-use the captured CO2. The captured CO2 can be stored deep underground in locations such as depleted oil and gas reservoirs, basalt formations, saline aquifers, and unrecoverable coal deposits. Once stored, it can be repurposed for various industrial applications, including mineralization, chemical synthesis, algae synthesis, and artificial photosynthesis. Nevertheless, developing large-scale carbon capture, utilization, and storage (CCUS) infrastructure requires substantial upfront investment. This will likely require partnerships across the entire value chain.

6.2.6 Energy Efficiency

The most cost-effective and impactful way for refineries to reduce their carbon footprint is by enhancing their operational energy efficiency. Refineries can achieve substantial improvements in their day-to-day operations by optimizing their plants, thereby reducing the consumption of natural gas, steam, and power needed for operation. Indian refineries steam size network is one of the largest in the world, which shows Indian refineries have the protentional to improve their energy efficiency through electrification.

Several emerging technologies also offer the potential to boost refinery efficiency. These include waste heat-recovery technologies to recover small quantity of heat which are being dissipated to the atmosphere, electrical furnaces, and thermal energy storage for coastal refineries. Further, Refineries can also leverage new digital solutions to ensure efficient energy use across each refinery unit. Digitization will be crucial for all aspects of refinery decarbonization efforts. This not only secures their "license to operate" but also drives increased margins and minimizes operating cost.

6.3 Rethinking refinery operations

Globally, refiners have the capacity to process nearly 100 million barrels of crude oil per day, utilization of refinery could drop from the current rate of 85 percent to percentages in the low 70s. Overall, the drop in utilization and profitability could result in capacity closures that will affect the least efficient plants and those less able to adapt to new demands. Many refiners are considering shifting away from refining crude into mostly fuels and looking forward to refine crude into direct chemicals.

6.3.1 New process technologies

The individual process unit that receives the most attention is the fluid catalytic cracker (FCC), the longtime workhorse of refining. Refiners have shifted toward catalysts that produce higher olefin yields, but output generally tops out at 10 to 15 percent of the total. New technologies under development could allow FCCs to produce much higher petrochemical yields, which in turn could lead to increased production of olefins, aromatics, and steam cracker feeds such as LPG and naphtha.

6.3.2 New refinery configurations

Hydrocrackers typically compete with FCCs for the same feedstock, with hydrocrackers yielding more (and higher quality) diesel, jet fuel, and steam cracker feed such as LPG and naphtha. FCCs yield more (and better-quality) gasoline. Refiners can boost potential petrochemical output while still preserving diesel and jet fuel production by increasing hydrocracker capacity and shifting toward a higher yield of light-ends feedstock, such as LPG. This process can also generate additional naphtha.

6.3.3 Maximizing aromatics reforming

Reforming is a common refining technology used primarily to upgrade low-value naphtha into higher-value gasoline by raising its octane. Reforming can also be used to produce aromatics instead of gasoline. Refiners can maximize value from aromatics by increasing reformer severity, leaving benzene precursors in the feedstock, and adding aromatics separation and conversion units at the back end (Stream Sharing). This approach could also complement an increase in the production of hydrocracker naphtha and a modification of the FCC for aromatics extraction.

6.3.4 Direct crude to chemicals conversion

considering new technologies to move directly from crude oil to petrochemicals without using traditional refining technologies Different oil-to-chemicals technologies have varying costs and degrees of conversion. The simplest modification, employing new technology in a single FCC unit, would result in up to 40 percent of refinery output as petrochemicals.

6.3.5 Enabling a circular economy

The energy transition and shift to a more circular value chain (recycling) will provide refiners with new integration opportunities—for example, supplying renewable and bio-based feedstock to petrochemical units, as demonstrated by Finnish firm Neste in partnership with petrochemical producers. In addition, we see opportunities for refiners to play an important role in enabling advanced recycling of plastic waste or integrating with waste gasification units

Given the range of approaches, a single strategy is unlikely to work for all refiners. Some refineries may not be candidates for a major shift to petrochemicals and will have to consider other strategies for survival or even plan to shutter their plants. For those that are ready for a crude-to-chemicals shift, a number of factors will underpin their decision about the best way forward.

Not all plants are equally well placed to shift toward higher petrochemical yields. Larger refineries typically are in a better position to add new process units because their scale reduces unit capital costs and provides greater flexibility in design, location, and integration.

7. Conclusion

The global energy system is undergoing significant transformation with wide ranging implications, a comprehensive strategic approach is therefore essential to address energy supply and demand, economic and market trends and systems flexibility. The new global energy system will rely on key pillars of energy supply security, including resilient supply chains, energy efficiency policies, strategic trade partnerships and advanced infrastructure investment models.

The refining industry has a unique expertise, which is to process and convert multiple feedstocks made of highly complex molecules. Refining should think of its future by building on this unique know-how, aiming to provide low carbon fuels and chemicals needed by society, while decreasing its environmental footprint

India's refining sector is a testament to resilience, innovation, and strategic foresight. By balancing operational excellence, petrochemical integration, and decarbonization, Indian refineries are not only meeting today's energy needs but also shaping a sustainable future. Key priorities include:

- Maximizing energy efficiency through digitalization and catalyst optimization.
- Scaling petrochemical production to capture growing demand.
- Investing in low-carbon solutions like green hydrogen and CCUS.
- Strengthening global trade and circular economy initiatives.

With a roadmap to 309.5 MMTPA by 2030 and a vision for net-zero by 2070, Indian refineries are poised to lead the global energy transition, fuelling a self-reliant and sustainable India.

Gujarat (IndianOil); Estd. -1965

4 Refining is not Dying – It's Relocating and Reinventing Itself: A Shifting Global Narrative —India at the Heart of Refining's Future

Shri SM Vaidya, Former Chairman,
Indian Oil Corporation Ltd.

1.0 A Shifting Global Narrative — India at the Heart of Refining's Future

For over a century, the refining industry has served as the bedrock of industrial development, energy security, and economic resilience. However, in today's world of accelerating energy transitions, climate imperatives, and shifting geopolitics, the future of refining is being viewed with increasing ambivalence—especially in parts of the developed world. While some argue that refining's best days are behind it, a closer examination—particularly through the lens of India and the Global South—reveals a different, and far more consequential, narrative.

1.1 Petroleum Demand: Global Divergence, Indian Momentum

Official data from the Petroleum Planning & Analysis Cell (PPAC) confirms that India's petroleum consumption rose to a record 239.171 million metric tonnes (MMT) in FY 2024–25, reflecting a robust 2.1% year-on-year growth over FY 2023–24 levels of 234.259 MMT. This 10-year journey—from 158

MMT in FY 2013–14 to 239 MMT in FY 2024–25—represents a cumulative growth of over 51.3%, strongly aligned with India's consistently high GDP trajectory (~3.8% CAGR over the decade).

China, the other major growth engine in the Global South, also expanded its petroleum consumption by 18.2% between 2014 and 2023, driven by petrochemical demand and industrial activity. However, signs of a potential demand plateau are beginning to emerge, particularly due to rapid electrification of transport and a slowing economy.

By contrast, in the developed world:

- The United States has witnessed a 6.4% decline in petroleum consumption over the past decade.
- Europe's demand has contracted by over 18%, owing to fuel switching, policy interventions, and economic stagnation.

This divergence is stark—and telling. While OECD nations are experiencing plateauing or negative growth, India and, to an extent, China remain the world's most reliable demand centres. This reaffirms the strategic case for India to not only expand its refining infrastructure but to reposition itself as a regional export and transformation hub for refined fuels, petrochemicals, and bio-based products.

More importantly, India's refining trajectory is now geared toward reinvention, not replication. With rising expectations for clean fuels, tighter carbon norms, and greater energy efficiency, India is advancing a model where refining capacity is being reshaped, retooled, and reimagined to stay future-ready. 2.0 The Global Restructuring of Refining – Context and Prescriptions for India

The refining landscape across the world is undergoing a tectonic shift—not because refining is obsolete, but because it is being re-evaluated, repurposed, and relocated in response to new geopolitical, environmental, and economic realities.

2. Key Global Trends

- OECD nations are downsizing capacity: Europe, the UK, and parts of North America are witnessing refinery shutdowns due to rising carbon costs, aging infrastructure, and flat or declining demand. According to Wood Mackenzie, over 100 refineries (21% of global capacity) are at risk of closure by 2035.
- Asia and the Middle East are emerging as refining hubs: These regions, with lower regulatory costs and growing domestic markets, are adding significant capacity. Major projects in China, Saudi Arabia, Kuwait, and India underscore this pivot as this is the place where the damand is.
- Decarbonization is redefining margins: The 'crack spread' is no longer the only determinant of viability. Carbon intensity, hydrogen availability, energy efficiency, and integration with petrochemicals are now vital for competitiveness.
- Petrochemical integration is imperative: With transportation fuels expected to peak globally before 2040, future-ready refineries must derive 30–40% of their revenue from petrochemicals, especially for naphtha and aromatics.

3. Strategic Takeaways for India's Refining Sector

Given these trends, India's refining strategy must pivot from volume expansion alone to value-enhancing reinvention. The following prescriptive suggestions are offered:

3.1. Build Only Quartile-One Refineries from Day One

Refineries sanctioned today must achieve top-quartile operational efficiency on parameters such as energy consumption, emissions, turnaround cycles, and cost per barrel processed. The refinery operations must be safe, reliable, efficient and sustainable.

Suggestion: Future refinery investments should embed digital control systems, AI-assisted diagnostics, and energy recovery loops from inception. Design for flexibility across multiple crude types and product slates.

Rationale: The era of strong crude cracks may wane post-2030. Margins must increasingly be protected through superior efficiency.

3.2 Shift from Standalone Refineries to Fully Integrated Petrochemical Complexes

In a world of demand fragmentation, petrochemical integration provides margin stability.

- **Prescription:** All Greenfield and major Brownfield expansions should include ethylene, propylene, and BTX (benzene-toluene-xylene) streams, alongside conventional fuels. Apetrochemical intensity of 30–40% should be targeted.
- **Rationale:** India's petrochemical imports are rising. Integrated complexes lower risk by enabling cross-subsidization when fuel cracks fall. India is a big importer of petrochemicals. Existing refineries with low petchem intensity to be encouraged for certain petchem units to improve their petchem intensity, or else to be encouraged for appropriate intermediate stream transfer. Taxations on these intermediate stream transfer to be reviewed.

3.3 Establish Bio-Refineries as Strategic National Assets

Inspired by models like NESTE (Finland), India must develop dedicated bio-refineries to produce bio-diesel, ethanol, bio-bitumen, SAF (Sustainable Aviation Fuel), and renewable naptha.

- **Suggestion:** Public Sector Enterprises should be tasked with developing first-of-its-kind bio-refinery clusters under viability gap funding (VGF) or carbon-market-based incentives.
- **Rationale:** These capital-intensive, low-IRR assets may not attract early private capital. Yet they are essential for achieving India's net-zero roadmap and export leadership in green molecules.

3.4. Recalibrate for Export-Oriented Growth

Given regional deficits in countries like Sri Lanka, Nepal, Bangladesh, and parts of East Africa, India has the geographical and logistical advantage to emerge as a refining and product supply hub.

- **Suggestion:** Coastal refineries with integrated jetties, large tankages, and multi-modal dispatch capabilities should be prioritized. Market design must incorporate regional demand- supply intelligence and bilateral agreements.
- **Rationale:** Export orientation will add resilience against domestic demand shocks and reinforce India's energy diplomacy.

3.5 Incentivize Carbon-Efficient Operations

Carbon costs are already reshaping competitiveness in Europe. India must prepare pre- emptively.

- **Suggestion:** Introduce a phased internal carbon price for refineries above a certain throughput threshold. Revenues can fund energy audits, efficiency upgrades, and green hydrogen projects
- **Rationale:** Global supply chains will increasingly favour low-carbon producers. India must future-proof its exports and imports against CBAM-like regimes.

This restructuring of the global refining map offers India a strategic opening. Unlike many Western nations that are forced into decommissioning, India has the luxury of designing the refineries of the future—cleaner, integrated, and globally competitive—from the ground up.

4.0 India's Roadmap to 2047 – Building Future-Ready Refineries

India's journey to 2047—the centenary of its independence—coincides with a transformative period for the global energy system. By mid-century, most OECD countries may havealready peaked in fossil fuel use, but India's economic growth, demographic momentum, and infrastructure build-out will continue to anchor robust demand for petroleum products. The refining sector, therefore, must not only endure—it must evolve and lead the charge toward cleaner, smarter, and more resilient infrastructure.

4.1 India's Current Expansion Pipeline (Approved Projects Only)

To meet future energy demand, India is already progressing with a mix of Brownfield and Greenfield refinery projects. As per official industry sources and current project timelines:

Project Type	Capacity Addition (MMTPA)	Capacity Addition kbpd	Commissioning Timeline
Brownfield Expansion	25–26	~500–520	~ 2026–2027
Greenfield Projects	9	~180	2025–2026

Note: Only approved and under-construction projects are considered. Announced or proposed projects pending final investment decision are excluded for consistency.

These projects reflect a pragmatic balancing act—adding capacity where demand is demonstrably rising, while embedding design flexibility, energy efficiency, and downstream integration into future assets.

5.0 Strategic Policy Suggestions: India 2047

To make India's refining industry future-proof, globally competitive, and aligned with its net- zero ambitions, the following policy and institutional actions are recommended:

5.1 Create "Refinery 2047" Investment Benchmarks

- Establish a national benchmark framework that evaluates new refinery proposals on:
- Petrochemical intensity
- Energy consumption (Gcal/ton of throughput)
- Emissions per barrel processed
- Digital maturity and asset resilience

Suggestion: MoPNG, in consultation with NITI Aayog and CPSEs, may institutionalize a "Refinery 2047 Compliance Framework" applicable to all upcoming investments.

5.2 Institutionalize Bio-Refineries as a Parallel Track

- While traditional refining will remain critical, the government should mandate that a minimum proportion of public capex in downstream fuels is reserved for bio-refining assets.
- Bio-refineries should be enabled through:
- Land allocation fast-tracking
- Green molecule offtake assurance
- Mandated procurement of SAF for aviation from Indian producers

Suggestion: A tripartite policy between MoPNG, MoCA (Civil Aviation), and MoEFCCcould create a pipeline of sustainable aviation fuel from domestic producers by 2030.

5.3. Champion Regional Export Hubs

India's proximity to fuel-deficit countries (e.g., Sri Lanka, Bangladesh, Nepal, Myanmar, East Africa) provides a geopolitical opportunity.

- Future coastal refineries should be:
- Integrated with bulk terminals
- Linked to pipeline corridors for hinterland dispatch
- Digitally synchronized with regional demand centres

Suggestion: Designate 2–3 refineries as "Regional Export Flagships" with dedicated MoPNG and MEA support, incentivizing long-term export contracts also looking at it as strategic move for influencing countries in South Asia, Southeast Asia, and East Africa.

5.4 Promote Petrochemical Clusters Co-Located with Refineries

The demand for petrochemicals is rising at 2.5x the rate of transportation fuels in India. Yet, India imports a significant share of its naphtha derivatives and aromatics.

- New refineries should be mandated to:
- Achieve minimum 30–40% petrochemical intensity
- Co-develop naphtha crackers, C2-C3 separation units, and polymer plants

Suggestion: Extend PLI-type benefits or accelerated depreciation to "Refinery + Petrochemical" integrated complexes and form focussed groups MoPNG, Dept. of Chemicals and Fertilisers

5.5 Carbon Competitiveness Certification

Refineries that achieve top-quartile energy performance and emissions metrics should be certified for carbon competitiveness, aiding global recognition and export readiness.

Suggestion: A national "Green Refining Index" could be instituted—similar to the PAT (Perform Achieve Trade) scheme—for transparent benchmarking. MoPNG and MNRE and MoEFCC to coordinate

5.6 Fast tracking the New Refinery Projects announced

The new refinery projects announced have to be fast tracked , should have a high petchem intensity and target must be to get the investment approvals in next couple of years. They all should be targeted for mechanical completition by 2032-33 considering a 60 month construction schedule. If we slip-on these timelines ,then these projects will lost their significance as projects contributing to our energy security and may be irrelevant. Focussed groups consisting of MoPNG and respective state Governments to work on these projects.

These may be preferably be coastal complexes but if suitable land parcels availability is an issue then even inland complexes may be considered.

India's refining story for the next two decades is not about survival—it is about strategicreinvention. If executed well, India can not only meet its domestic needs but become a trusted export hub and technology leader in advanced refining and clean fuels.

6.0 Conclusion: From Energy Legacy to Energy Leadership

India stands today at a defining crossroad—where energy security, economic growth, and climate imperatives intersect. While the world debates the twilight of refining, India must write a new chapter—not of retreat, but of reinvention. A chapter where refining is not seen as a sunset industry, but as a strategic enabler of transition, providing the vital bridge between today's fossil-heavy systems and tomorrow's diversified energy mix.

<u>**This reinvention must be deliberate and multidimensional:**</u>

- Petrochemical integration is no longer optional—it is imperative. Future-ready complexes must deliver not just fuels, but high-value petrochemical derivatives to support India's growing industrial and consumer economy.
- Operational excellence will define competitiveness. As global product cracks become less generous beyond 2030, new refineries must aim for quartile-one performance from Day One to protect margins through energy efficiency, digitalization, and low-carbon operations.
- Greenfield bio-refineries, modelled on successful international examples, should form a parallel track of investment, producing sustainable aviation fuel, bio-bitumen, biodiesel, and ethanol. These projects must be nurtured by public sector commitment, innovation incentives, and assured off take mechanisms.
- Strategic capacity planning should align with India's long-term POL demand growth and export ambitions to neighbouring geographies—South Asia, Southeast Asia, and East Africa—where refining gaps and energy needs remain acute.

India's unique position—as the world's third-largest energy consumer, a fast- growing economy, and a responsible global stakeholder, demands an equally unique refining model: one that is resilient, efficient, integrated, and clean.

This is not a call to resist the transition. It is a call to lead it—on India's terms and in India's context. Because refining, as a sector, is not dying. It is simply relocating to where the demand is and reinventing itself to meet the realities of the new energy age.

India must seize this moment—not just to refine fuels, but to refine its future.

5 Unlocking Catalyst Technologies for Modern Refineries Marching Towards Sustainability: Indian Oil's Indigenization efforts

Dr. Alok Sharma, Director (R&D); Dr. Alex C Pulikottil, ED (Petrochemicals & Catalyst); Sh.Survesh Kumar, CGM (Hydroprocessing, Catalyst & Technical Service); Dr. A V Karthikeyani, GM (Catalyst & Analytical); Dr. K O Xavier, DGM (Catalyst)

Indian Oil Corporation Ltd., R&D Centre

Energy transition for environmental sustainability

Fossil fuels have been the dominant global energy vehicle over the last several centuries. Globally, the demand for fossil fuels is expected to plateau in coming years and eventually tend to drop beyond 2030. India, on the other hand, being one of the fastest growing economies in the world, is projected to witness hikes in fuel consumption at least in the next two decades. The growing concerns on impacts of climate change prompts to adopt cleaner energy solutions worldwide. India too is deeply committed in the global efforts to mitigate climate change and has embarked upon a journey of transitioning the existing energy system to cleaner alternatives with an ambitious net-zero target by 2070.

The current focus on energy transition and decarbonization enforces refiners to try and quickly adapt to the changing regulations, market demand and reorient their operations to meet the net-zero goals. Operating existing refinery units with higher energy efficiency and productivity is of paramount importance in the current scenario. Besides the strategic investments in green hydrogen, electric vehicles, solar energy, etc. as alternatives to fossil fuel, the adoption of bioenergy is a promising approach for advancing energy transition. Further, since the demand for petrochemicals is expected to see continual increase in the region, refiners have avenues to value-add their existing assets by shifting the product slates towards chemicals and thereby ensuring enhanced sustainability and profitability. In short, refinery operations need to be recalibrated with advanced processes, high performance catalysts, alternative feedstocks and product flexibility to ensure sustainability and profitability while fulfilling the ever-increasing societal demands.

Refining Industry in India

India holds a significant position in the global refining landscape, with a total refining capacity of approximately 258.12 MMTPA, making it the fourth largest refining hub globally. IndianOil Corporation Ltd. (IOCL) and its subsidiary CPCL alone accounts for 80.75 MMTPA of this capacity, with plans to increase it to 107.4 MMTPA. IndianOil Group holds around 35% of the nation's refining capacity.

The refining industry is producing a wide array of refined fuels and petrochemical feedstocks through various process routes such as Fluid Catalytic Cracking (FCC), catalytic hydroprocessing (including hydrotreating and hydrocracking), reforming, and other feed/product treatment units. In Indian refineries, FCC units contribute 40–60% of gasoline production, while over 90% of diesel is derived from Diesel Hydro Desulfurization (DHDS) and Diesel Hydro Treating (DHDT) units. These technologies are the major workhorses to produce value added light olefins, clean fuels meeting regulatory norms and many other petroleum products. FCC and hydroprocessing technologies must be aligned to the needs of emerging market as necessitated by the energy transition.

Further, in response to government mandates on sustainable aviation fuel (SAF), Indian refineries too need to meet blending requirements in a phased manner viz. 1% SAF by 2027, 2% by 2028, and 5% by 2030. India's petrochemical sector continues to grow at a Compound Annual Growth Rate (CAGR) of ~6%, for which the FCC units can also serve as a key source for feedstocks like ethylene and propylene.

Refining Catalyst Demands

Catalysts are at the heart of any major refinery processes and play a pivotal role in converting heavier hydrocarbon molecules such as Vacuum Gas Oil into lighter, more valuable fractions and cleaner fuels that meet increasingly stringent environmental regulations. The global refinery catalyst market is projected to grow at a CAGR of approximately 4% from 2025 to 2031. This growth is driven by increasing demand for clean transportation fuels, including gasoline and diesel, and SAF, alongside the rising need for petrochemical feedstocks such as ethylene and propylene.

The current demand for refinery catalysts in India stands at approximately 50,000 metric tonnes annually, with a projected CAGR of 5.81% from 2025 to 2032. However, the country remains heavily reliant on catalyst imports from foreign suppliers, resulting in substantial foreign exchange outflows. To reduce dependence on foreign suppliers and promote strategic self-reliance, IOCL has rigorously pursued the development of various catalyst technologies at its R&D, thereby offering alternatives alongside the benefits of import substitution and indigenization of customized catalyst technologies.

India Oil's Innovation Journey in Refining Catalysis

Recognizing the need for self-sufficiency, IndianOil began its journey in catalyst development in 2000. Over two decades, the innovative research efforts exerted in the domain, cultivated significant expertise in catalysts for FCC and hydroprocessing applications, making IndianOil a pioneer in indigenous commercial catalyst technology. Commercialization efforts commenced in 2002 through licensing of the catalyst technologies to an Indian partner. Initial sales began modestly with 4 MT of ZSM-5 additive in 2004, yielding INR 1.5 lakh as royalty initially. Since then, sustained innovation has resulted in spurt of successful product launches and broad market acceptance and commercial utilization, culminating in cumulative sales of approximately 25,000 MT so far.

IndianOil offers a broad range of catalysts for FCC and Hydroprocessing applications:

Catalysts for FCC Applications	
Lotus FCC Catalyst	**Lotus Series (Lotus-24, Lotus Prime, Lotus Supreme)**: Designed for VGO cracking and middle distillate maximization
i-MAX Maximizing LPG	**i-MAX Series (Premium, Supreme, Ultra, Value, Value-Plus, ACE)**: ZSM-5-based additives tailored for LPG and propylene yield enhancement
INDMAX Catalyst Boosting Light Olefins	**INDMAX Catalyst**: Proprietary catalyst for INDMAX Process to maximize LPG and light olefins enhancement
RUA Bottoms Upgradation Additive	**Residue Upgradation Additive (RUA)**: Large-pore matrix technology for upgrading heavy feedstock
Eco-MAX CO Combustion Promoter	**Eco-MAX Series (500, 800)**: CO combustion promoters for FCC regenerators
i-MAX OCTA Plus Gasoline Octane Booster	**OCTAZOOM**: Octane booster without gasoline yield loss
IndGSR Gasoline Sulfur Reduction	**GSR Additive**: Gasoline Sulfur Reduction

Catalysts for Hydroprocessing Applications	
IndiCAT Prime DHDT Catalyst	**IndiCAT Prime Series**: Hydrotreating of diesel
IndiCAT Flexi Desulfurization Catalyst	**IndiCAT Flexi Series**: Hydrotreatment of naphtha, Kerosene & ATF enhancement
INDAdept Deep Desulphurization Technology	**INDAdept:** Adsorbent for sulfur reduction in gasoline
indSelect Di Olefin Saturation Catalyst	**indSelect:** Catalyst for Selective diolefin saturation in gasoline
indLPet Selective Hydrocracking Catalyst	**indLPet**: Catalyst for Selective hydrocracking of middle distillate

Catalyst prowess to navigate energy transition

As the thrust on energy transition and decarbonization increases, refineries have to adopt new customized solutions based on challenges and opportunity specific to each refinery. The role of catalysts is particularly crucial for the resilience of refining industry in the current era of energy transition. IndianOil's proprietary FCC catalysts & additives and hydroprocessing catalysts allow refiners not only to operate their respective units optimally but also enable them to process diverse feedstocks to harness the required product slates. The performance of IndianOil's in-house catalyst platforms for FCC and hydrotreating applications to meet the challenges posed by energy transition are discussed as below:

Catalysts for Maximizing Petrochemicals feedstock in INDMAX process

Currently, petrochemicals like light olefins (Ethylene, Propylene, isobutene etc) are mainly produced through steam cracking and FCC process. FCC process offers attractive flexibility for tuning the product selectivity for producing different olefinic products with lower energy intensity. IndianOil's proprietary INDMAX process has been designed to maximize production of olefins by converting feedstocks having higher residue fraction at elevated operating temperature with proprietary catalyst solutions. This process is well suited to maximize propylene production with a yield in the range of 17-21% along with ethylene and other lighter olefins. INDMAX technology has been adopted in several refineries in India suiting for petrochemical integration and new such installations are in pipeline.

Traditionally, FCC catalyst system comprises of a primary cracking component based on Y type zeolite and a secondary shape selective cracking component made of medium pore pentasil zeolite like ZSM-5 zeolite. ZSM-5 additives are very effective in increasing propylene yield by selectively cracking olefins in the gasoline range hydrocarbons. INDMAX technology indispensably employs a proprietary catalyst system, namely the IMX Series Catalysts, specially customized with high intrinsic activity for substantially converting gasoline range olefins to maximize propylene and ethylene simultaneously alongside maintaining the olefin content required in gasoline by selectively cracking the heavier feed molecules.

The product yield benefits of IMX Series catalysts over similar commercial processes are depicted in Figure 1. IMX Series catalyst exhibits substantial improvements in yield of light olefins, coke selectivity and bottom upgradation with high resistance against thermal and hydrothermal deactivation. INDMAX catalyst system is designed to operate at high severity conditions yet provides stable operational characteristics as demanded in INDMAX process.

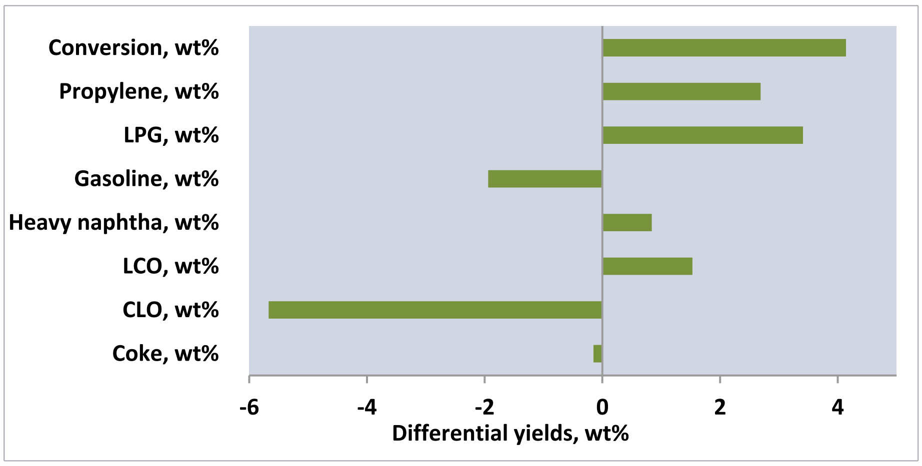


Figure 1: Differential performance benefits of IMX Series catalysts over commercial reference

FCC Catalyst Additives for Harnessing operational flexibility of FCC units

Indian Oil's high performing i-MAX Series ZSM-5 additives for producing LPG and Propylene are available in three platforms: i-MAX Premium, i-MAX Supreme and i-MAX Ultra that are customizable to meet the needs of refiners. These additives are based on a stabilized and tailored ZSM-5 zeolite, employing a patented methodology that is embedded in the additive microsphere having unique matrix technology that also optimized to retain the crystallinity of zeolite. Figure 2 shows the efficacy of different genres of i-MAX Series ZSM-5 additives for propylene. i-MAX series additives can be customized as per the needs of the refiner and are commercially offered. i-Max ZSM-5 additives are being supplied to several refineries in India and have enabled refiners to tweak their product slate to maximize profitability.

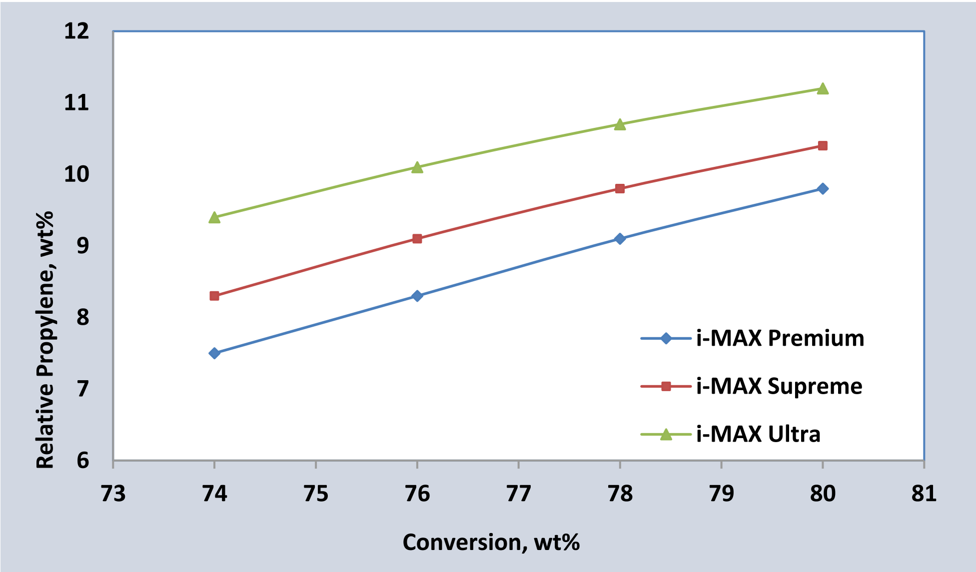


Figure 2: Relative propylene selectivity of i-MAX Series additives for a typical feed & operating conditions

Residue Upgradation Additive (RUA), is a commercially established additive system from Indian Oil's catalyst basket, designed with large pore matrix technology to crack heavier feedstock and produce more valuable distillates. This customized additive improves bottom upgradation and coke selectivity in FCC unit. Eco-MAX CO Combustion Promoter is another best-in-class additive that increases combustion efficiency in FCC regenerators, converting more than 95% of CO at appropriate operating conditions. Eco-MAX is designed for longer retention in the unit with high active-metal dispersion for maximum efficiency, even in high severity commercial FCC units. IndianOil's additive systems have several commercial references with successful operation in FCC units meeting the process requirements and are continually improved to offer more benefits to refineries in the emerging scenario.

Hydrotreating catalysts for capturing margin advantages

Hydrotreating processes play a pivotal role in the changing landscape of refinery operation, be it the feed treatment to produce cleaner feedstocks that will have a positive impact in subsequent process units or to produce cleaner products like gasoline and diesel. Further, with the need to valorize maximum benefits from existing hydrotreating units in emerging scenario, focus will be to leverage productivity and efficiency of these units. Deployment of newer high-performance catalysts would be the differentiator. Innovations in hydrotreating catalyst technology will enable cost-effectiveness and higher activity thus enabling operation at lower temperature and effective processability of heavier feedstocks.

With focus in hydrotreating catalysis, over the years IndianOil has developed and commercially deployed its high-performance Diesel and VGO hydrotreating catalyst platform (IndiCAT Series) as depicted in Figure 3. The catalyst platform has design features with functionalities tailored for removal of various hetero-atoms S, N & O as well as for the deep hydrogenation of aromatic & olefinic compounds in the feedstocks for meeting fuel specifications like sulfur and nitrogen content, density, distillation end point, cetane number etc. The diesel hydrotreating catalyst system can also be designed with high hydrogenation functionality for boosting volume swell of the product. The catalyst technology is designed to tailor the nature of active sites (NiMoS phase) through unique metal chemistry employed in conjunction with support characteristics. Catalyst systems with high resistance to deactivation and improved performance characteristics are pivotal to efficiency of hydrotreating processes in the era of energy transition.

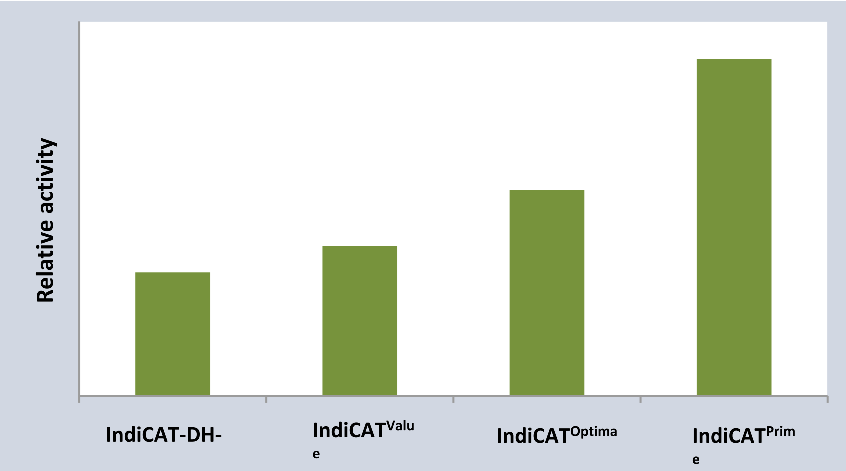


Figure 3: Evolution of IndianOil's IndiCAT series catalyst platform

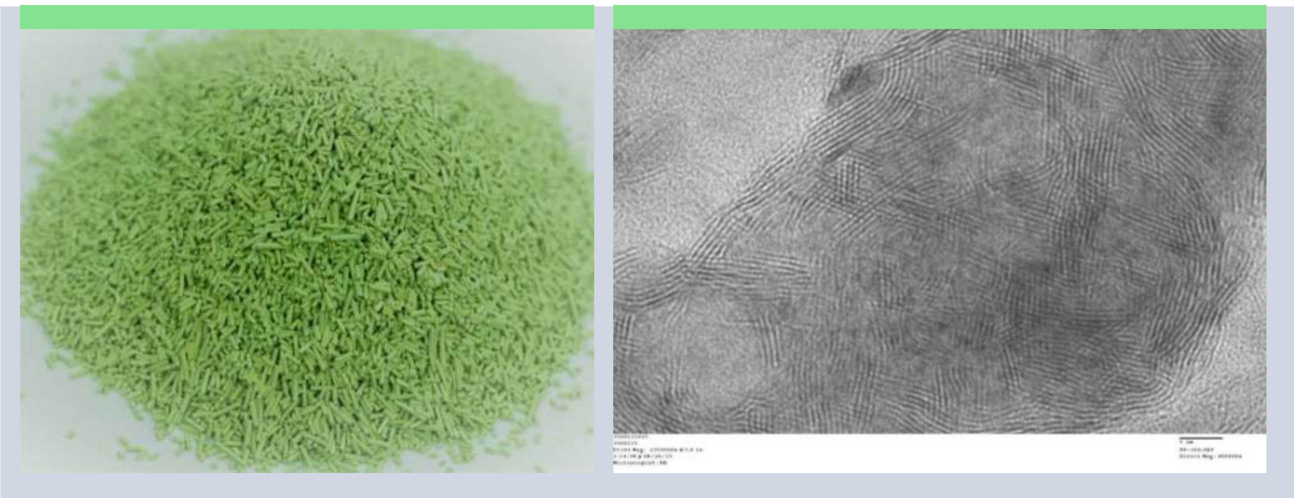


Figure 4: IndiCATPrime catalyst and Transmission Electron Microscopy (TEM) images

Co-processing of Bio-Oils

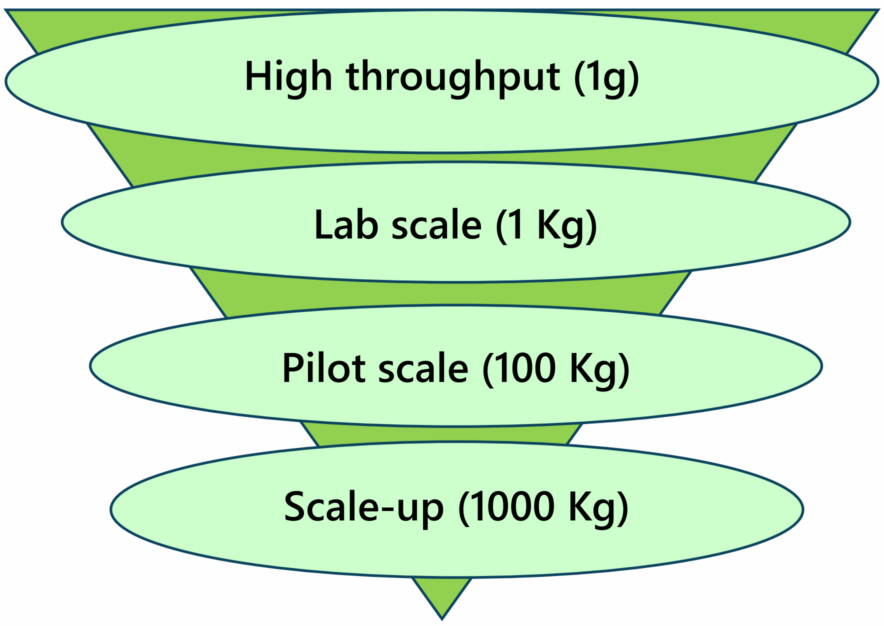
The co-processing of renewable and recycled feedstocks, including plastic pyrolysis oils, biomass-derived oils and vegetable oils offers a viable pathway to reduce carbon footprints. Despite the promising opportunity, these alternative feedstocks pose several challenges like variability in composition, high level of contaminants such as chlorides, alkali metals and heavy metals etc. Tailored FCC catalysts and additives can enable processing of complex renewable streams in FCC units without compromising operational efficiency or unit productivity.

With the growth trajectory of aviation industry, the demand for sustainable aviation fuel (SAF) is rising globally due to increasingly stringent regulatory pressures. However, the expansion of SAF supply is constrained by the high capital costs and long lead times required to build or revamp standalone production facilities. The co-processing of Used Cooking Oil (UCO) in kerosene hydrotreaters offers a cost-effective and convenient option that can be easily employed in the existing hydrotreating units for SAF production. This approach enables for launching SAF in the market within a short timeframe. However, the challenges in terms of feed availability, handling feedstock impurities, achieving mandatory cold flow properties and removal of oxygen are to be suitably overcome. The advancement in catalyst technologies and selective process configurations will act as the levers for addressing these challenges. IndianOil, with its own technical expertise gained in the past years, is in a process of advancing the development of in-house catalysts and process for co-processing complex renewable streams.

Commercialization of Indigenous Catalysts

IndianOil's catalyst platforms are proprietary technologies, for which patents have been granted in India, USA and other countries, underscoring their technological novelty and performance edge. The concerted R&D efforts focused in the initial stage on understanding preparation-structure-property correlations in catalysis and in the development of preparation schemes. For example, in the case of hydrotreating catalysts, the new generation INDICATPrime catalyst was designed with Type II Catalytic Active Sites for its high intrinsic performance. Modern tools like high throughput catalyst preparation and screening units with automated robotic arms and other tools and various sophisticated characterization instruments have aided in accelerating the pace of achieving the optimal catalyst recipe.

With its genesis in gram scale, the catalyst recipes were scaled up to commercial level of metric tons for validating the manufacturing process and catalyst technology. The manufacturing process was established through rigorous protocols for quality and consistency in manufacture and validation of catalyst performance. The commercial worthiness of the newly developed catalysts was demonstrated in the commercial units in various refineries. The development stages during catalyst research are indicated in **Figure 5.**



The catalyst recipes were initially manufactured for plant demonstration runs in various refinery units. Based on the success in demonstration runs, the catalyst platforms are being commercially offered to refineries through licensing of know-how to Sud-Chemie India Ltd (SCIL). Notably, such indigenization drive has so far culminated into the manufacture and deployment of around 25000 MT of indigenous catalyst in various refinery units and some of the major catalyst supplies are summarized as below:

- **Diesel Hydrotreating:** CPCL, Mathura Refinery, Digboi Refinery, Gujarat Refinery, Guwahati Refinery, Bandar Abbas (Iran) Refinery
- **Naphtha/Kerosene/ATF Hydrotreating:** Guwahati Refinery, Bongaigaon Refinery, Paradip Refinery, Barauni Refinery
- **FCC Additives:** Supplied to IOCL FCC Units (Panipat, Mathura, Haldia), INDMAX units (Guwahati, Paradip, Bongaigaon, Barauni), CPCL, BPCL, and HPCL refineries
- **FCC Catalyst:** Mathura Refinery

Envisaging the need for augment the indigenization drive for self-reliant, IndianOil has made a strategic move by launching its own Catalyst Manufacturing Unit (CMU) in Jan'24 for FCC catalyst additives and hydroprocessing catalysts at Panipat Refinery & Petrochemical Complex (PRPC) in line with "Make in India" initiative of GoI. CMU has the capability to manufacture 500 MPTA of FCC catalyst additives & 1000 MTPA of hydroprocessing catalysts for captive consumption in refineries. Considering that this facility was entirely designed, engineered and erected using domestic capabilities and machineries and the indigenous products are being manufactured, Catalyst Manufacturing Unit stands out as an absolute example of Atmanirbhar initiative.

Summary and Way forward

In view of the quest for reducing India's dependence on multi- national companies for cutting edge refining catalyst technologies, IndianOil, through concerted R&D efforts of more than two decades, has developed and commercialized several platforms of catalysts for FCC and hydroprocessing applications, in line with the "Make in India" & "Athmanirbhar" initiatives. Research pursued over the years focused on tailoring support materials with desired physico-chemical and structural properties, designing highly reactive active sites and optimizing the preparation protocols. IndianOil has also gained experience and capability in scaling up catalyst recipes from the conceptualization phase to commercial scales and offering such catalyst systems to refinery units. In view of growing commercial potential of refining catalysts and the demand for more active and selective catalysts to address the challenges of energy transition, fundamental knowledge and experience gained prompts IndianOil to further develop and innovate new improved catalysts to meet the ever-changing commercial challenges.

Barmer (HRRL); Under Construction

6

Boosting Energy Security and Petrochemical Self-Reliance: A Case Study on HRRL's Greenfield Refinery Expansion

Shri S. Bharathan, Director (Refineries)

Hindustan Petroleum Corporation Limited (HPCL)

"HPCL Rajasthan Refinery Limited (HRRL) stands as a landmark in India's energy journey—combining cutting-edge refining and petrochemical technology with a vision for sustainable, inclusive growth. As India moves toward its Viksit Bharat 2047 goal, HRRL exemplifies how strategic energy infrastructure can transform regional economies, create thousands of jobs, and uplift communities through innovation, education, and healthcare. This refinery is not just about fuel—it's about fuelling India's future."

1.0 Background: A Legacy of Growth and Innovation

India's refining journey began over a century ago with the commissioning of the Digboi Refinery in Assam in 1901. Since then, the Indian refining sector has evolved remarkably, achieving a total refining capacity of 258 million metric tonnes, positioning India among the top three refining nations globally. Notably, India also hosts the world's largest refining complex.

Pic1: Crude Distillation Unit construction at HRRL

While many countries are witnessing a stagnation or decline in refining capacities, India's refining sector continues on a robust growth trajectory. Projections indicate an increase to 310 MMT by 2030, with further expansion beyond, aligning with the nation's rising energy and development needs.

Parallelly, the petrochemical industry, which took root in the 1960-1970s, has witnessed rapid growth. India now stands as the third-largest consumer of polymers, the fourth-largest producer of agrochemicals, and the sixth-largest chemical producer globally. However, the country still imports nearly 10 million tonnes of petrochemicals annually—indicating a significant opportunity to strengthen domestic production and reduce import dependence.

2.0 India@2047 – The Vision of Viksit Bharat

As India approaches 100 years of independence, the national vision of Viksit Bharat aspires to transform India into a fully developed nation by 2047. This vision encompasses robust economic growth, global competitiveness, industrial modernization, environmental sustainability, and inclusive development.

The refining and petrochemical sectors will play a crucial role in realizing this vision. With the ambition to become a global hub for petroleum products, the Indian refining industry is poised for technological advancement, strategic investments, and sustainable practices. Simultaneously, the petrochemical sector holds immense potential, driven by a substantial gap between domestic demand and supply. Petrochemical demand is projected to grow over 3.5 times the current levels by 2047.

India's polymer consumption currently stands at roughly one-third of the global average. As the economy grows and per capita income rises, this consumption is expected to align more closely with global benchmarks, creating vast opportunities for expansion, innovation, and value addition.

3.0 HPCL: Driving India's Energy Future

Hindustan Petroleum Corporation Limited (HPCL), a Maharatna Central Public Sector Enterprise, has a rich and inspiring legacy that is deeply intertwined with the evolution of India's petroleum industry. Although HPCL was formally established in 1974, its roots trace back to the early 1900s, through its predecessor companies.

HPCL's Mumbai Refinery was the India's first modern and complex refinery setup in 1954. This marked the beginning of sophisticated refining operations in the country.

Today, HPCL operates over 37 million metric tonnes per annum of refining capacity, including its joint venture refineries. Throughout its journey, HPCL has consistently distinguished itself by modernising its refineries with world-class technologies, integrating petrochemical production, and developing specialty products to meet evolving market needs.

Continuing its legacy of innovation and leadership, HPCL is now setting up India's highest Petrochemical Intensity refinery—a state-of-the-art refining-cum-petrochemical complex—demonstrating its commitment to value addition, energy security, and future-ready growth.

4.0 Formation of HRRL: A historic Collaboration

Following the discovery of oil and the commencement of production from the Barmer oil field in 2005, effort was made for establishment of a 4.5 MMTPA grassroots refinery in Barmer. However, the project was not pursued due to its relatively small refining capacity and associated economic challenges.

To support its continued growth and meet the projected demand for petroleum products, HPCL subsequently explored the feasibility of setting up a larger, 9 MMTPA refinery in Rajasthan. This initiative also took into account the unique characteristics of Rajasthan crude.

Rajasthan crude is a 29.6° API low-sulfur crude with a high proportion of heavy ends and a relatively high hydrogen content. This paraffinic crude possesses inherently high crackability compared to other similar crude types. Its elevated hydrogen content enhances the breakdown of heavy hydrocarbon molecules, making it particularly suitable for the production of high-value petrochemical products.

These characteristics were validated through rigorous configuration studies carried out by world-renowned consultants. The studies confirmed that the Barmer crude was ideally suited for a petrochemical-intensive refinery setup. Accordingly, a state-of-the-art configuration was finalized with a focus on maximizing petrochemical output while also producing clean fuels.

To bring this vision to life, a joint venture was established between Hindustan Petroleum Corporation Limited (HPCL) and the Government of Rajasthan, with equity participation of 74% and 26% respectively. This collaboration marked the birth of HPCL Rajasthan Refinery Limited (HRRL)—a historic partnership to develop India's highest petrochemical-intensity refinery.

5.0 Engineering an Oasis in the Desert – HRRL's Unparalleled Infrastructure

HPCL Rajasthan Refinery Limited (HRRL) is more than just a refinery—it's a landmark in engineering, energy efficiency, and self-reliance. Designed with a petrochemical intensity of 26%—the highest in India—and a Nelson Complexity Index of 17, the refinery has been configured for maximum energy integration and product value addition. True to its vision, it has been conceived as a Quartile 1 energy-efficient refinery from Day One (Q1D1).

Pic2: HRRL's Dual Feed Cracker

The complex will produce 2.5 million tonnes per annum of petrochemicals—including polypropylene, LDPE, HDPE, butadiene, and BTX—alongside 5 MMTPA of clean fuels (limited to MS and HSD), showcasing its high level of integration with the petrochemical value chain.

A 1 MMTPA cracker is central to this configuration, enabling integration with world-class downstream polymer units. A total of 35 polymer grades—14 polyethylene and 21 polypropylene grades—will be manufactured, reflecting the complexity and depth of the product slate.

5.1 Unmatched Construction & Scale:

- Earthwork volume: Over 150 lakh m^3, more than six times the volume of Great Pyramid of Giza
- Concrete used: Approximately 16 lakh m^3, five times more than the Burj Khalifa
- Structural steel: About 3 lakhs metric tons of structural steel is used, a quantity 40 times more than the amount used in the construction of the Eiffel Tower.
- Cabling: Approximately 28,000 Km of electrical and instrumentation cables are being installed, surpassing twice the Earth's diameter
- Control rooms: Refinery Main Control Room / Petrochemical Main Control Room are one of the largest in the country.
- Spread across 4000 acres, HRRL is among the largest integrated refining and petrochemical complexes in India
- Over 85% indigenous content in construction and equipment sourcing, reinforcing the commitment to Atmanirbhar Bharat
- Designed with Zero Liquid Effluent Discharge (ZLD) capability
- Home to India's first composite flare structure — a 140-meter-high stack accommodating 9 flares within a single structure, weighing over 1,700 MT

6.0 Challenges in Implementation

Implementing a mega-scale, first-of-its-kind refinery and petrochemical complex in the remote and arid region of Pachpadra (Rajasthan state) posed formidable challenges across multiple fronts—environmental, logistical, infrastructural, and operational.

Pic3: ODC movement inside Refinery

The harsh desert climate, characterized by extreme temperatures, high winds, and frequent dust storms, made construction activities particularly demanding. Moreover, the absence of pre-existing industrial infrastructure in the region necessitated the creation of basic enablers from scratch—power, water supply, roads, housing, and worker amenities—before full-fledged construction could begin.

Pic4: ODC movement outside of Refinery

One of the most daunting aspects of the project was logistics. Transporting large and heavy equipment to the landlocked site required meticulous planning and extraordinary execution.

A prime example was the movement of the VGO-HDT reactor from Mundra Port to the refinery site—a journey that spanned over 245 days. This operation involved the creation of temporary infrastructure such as bypass roads, bridges, and culverts, along with the temporary shutdown of electrical lines, removal of toll booths, and coordination across multiple administrative jurisdictions over a 500-kilometer corridor.

The project witnessed a historic feat in industrial logistics with a 4-kilometer-long convoy of Oversized Dimension Cargo (ODC), setting new benchmarks in engineering transport in India.

Overcoming these implementation challenges not only demonstrated the engineering excellence and resilience of the HRRL team but also underscored India's growing capability to execute complex, integrated energy infrastructure in challenging geographies.

HRRL is not just building a refinery—it is shaping a new future. Through job creation, industrial growth, better education and healthcare, and revitalized communities, it stands as a beacon of inclusive development. As India marches toward its Viksit Bharat 2047 vision, HRRL exemplifies how strategic energy infrastructure can fuel not just the economy, but also human potential.

Night view of Refinery

7

Strategic Refinery Expansion and Petrochemical Integration: Charting the Future of NRL

Shri Bhaskar Jyoti Phukan, Managing Director
Numaligarh Refinery Limited (NRL)

The energy and industrial landscape in India is undergoing a transformative shift. At Numaligarh Refinery Limited (NRL), we recognize this change as both a challenge and an opportunity. Our strategic expansion and petrochemical integration plan is a bold, future-oriented response to evolving market dynamics, energy security imperatives, and the rising importance of value-added products in refining economics.

The Evolution of Our Expansion Strategy

Originally envisioned as a capacity enhancement project from 3 MMTPA to 9 MMTPA, the Numaligarh Refinery Expansion Project (NREP) was sanctioned to bolster energy security in the Northeast and ensure long-term competitiveness of NRL. However, since its inception, evolving market dynamics — especially the rapid growth in petrochemical demand and emerging challenges in auto fuels — have warranted a strategic re-evaluation of the project.

This led us to undertake a limited but significant revision of the refinery configuration to ensure alignment with future market needs and to tap into the high-growth petrochemical segment.

Petrochemical-Ready Configuration: Building Flexibility into the Core

The revised refinery configuration emphasizes increased production of light distillates with the capability to swing towards petrochemical feedstocks. Central to this shift is the integration of a Petro-FCC unit, which provides a robust pathway to produce propylene — a key input for polypropylene, one of the fastest-growing polymers in India and neighbouring markets.

This configuration offers multiple advantages:

- **Product Flexibility:** Ability to adjust production between traditional fuels and petrochemicals based on market trends.
- **Higher Value Addition:** Transition from low-margin products to high-margin petrochemicals.
- **Regional Market Leverage:** Strategic location advantage to serve emerging polypropylene demand in Eastern India, Northeast India, and Bangladesh.

Adoption of Advanced Bottom Upgradation Technology: Resid Processing and Treating Unit

As part of the reconfigured strategy, Numaligarh Refinery has integrated a Resid Processing and Treating Unit into its refinery configuration to enable efficient bottom-of-the-barrel upgrading. This advanced unit is designed to process heavy residues and convert them into higher-value, lighter distillates such as diesel and naphtha, thereby significantly reducing the production of low-value fuel oil. The adoption of this technology enhances the overall distillate yield, improves refinery complexity, and ensures greater flexibility in crude slate selection. Moreover, by minimizing residue generation and supporting cleaner fuel output, the unit contributes meaningfully to NRL's sustainability and energy transition goals while complementing the downstream petrochemical configuration.

Leveraging Advanced Technologies: RPTU & PFCC

At the heart of our revised configuration lies a dual focus on upgrading low-value residue and capturing petrochemical value:

- RPTU (Residue Processing and Treating Unit) or similar residue upgradation technologies have now matured globally and are being implemented across major Indian refineries. This allows us to efficiently process heavy residue into lighter, high-value products. With assured natural gas supply via the North-East Gas Grid, hydrogen production for this process becomes both viable and cost-effective.
- The PFCC unit, integrated with VGO hydrotreater and gasoline treatment units, is configured to produce up to 360 KTPA of propylene. This will eventually support the establishment of a polypropylene unit, placing NRL firmly on the petrochemical map.

These technologies represent a strategic inflection point — moving from conventional fuels to a product portfolio geared for future markets.

Strategic Drivers Behind the Shift

Several converging factors have influenced this strategic transition:

- **Changing Fuel Landscape:** Electric mobility, alternate fuels, and policy shifts are expected to moderate long-term growth in petrol and diesel consumption.
- **Petrochemical Growth Potential:** The petrochemical sector, especially polypropylene, continues to witness robust demand growth, outpacing that of conventional fuels.
- **Technological Readiness:** Maturation of residue upgradation technologies and assured availability of natural gas via the North-East Gas Grid have enabled economically viable production of hydrogen and other feedstocks necessary for petrochemical production.

Redesigning Execution for Efficiency

To optimize capital intensity and execution efficiency, select components of the project are being implemented through innovative models:

- The product pipeline to Siliguri is being augmented through an existing pipeline system operated by Oil India Limited.
- The hydrogen generation unit (HGU) will be developed under a "Build-Own-Operate" model.
- The crude oil import terminal at Paradip will be executed under a "Build-Own-Operate-Transfer" model.

These models reflect our focus on risk-sharing, private sector participation, and long-term efficiency.

Towards Petrochemical Integration

As a natural extension of the revised refinery configuration, NRL is actively preparing for downstream integration into petrochemicals. The proposed polypropylene unit, backed by robust market studies and logistical advantage, will cater to identified demand centers in the region, including the Northeast, Eastern India, and Bangladesh — with applications spanning packaging, textiles, and infrastructure.

Necessary provisions for land, utilities, and future expansion have been made in the master plan, ensuring seamless integration when the polypropylene unit is established.

Execution with Excellence: Embedding Innovation and Efficiency at Every Step

Executing a mega-scale brownfield and greenfield integrated refinery and petrochemical project in one of India's geographically complex terrains requires not just engineering excellence but also innovation in planning and delivery mechanisms. NRL has undertaken several pioneering measures to ensure the project is future-ready, cost-efficient, and aligned with the highest benchmarks of sustainability and performance.

- **Cost-Effective DCU Revamp:** A least-cost revamp strategy has been adopted for the Delayed Coker Unit (DCU), aimed at enhancing throughput and conversion efficiency without requiring a complete rebuild. This has enabled resource optimization and reduced project turnaround time.
- **Reducing Scope 1 Carbon Emissions through Grid Power Sourcing:** In a first for a major refinery expansion in the region, NRL has strategically opted to source power from the regional grid rather than installing a captive thermal power plant. This not only minimizes Scope 1 carbon emissions but also leverages the cleaner energy mix evolving in the national grid.
- **Q1D1 Energy Benchmarking with Licensor Alignment:** As an industry-first initiative, NRL has embraced the “Q1D1” approach—aiming for Quartile 1 energy performance from Day 1 of operations as per Solomon benchmarking standards. This was achieved by involving process licensors at the conceptual stage itself, thereby ensuring that tender specifications were aligned to deliver Q1D1 outcomes. This early-stage integration of performance criteria into procurement marks a paradigm shift in public sector project design.
- **IEEDMS for Single Source of Truth:** NRL is deploying a state-of-the-art Integrated Engineering Electronic Document Management System (IEEDMS) to ensure that all technical, construction, and compliance data exists in a verified, traceable digital format. This fosters transparency, enhances team collaboration, and ensures that a soft copy record is preserved for posterity and audit.
- **Water Sustainability and Advanced Treatment Infrastructure:** Given the ecological sensitivity of the region, water management is a key priority. The project features full bifurcation of potable and process water streams, an overground Oily Water Sewage (OWS) network to prevent seepage, and a modern Effluent Treatment Plant (ETP) compliant with stringent discharge norms. These measures together reduce freshwater consumption and ensure responsible wastewater handling.
- **Logistics Innovation for ODC/OWC Movements:** One of the most challenging aspects of this project has been the transportation of Over-Dimensional Cargo (ODC) and Over-Weight Consignments (OWC), most of which are fabricated in the industrial hubs of Maharashtra and Gujarat. These components must traverse the Arabian Sea, the Bay of Bengal, and finally enter Assam via the Brahmaputra River. The logistics planning for these movements—coordinated across multiple ports, customs, river navigation, and inland transport authorities—is a project in itself, exemplifying NRL's capability in managing complex supply chains in remote geographies.

A Vision Beyond Expansion

This journey is not merely about increasing capacity — it's about transforming NRL into a versatile energy and materials company, aligned with the future. Our approach integrates:

- Strategic foresight in aligning with petrochemical demand trends,
- Operational flexibility to respond to market volatility,
- Sustainability through better yield and value-added product mix, and
- Regional development by anchoring industrial growth in the Northeast.

With the steadfast support of our promoters and the Ministry of Petroleum & Natural Gas, NRL is poised to become a key pillar in India's petrochemical future while continuing to serve as a catalyst for progress in the Northeast.

The future is not just about refining more — it's about refining better, smarter, and with purpose. At NRL, we are proud to be building that future.


Bhatinda (HMEL); Estd. -2012

8 Digital Refining: AI, ML, and Digital Twins in Operational Excellence

Shri Prabh Das, MD & CEO

HPCL-Mittal Energy Limited (HMEL)

Introduction: Refining India's Energy Future

India stands at the cusp of a transformative energy era - poised to lead global demand growth while advancing towards its long-term vision of energy independence and sustainability. The refining sector, a cornerstone of the country's energy security, is undergoing profound structural shifts in response to rapid global technological advances, the low-carbon imperative, and evolving consumption patterns.

With a current installed refining capacity of over 258 MMTPA, India ranks fourth globally in terms of Refining capacity and has established itself as a vital energy processing hub for domestic and international markets. India's refining capacity is expected to reach 309 MMTPA by 2030 which underscores the strategic importance of refining in powering India's industrial growth and socio-economic development.

Simultaneously, India is strengthening its energy mix by integrating advanced technologies across both conventional and alternative energy domains, having committed to net-zero emissions by 2070. This dual challenge of scaling capacity while improving energy efficiency and environmental performance calls for a paradigm shift in how refineries operate. The answer lies in a smart convergence of digital technologies and decarbonization strategies, aligned with the national blueprint of "Viksit Bharat 2047" - a self-reliant, technologically advanced, and environmentally resilient India.

At HMEL, we recognize that digital transformation - rooted in data, intelligence, automation, and real-time adaptability - will be the defining enabler of this transition.

India's Refining Future: Smart, Sustainable, and Self-Reliant

India is set to emerge as the global energy demand center over the next two decades, driven by industrial growth, urbanization, and rising per capita consumption.

In this context, the refining sector must evolve into a future-ready engine-agile, efficient, digitally intelligent, and environmentally sustainable. Legacy systems and traditional operating models are no longer sufficient to meet the dynamic needs of a net-zero world. The integration of AI, ML, and digital twins offers us a powerful lever to modernize at scale.Digital Transformation at HMEL: Strategic Intent to Operational Execution

HMEL has embarked on a structured digital transformation journey aimed at redefining the benchmarks of operational excellence in India's refining and petrochemical landscape. In alignment with our long-term sustainability roadmap, we have initiated enterprise-wide programs to embed AI and ML across production, planning, reliability, safety, and energy management.

A recent milestone in this journey has been the signing of a strategic Memorandum of Understanding (MoU) with 2 global digital technology leaders to accelerate our shift toward predictive, intelligent, and autonomous operations. This partnership reflects our commitment to harnessing next-generation tools that empower our workforce, optimize assets, and lower our environmental footprint.

AI and ML in Action: From Data to Decisions

The heart of AI and ML implementation lies in the ability to convert large volumes of process and engineering data into actionable insights. Refineries that implement AI/ML and digital twins have demonstrated up to 15-30% improvement in energy efficiency and 10–20% reduction in unplanned downtime, highlighting the transformative potential of digital intelligence.

Global consulting firms estimate that full-scale digital implementation in refining can deliver an 8-12% improvement in EBITDA, underscoring that digital transformation is not just a technology upgrade—it is a value creation engine.

Globally, predictive maintenance powered by AI/ML has enabled up to 25% reduction in unplanned downtime, based on benchmarks across multiple refining operations. These outcomes reinforce the scalability and maturity of AI-driven reliability programs that anticipate equipment failure and enhance asset longevity.

At HMEL, we have deployed several high-impact AI/ML programs:

- **Lime Optimization and SOx Control:** A closed-loop ML algorithm controls petcoke- limestone reactions in our CFBC boilers, resulting in a reduction in limestone use while predicting & controlling SOx emission. This proprietary innovation is one of the first known closed-loop ML models for solid-solid reaction control, with patents filed in India and the US.

- **Petcoke Particle Size Distribution (PSD):** A computer vision-based AI model monitors PSD in real time to optimize crushers-built in-house with high ROI at a fraction of vendor costs.
- **Furnace Oxygen Optimization:** A predictive ML model enables dynamic control of excess oxygen in furnaces, reducing fuel loss, improving combustion, and lowering CO_2 emissions.
- **Advanced Analytics in DCU:** Advanced anomaly detection and performance analytics piloted in the Delayed Coking Unit, achieving payback in under four months and now being scaled to other units.

These innovations reflect a culture of ownership, experimentation, and scalable value creation.

Digital Twins and Real-Time Optimization: Intelligence at the Core

The deployment of digital twins in refining enables real-time simulation, scenario analysis, and control-bridging the physical and virtual worlds of operations. More than half of global refineries have begun digital twin initiatives as of 2024, reflecting their growing value in operational agility. Adoption of these systems is known to improve decision-making accuracy by 25–35% and reduce CAPEX and OPEX by 10–15%.

In one Asia-Pacific refinery, digital twin deployment led to a 12% reduction in energy consumption and 8% improvement in crude-to-product optimization, validating the transformative potential of real-time digital replicas in complex environments.

At HMEL, our digital twin journey is complemented by powerful real-time optimization platforms:

- **Real Time Optimization (RTO):** By using an industry leading solution, we implemented a real-time, equation-based optimizer deployed at the CDU unit. Based on this success, the solution is now being extended to other key process units such as the FCC and VGO-HDT.

Sustainability Through Digitalization: Decarbonizing the Barrel

AI, ML, and digital twins are instrumental in reducing the carbon intensity of refining:

- **Lower Scope 1 and 2 Emissions** through fuel optimization, flaring reduction, and heat integration.
- **Real-Time Monitoring** of emissions and effluents for compliance and transparency.
- **Resource Optimization** across hydrogen, steam, and cooling utilities-directly supporting ESG goals.

People and Platforms: The Human Side of Digital Excellence

Technology transformation is effective only when paired with organizational capability. At HMEL, all employees-including senior management-have undergone formal AI training. This shared understanding of data science, process control, and AI logic has enabled a bottom- up approach where operational teams themselves suggest use cases.

Such initiatives are supported by a robust digital architecture-cloud-integrated systems, secure OT-IT platforms, and centralized data repositories ensuring scalability, performance, data democratization and governance.

Challenges and the Road Ahead

Despite its enormous potential, the digitalization of refining faces several real-world challenges:

- **Cybersecurity:** As refineries become more connected, safeguarding operational technology (OT) systems from cyber threats becomes paramount. A resilient cybersecurity strategy must evolve in tandem with digital infrastructure.
- **Change Management:** Shifting from manual processes to data-driven decision- making demands a cultural transformation. Building digital champions, aligning cross-functional teams, and establishing a "fail-fast, learn-fast" mindset are critical enablers.
- **Data Governance and Integration:** Interfacing legacy systems with modern platforms presents integration issues. Ensuring data quality, availability, and interoperability across systems is a foundational task.
- **Regulatory Support:** Policies that encourage open architecture, standards, and cross-industry learning will play a crucial role. Facilitating experimentation, sandboxes, and funding for applied AI pilots can accelerate adoption.
- **Industry Collaboration:** As a sector, we must share best practices and co-develop platforms that benefit the entire ecosystem-OEMs, refiners, and technology providers alike.

At HMEL, we are approaching these challenges with strategic intent and operational focus, ensuring our transformation is not only technically sound but also culturally embedded and future-proof.

India 2047: Building the Refinery of the Future

As we envision India's energy architecture for 2047, digital transformation will be a defining pillar. The refinery of the future will not be a linear process plant-it will be a dynamic, learning system powered by AI, resilient to market shocks, optimized for environmental performance, and responsive to societal needs.

At HMEL, we are committed to playing a leadership role in this transformation. Our roadmap includes scaling AI-based optimization, expanding digital twins, and building intelligent platforms that support real-time decision-making and sustainability outcomes.

Conclusion: A Strategic Imperative for the Industry

The digitalization of refining is no longer optional. As the world moves towards stricter regulations, and volatile markets, only those refiners who can think digitally, act intelligently, and operate sustainably will thrive.

India's refining sector has the talent, scale, and ambition to lead this revolution. At HMEL, we stand ready to contribute our share-by building smarter assets, empowering our people, and delivering energy solutions that are not only efficient and profitable but also aligned with India's aspirations for 2047.

Panipat (IndianOil); Estd. -1998

9

Advanced Residue Upgrading: Toward Zero- Waste, High-Value Refining

Shri Arvind Kumar, Director (Refineries), Shri Subhajit Sarkar, Executive Director (Operations)- Refineries;

Indian Oil Corporation Limited

Abstract

This paper explores the evolution and strategic importance of advanced residue upgrading technologies in modern refining, with a focus on achieving a zero-waste, high-value output model. It analyses global advancements in residue processing methods—such as residue hydrocracking, residue fluid catalytic cracking (RFCC), delayed coking, solvent deasphalting (SDA), and gasification—and benchmarks their performance in terms of conversion efficiency, capital intensity, and decarbonization potential. Special emphasis is placed on IndianOil's INDMAX technology, an indigenous high-severity RFCC process designed for maximizing light olefins from residual oil, deployed across IOCL Refineries at Paradip, Bongaigaon, Panipat, Gujarat, and Barauni refineries. The integration of residue upgrading with petrochemical value chains is highlighted as a key enabler of future-ready refining complexes, where residues are transformed into propylene, aromatics, and clean fuels, effectively eliminating black oil production. The study underscores how such technologies align with India's 2047 vision of energy independence, industrial self-reliance, and carbon minimization. By showcasing technology deployment, policy alignment, and commercial strategies, this paper positions advanced residue upgrading as the cornerstone for sustainable, flexible, and value-driven refining in the era of net-zero commitments.

Introduction: The Bottom of the Barrel as a Top Priority

Residue upgrading has emerged as a strategic priority for refiners worldwide, transforming what was once considered "bottom of the barrel" waste into high-value products. The heavy residual oils left after distillation (vacuum residue, tar, etc.) are rich in carbon, metals, sulfur and other contaminants, making them challenging to process.

Yet, with fuel oil markets shrinking (e.g. after IMO 2020 sulfur limits on bunker fuel) and demand rising for cleaner fuels and petrochemicals, refineries are investing heavily in technologies to convert residual oil into valuable fuels and chemical feedstocks. High-conversion refineries that can process heavy crude and upgrade residues enjoy a competitive edge – they can buy cheaper heavy crudes and still meet environmental specs by eliminating low-value "black oil" outputs.

The ultimate vision is a "zero-waste" Refinery where even the heaviest fractions are fully converted into saleable products, aligning with decarbonization goals by avoiding wasteful burning of resid or petcoke. A typical refining scheme with a high bottom of barrel conversion is provided below

(Source: M/s Honeywell UOP).

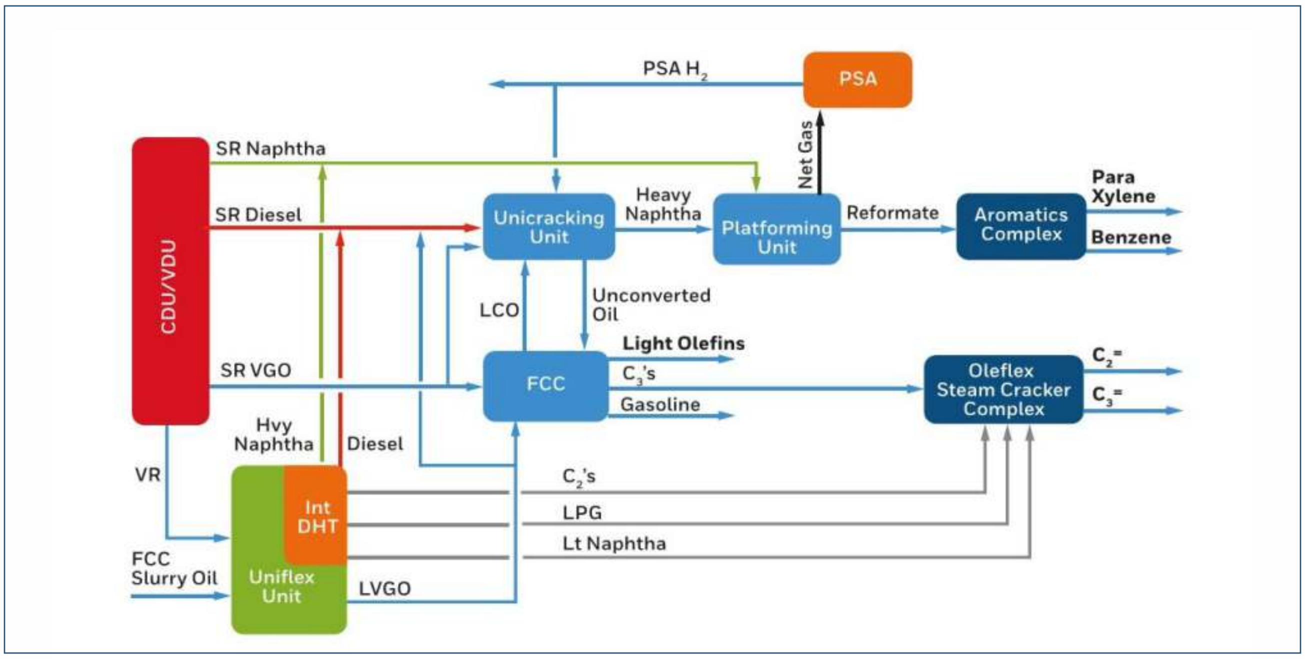


Figure 1: High bottom of barrel conversion Configuration (M/s UOP Honeywell)

Global Advances in Residue Upgrading Technologies

Around the world, refiners are deploying a combination of residue upgrading technologies to maximize liquid yields and minimize residual by-products.

Broadly, these technologies follow two pathways:

a) Carbon Rejection:

Removing carbon from heavy oil molecules to produce lighter products but leaving behind a solid or heavy carbon-rich by-product. Examples include thermal processes like Delayed Coking (yielding solid coke) and Vis-breaking, and catalytic processes like residue fluid catalytic cracking (RFCC) that reject carbon as coke on catalysts.

b) Hydrogen Addition:

Adding hydrogen to heavy molecules (under high pressure and temperature) to crack and saturate them into lighter, hydrogen-rich products, with minimal solid residue. This includes residue hydrocracking and high-pressure hydro-processing technologies.

Many modern refineries use integrated schemes that combine both pathways – for example, using solvent deasphalting to separate resid, feeding the deasphalted oil to a hydrocracker and the concentrated asphalt to a coker or gasifier. Such combinations can dramatically raise overall conversion and profitability. The choice of technology depends on the feed characteristics (contaminant levels), desired product slate, and economic factors. Figure 2 illustrates how different residue upgrading technologies are selected based on the feed's content of asphaltenes and metals (contaminants that can deactivate catalysts):

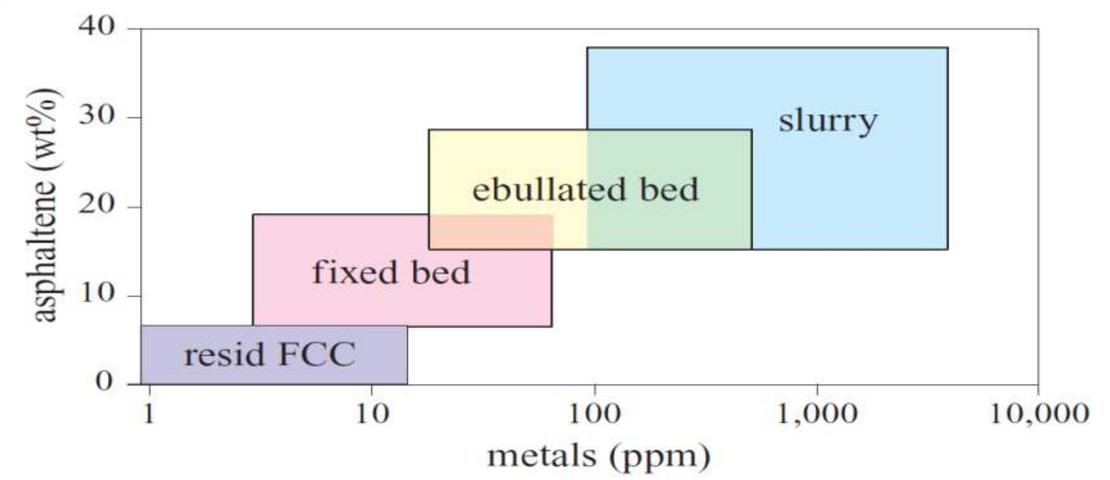


Figure 2: Applicability of residue upgrading technologies vs. feed contaminants (asphaltene and metals content). (Source: Encyclopedia of Hydrocarbons, 2006)

Refineries worldwide are scaling up residue conversion due to heavier crudes, better integration and to improve margins.

Delayed Coking: The most conventional and common carbon rejection process, delayed coking handles the heaviest feeds without catalysts. It is accounted for over 50% of global resid upgrading capacity. Its main drawback is the large volume of petroleum coke – a low-value by-product unless monetized or gasified.

Residue Hydrocracking: Gaining ground in complex refineries (especially in Asia & the Middle East), these units convert >90% of residue into clean fuels, leaving behind minimal pitch-like residue. Though capex and hydrogen intensive, the advantage of conversion of bottom of barrel to fuels / petchem feedstocks supersedes them.

RFCC for Petrochemicals: Residue FCCs are evolving to maximize petrochemical outputs. Advanced designs like INDMAX™, PetroFCC™, and HS-FCC™ boost light olefins yield from ~10% to ~17%, operating at higher severities (600°C+, specialized catalysts). New units in China, India, and the Middle East are targeting up to 50% petrochemical yield – far above the 10% norm in traditional integrated refineries.

Residue Gasification: Used for petchem/chemicals feed stocks and internal energy, gasification converts residue or coke into syngas for hydrogen, power, or chemicals. Reliance's $4B Jamnagar complex, for example, gasifies 6–9 MTPA petcoke to produce hydrogen, power & chemicals, now being repurposed for blue hydrogen. Though highly capital-intensive, gasification with CO_2 capture offers a path to near-zero emissions and full barrel utilization.

Comparing Key Residue Upgrading Technologies

Each residue upgrading technology has unique technical and economic characteristics. Below we highlight the key processes – hydrocracking, RFCC (including INDMAX), solvent deasphalting, gasification, and coking – and their roles in **a zero-fuel-oil refining strategy.**

A. Residue Hydrocracking (Hydrogen Addition)

Residue hydrocracking is a high-pressure catalytic process that converts heavy oils into lighter products (naphtha, kerosene, diesel) while removing impurities like sulfur and metals. It typically operates at 350–450 °C and 150–250 bar. Key configurations include:

i. **Fixed-bed residue hydrotreaters/hydrocrackers:** Multiple reactors packed with catalyst in series. Suitable for vacuum gas oils or less contaminated feeds. Catalyst deactivates quickly with high metals/asphaltenes, requiring either cleaner feeds or frequent replacement.

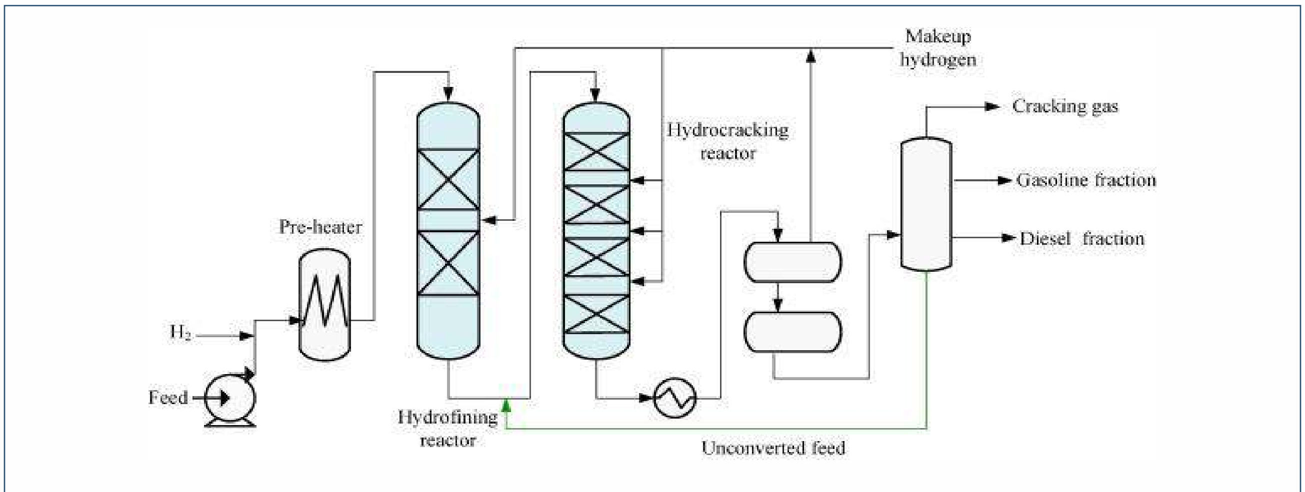


Figure 3: Typical Fixed Bed Hydrocracker

ii. **Ebullated-bed hydrocrackers:** Technologies: Axens H-Oil™, LC-Fining™, Shell Hycon™. Use fluidized catalyst beds with continuous catalyst addition/removal, allowing high feed flexibility. Can handle heavy, high-metal residue with 80–95% conversion. IndianOil's Panipat new resid hydrocracker uses Axens H-Oil technology (~75 wt.% conversion) integrated with a delayed coker. The technology can be integrated with a SDA for ~90-95 wt.% conversion.

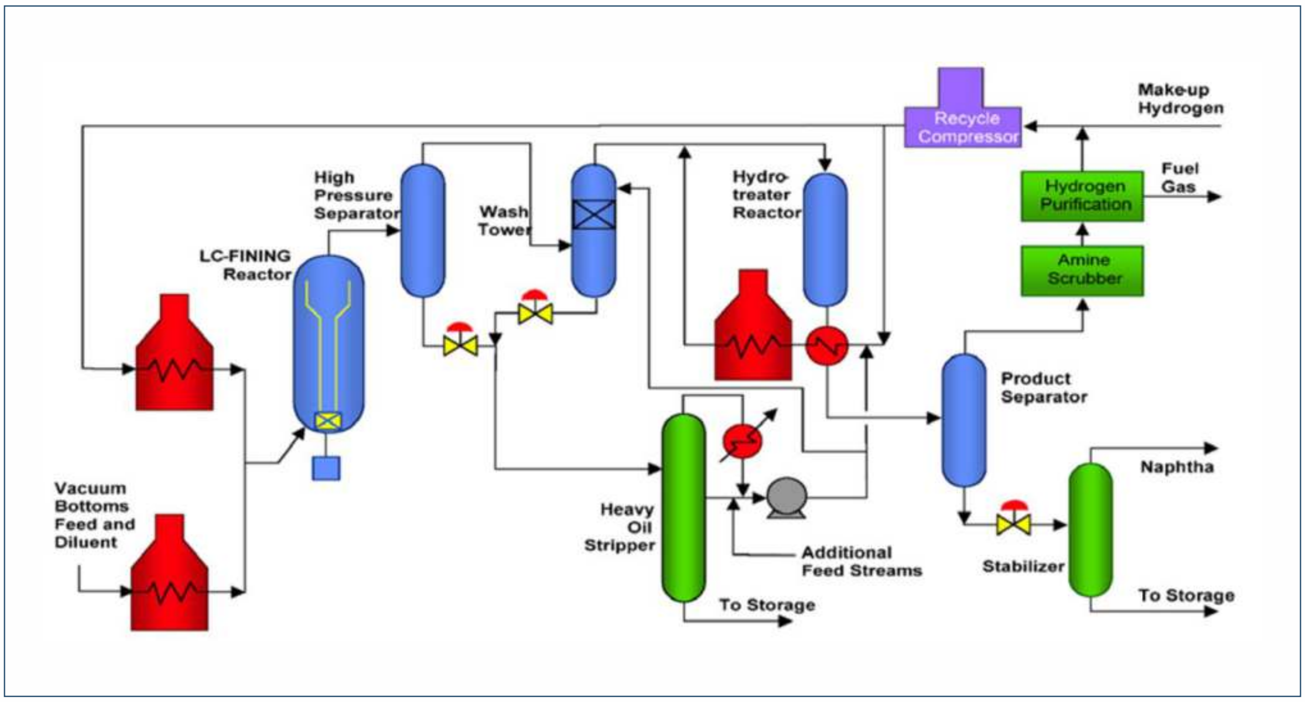


Figure 4 A: LC Fining-by M/s CLG

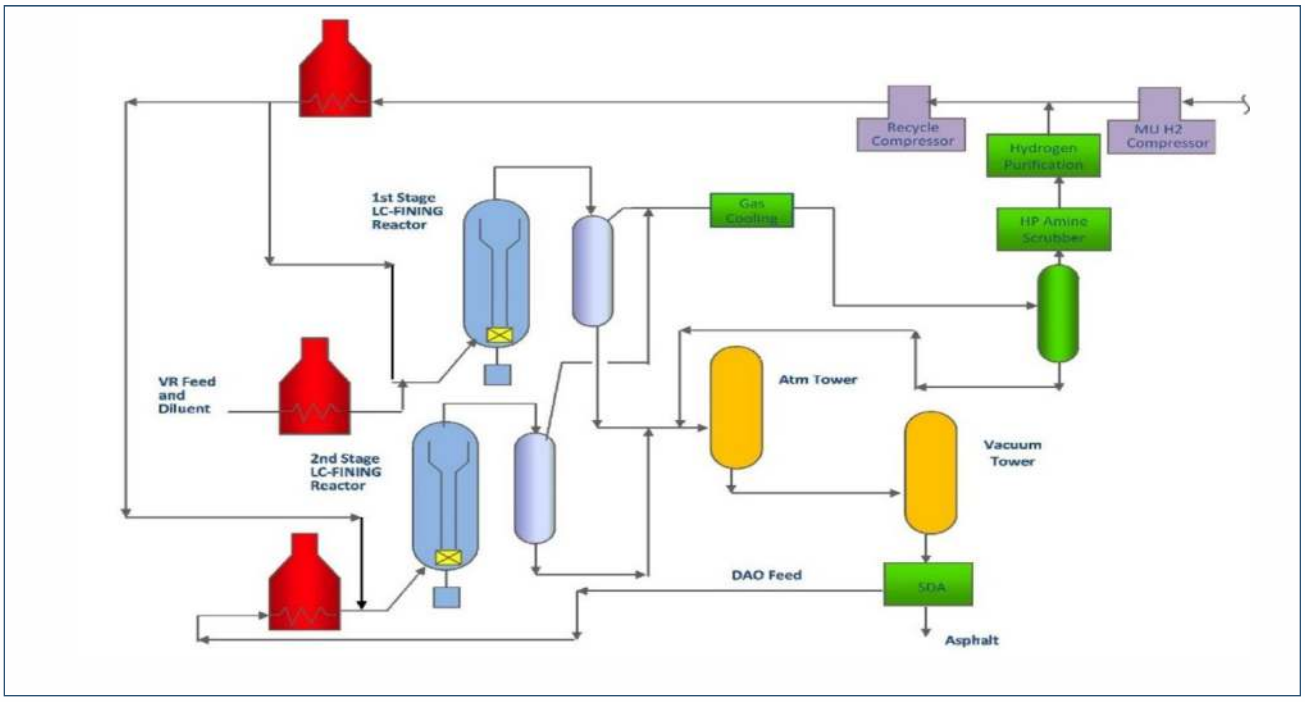


Figure 4 B: LC-Max Technology- by M/s CLG

iii. **Slurry-phase hydrocrackers:** Technologies: *Eni EST*™, *KBR VCC*™, *UOP Uniflex*™, *HDH*™. Mix fine catalyst particles into the feed, achieving >95% conversion and near-zero residue. Ideal for extremely contaminated feeds, though still in early commercial adoption (e.g. Eni EST in Italy).

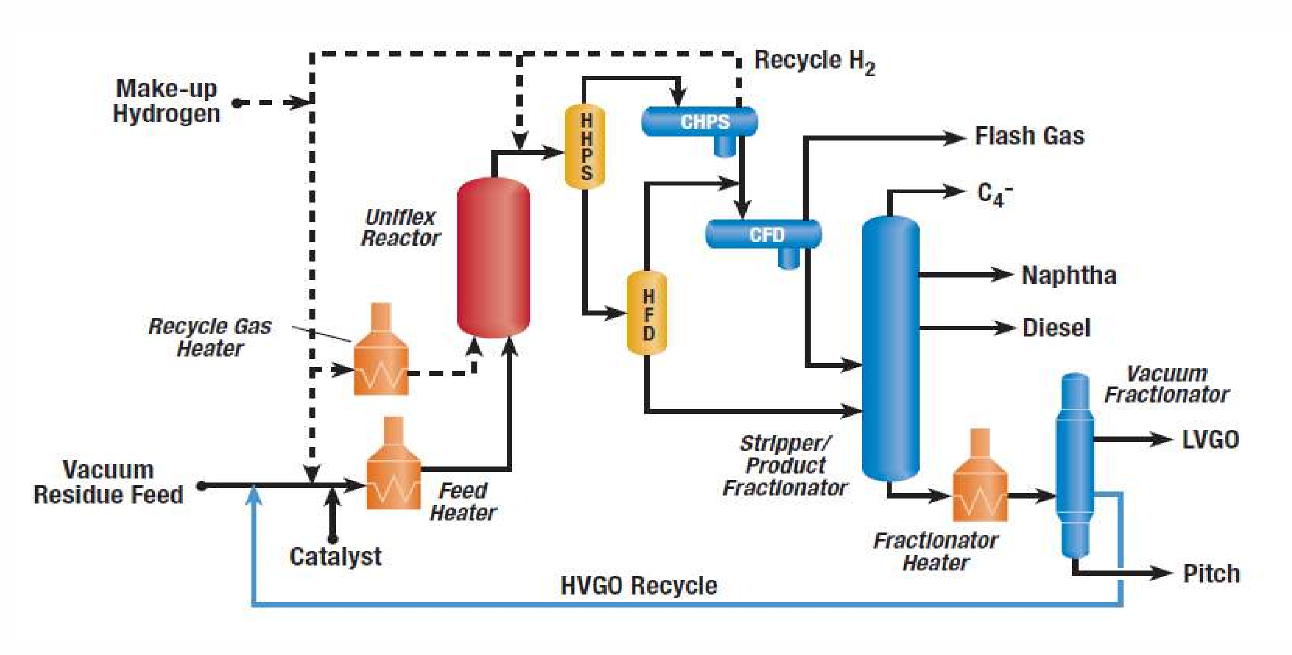


Figure 5: A M/s UOP Uniflex Slurry Hydrocracking Technology

A typical two-stage residue hydrocracking configuration is shown in Figure 4. The first stage focuses on heavy conversion and metals removal, and the second stage completes the cracking to maximize distillate yield. High-pressure separators between stages remove gases and improve performance. Ebullated-bed systems like LC-Fining often employ such two-stage setups with interstage separation.

Residue Hydrocracking: Products, Value, and Trade-offs

- **Product Value:** Hydrocracking maximizes middle distillates like diesel and jet fuel—critical for markets like India. The unconverted fraction is small, low in sulfur/metals, and usable as low-sulfur fuel oil or feed to cokers/asphalt units. The process also supports Group II/III base oil production when integrated with dewaxing units.
- **Clean Output:** It yields the cleanest product slate among resid processes by removing sulfur/metals into byproduct streams or spent catalyst, avoiding coke formation.
- **Cost & Challenges:** Hydrocrackers involve high capital and operating costs due to large reactors, high-pressure systems, and significant hydrogen demand. Hydrogen is usually produced via steam reforming or gasification—adding CO_2 emissions to manage.
- **Strategic Advantage:** Despite the cost, hydrocracking is essential for deep conversion, enabling processing of the heaviest, dirtiest crudes and meeting stringent fuel specs—making it a key decarbonization tool.

Typical comparison of the technologies is tabulated below:

Parameters	Fixed Bed	Ebullated	Ebullated +SDA	Slurry
Tolerance for impurities & feed flexibility	Low	Average	High	Very High
CCR wt.%	3 – 8	10 – 24	No restriction	No restriction
Conversion* (550°C-), wt.%	~50	~75	~90	≥ 95
Temperature (0C)	370 - 410	400 - 435	400 - 435	400 - 450
Pressure, bar	100 - 250	100 - 250	100 - 250	100 - 250
Available Major Licensor's	UOP, Axens, Chevron, Shell	Axens (H-OIL), CLG (LC-FINING)	Axens (Solvahl +H- Oil), CLG (LC-MAX)	ENI (EST), UOP (Uniflex), KBR (VCC), LG (LC-Slurry)
Catalyst	Extrudate	Extrudate	Extrudate	Powder/Liquid

*Feed Dependent

B. Residue Fluid Catalytic Cracking (RFCC) and INDMAX

RFCC adapts traditional FCC to handle heavier feeds like vacuum resid or HVGO. Operating at ~500-510 °C, it uses acid-zeolite catalysts to crack large hydrocarbons into gasoline, LPG, and light cycle oil. Coke formed on catalysts is burned off in a regenerator to sustain heat. To manage metal contaminants (Ni, V), RFCC units employ specialized catalysts, higher circulation rates, and often an upstream hydrotreater.

RFCC yields high gasoline and LPG. Propylene production (~10–16%) can be boosted by tuning severity. However, it doesn't remove sulfur/metals; downstream treating is needed. While some slurry oil remains, RFCC is effective in reducing fuel oil output and can integrate well with further upgrading units.

Developed by IOCL R&D with Lummus, INDMAX pushes RFCC toward petrochemical yields. It uses proprietary catalysts and ZSM-5 additives for high-severity cracking, maximizing LPG and light olefins. At IOCL Paradip INDMAX (4.17 MMTPA), delivers ~44 wt.% LPG (~16% propylene with potential up to ~18.5%) from heavy residue. IOCL Bongaigaon's 0.74 MMTPA INDMAX enabled total conversion of black oils in the refinery into LPG and Euro-VI gasoline, boosting LPG output fivefold and eliminating fuel oil.

INDMAX units are highly flexible and refineries like IOCL Barauni (BR-9 project) are revamping RFCCs into INDMAX mode, adding Propylene Recovery Units (PRUs) and PP plants. This creates a direct link from resid to polypropylene.

RFCC is a **carbon-rejection** process (forms coke), while hydrocracking is **hydrogen-addition** (yields clean fuels). Hybrid strategies (FCC + hydrocracker) are emerging in mega-refineries for >95% conversion. Example: Panipat's expansion will operate a 2.5 MMTPA INDMAX alongside a 2.5 MMTPA resid hydrocracker. Together, they eliminate fuel oil and optimize yields across diesel, LPG, and petrochemicals.

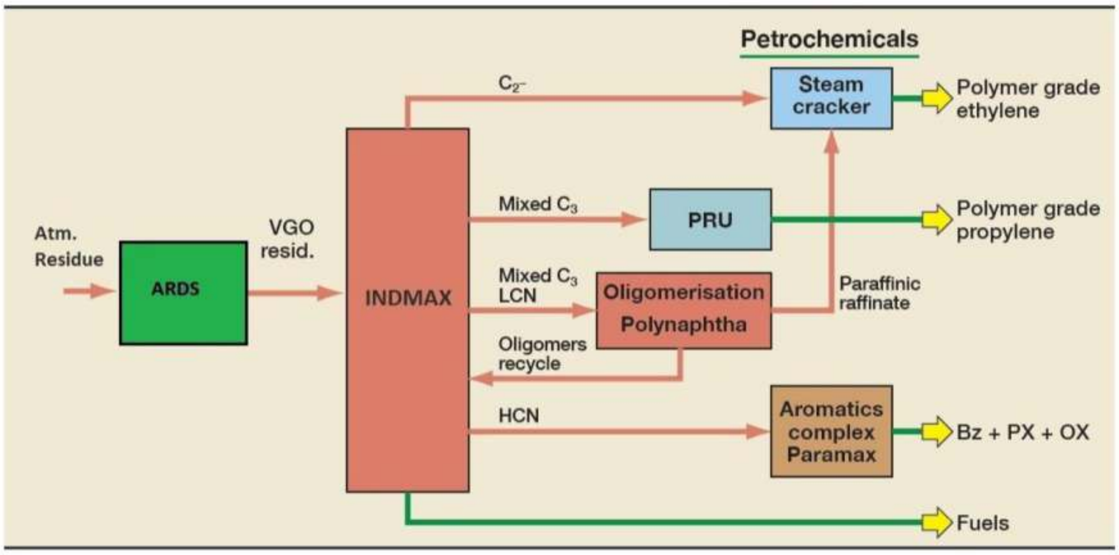


Figure 6: Refinery-petrochemical integration enabled by INDMAX FCC technology (M/s CLG Concept).

Figure 6 shows a conceptual flow of how an INDMAX FCC can be integrated in a refinery-petrochemical complex. The heavy residue feed is first hydrotreated (to reduce sulfur/metals), then cracked in the INDMAX FCC. The cracked products go through separation: LPG olefins are recovered (for petrochemicals like ethylene, propylene, butylenes), gasoline is upgraded (desulfurized and routed to either blending or aromatics extraction for BTX), and the small fraction of heavy cycle oil can be recycled or sent to other units. This kind of scheme demonstrates a zero-waste approach – even traditionally low-value streams like FCC off-gas and gasoline are further processed into polymer-grade olefins and aromatics.

C. Solvent Deasphalting (SDA)

Solvent Deasphalting (SDA) is a physical separation process where heavy resid is mixed with light solvents like propane, butane, or pentane to separate into two streams: Deasphalted Oil (DAO)—a low-metal, low-asphaltene fraction resembling vacuum gas oil—and pitch (asphaltenes), which is carbon-rich and high in metals and sulfur. DAO is suitable for hydrocrackers or FCCs, while pitch is typically sent to cokers or gasifiers, or used in asphalt or bunker fuel blending. SDA removes 20–30% of unconvertible material as pitch, enabling 70–80% DAO to be upgraded. It is often used as a pre-treatment to protect hydrocracking catalysts from fouling and increase throughput, as practiced by other refinery. Technically simpler and less capital-intensive than cracking units, SDA systems involve a high-pressure extractor and solvent recovery loop, with solvent recycled for reuse. The process is flexible—solvent type and conditions can be tuned to control the DAO-to-pitch split. In advanced refinery schemes, SDA is integrated with gasification and hydrocracking (e.g., ROSE + hydrocracker + gasifier) to achieve near-complete conversion of residues into valuable products and syngas, aligning with zero-waste and decarbonization objectives.

D. Delayed Coking (and Other Thermal Processes)

Delayed coking is the most established thermal residue upgrading process globally, widely adopted for its robustness and cost-effectiveness. The process involves rapid heating of vacuum resid to approximately 500 °C, followed by transfer to coke drums where thermal cracking occurs. Heavy hydrocarbons break down into lighter fractions while excess carbon polymerizes into solid petroleum coke. Operating in a semi-batch cycle, one drum fills while the other undergoes cooling and coke removal via high-pressure water cutting. The main liquid products—coker gasoil and coker naphtha—are typically high in sulfur and olefins, requiring downstream hydrotreating. Fuel gas and LPG are also generated. The coke produced ranges from fuel-grade (high sulfur, for cement/power) to anode-grade (low sulfur, for aluminium smelting), but in most cases, it is a low-value carbon-rich by-product.

Delayed coking is favoured for its ability to handle any resid feedstock, including high-asphaltene or high-metal crudes, since it uses no catalyst and is immune to poisoning. It also offers the lowest capital cost per barrel among residue conversion options. However, it has limitations in terms of coke yield, often converting 20–30% of the feed into solid coke, which challenges carbon efficiency and sustainability. In a decarbonization context, new process innovations such as low-pressure coking and the recycling of lighter cuts aim to reduce coke yields and enhance liquid recovery. Automation for coke cutting and drum switching has also improved operational safety and efficiency.

Advanced variants like Fluid Coking and Flexicoking (ExxonMobil technologies) take this further by continuously removing and combusting coke in a fluidized bed, partially gasifying it into low-BTU fuel gas usable for onsite energy or hydrogen production. While complex and requiring additional infrastructure (e.g., oxygen plants), these systems represent a path toward minimizing or eliminating solid coke formation. Refinery in middle east generally integrated petcoke gasification for power generation.

In India, delayed coking is already widely deployed. IndianOil operates around nine coking units with the biggest installed at Paradip (4.1 MMTPA), while Reliance's Jamnagar complex houses some of the world's largest coking capacities.

Moving forward, strategies integrating coking with downstream petcoke gasification—such as Reliance's hydrogen, chemicals production from coke with CO_2 capture—will be crucial for aligning delayed coking with zero-waste, low-carbon refinery goals. Even if coke remains a by-product, its use for hydrogen generation or calcination is far more sustainable than combustion in the fuel pool.

E. Residue Gasification and Future Pathways

Residue or petcoke gasification involves reacting feed with oxygen or air at high temperatures to produce synthesis gas ($CO + H_2$), which serves as an intermediate for hydrogen production, electric power, or chemical synthesis (e.g., ammonia, methanol, Fischer-Tropsch liquids). Unlike other upgrading methods, gasification fully decomposes the hydrocarbon matrix, handling highly contaminated feeds by converting metals into inert slag and sulfur into recoverable H_2S. However, gasification alone does not yield finished fuels, requiring further downstream conversion. Its application in refineries is primarily driven by the need for hydrogen, power self-sufficiency, or to eliminate fuel oil production. Notable examples include Reliance's Jamnagar complex, which gasifies all petcoke to produce hydrogen and power, with future plans to route syngas to chemical production. When coupled with carbon capture, gasification offers significant emissions reduction, producing blue hydrogen by capturing concentrated CO_2 from shifted syngas—supporting India's hydrogen mission and net-zero goals.

In modern refining, no single technology suffices. Deep-conversion complexes integrate multiple units—SDA, hydrocracking, coking, RFCC/INDMAX, and gasification—in tailored sequences such as SDA → hydrocracker + coker → gasifier, or resid hydrotreating → INDMAX → PRU + alkylation. These configurations aim to maximize liquid fuels and petrochemical yields while minimizing residual carbon. Though capital-intensive, they enhance adaptability, compliance with evolving fuel specs, and long-term margins by upgrading every fraction of the barrel.

Figure 7 illustrates the trade-off between conversion level and capital intensity for various resid upgrading routes. Simpler carbon-rejection processes (like visbreaking or basic coking) require less investment but leave a significant fraction of resid unconverted (or as coke). More severe processes (ebullated-bed HCU, slurry HCU) achieve near-total conversion but at substantially higher cost and complexity. Policymakers and refiners must weigh these factors in planning upgrades – often opting for a combination that suits the crude and market outlook.

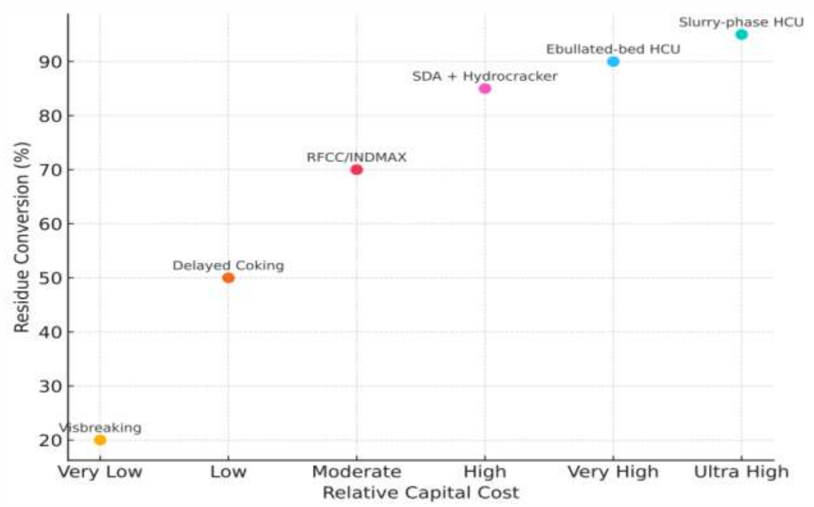


Figure 7: Residue upgrading options plotted by approximate conversion achieved vs. relative capital cost.

Petrochemical Integration: Residue Upgrading for Value-Added Chemicals

A defining pillar for future-ready refineries—especially in the context of "India 2047"—is Refinery–Petrochemical Integration. As transportation fuel demand plateaus due to electrification and efficiency gains, petrochemicals are emerging as the primary growth driver for crude oil. Advanced residue upgrading technologies play a vital bridging role, converting the bottom-of-the-barrel into olefins and aromatics, thereby eliminating low-value fuel oil and unlocking access to high-margin plastics and chemicals markets. Technologies like INDMAX and high-severity FCC enable direct conversion of residue into propylene, ethylene, and C_4 olefins, while resid hydrocrackers generate naphtha streams suitable for steam cracking or aromatics reforming. Global leaders such as Saudi Aramco–SABIC and Sinopec have developed crude-to-chemicals (COTC) complexes with >40% chemical yield, largely enabled by deep hydrocracking and integrated residue-to-petrochemical pathways.

In India, policy focus is shifting toward increasing the Petrochemical Intensity Index (PII) of refineries to enhance economic resilience and reduce import dependency. IndianOil targets increasing petrochemicals from 6% to ~15% of its output by 2030. Residue upgrading is central to this transformation—as straight-run naphtha is limited; petrochemical feedstocks must increasingly come from heavier fractions. IOCL's Gujarat refinery "LuPech" project embodies this strategy by installing a resid INDMAX for higher propylene yield, supporting a 500 TPD polypropylene unit and a 150 KTA butyl acrylate unit. Similar integrations are underway at IOCL Panipat and Barauni refineries, linking INDMAX or RFCC units directly to polymer plants. These steps support Atmanirbhar Bharat by boosting domestic chemical production, utilizing indigenous technologies like INDMAX, and even exporting them internationally.

In essence, residue upgrading has evolved from waste disposal to value creation—producing chemical building blocks from the heaviest crudes. By 2047, most large Indian refineries are expected to be fully integrated refining–chemical complexes, converting every molecule of crude—light or heavy—into fuels or petrochemicals. This model offers margin flexibility, energy security, and a robust platform for industrial growth, with advanced residue upgrading as its foundation.

IndianOil's Pioneering Role and Projects

IndianOil (IOCL), India's leading refiner, has been a pioneer in deploying advanced residue upgrading technologies aligned with energy security, self-reliance, and decarbonization goals. Among its key innovations is the indigenous INDMAX FCC technology, developed by IOCL R&D and globally licensed, which enables high propylene and LPG yields from residual feeds. The Paradip Refinery, commissioned in 2015, exemplifies this approach with a 4.17 MMTPA INDMAX unit, converting to high-value fuels and petrochemicals—achieving good refining margins with no high-sulfur fuel oil production.

Similarly, Bongaigaon Refinery (Assam) commissioned a 0.74 MMTPA INDMAX unit in 2020, eliminating black oil, boosting LPG output fivefold, and supporting near-universal LPG penetration in Northeast India. At Panipat, IOCL is executing the P-25 expansion, to scale capacity to 25 MMTPA with integrated residue hydrocracking (2.5 MMTPA Axens H-Oil™), INDMAX (2.5 MMTPA), and downstream polymer units, making it a swing complex between fuels and petrochemicals. IOCL Gujarat Refinery, under the LuPech project, is being modernized to produce Group III base oils and polypropylene, reducing import dependence on lube oils, and adding petrochemical flexibility. IOCL Barauni Refinery (Bihar) is expanding from 6 to 9 MMTPA with an RFCC revamp into INDMAX mode and new downstream PP and hydrocracker units, demonstrating how legacy assets can be retrofitted.

Across these projects, three strategic themes emerge. First, **decarbonization and efficiency:** IOCL is eliminating high-sulfur fuel oil to produce clean LPG, diesel, and petrochemical products while adopting technologies like resid hydrocrackers and resid INDMAX unit to lower emissions and improve margins. Second, **self-reliance through innovation:** INDMAX represents a major indigenous breakthrough, with export licensing (e.g., Serbia's NIS) furthering India's role in global refining technology. IOCL's R&D continues to develop advanced catalysts and next-gen processes, reinforcing the "Make in India" vision.

Third, **policy alignment:** These upgrades reflect India's 2047 roadmap goals—net-zero emissions, energy self-sufficiency, and reduced fuel and petrochemical imports. Residue upgrading supports use of heavy crudes and conversion of bottom of barrel to meet the energy demand of India by importing lower quantity of crude. Collectively, IOCL's initiatives demonstrate how integrated, high-conversion refining strategies can future-proof the industry while contributing to national energy resilience and sustainability.

Conclusion: Toward 2047 – Zero-Waste, High-Value, Self-Reliant Refining

Advanced residue upgrading is no longer just a technological enhancement—it is a strategic necessity for refineries seeking to thrive in an increasingly carbon-conscious, competitive, and efficiency-driven energy landscape. For Indian Oil Corporation Ltd. (IOCL), this journey toward transforming the 'bottom of the barrel' into high-value products represents a decisive shift from volume-driven refining to value-driven energy solutions. The global energy transition, characterized by declining fuel oil demand, rising petrochemical consumption, and stricter carbon regulations, has elevated the need for innovative residue conversion technologies that can sustainably unlock maximum economic value from every barrel of crude.

Through the deployment of advanced process units—such as ebullated bed hydrocracking (e.g., LC-Fining) and resid-to-chemical routes—IOCL will not only enhance its liquid yield profile but also significantly reduced its production of low-value products. These technologies facilitate deeper conversion, higher distillate recovery, and improved feedstock flexibility, while aligning with long-term decarbonization goals.

On the environmental front, the shift from fuel oil to lighter products directly supports IOCL's commitment to reducing carbon intensity, improving SOx/NOx profiles, and aligning with India's long-term vision of net-zero emissions. In further integration the advanced residue upgradation also plays a pivotal role in enabling circular economy concepts—by facilitating integration with bio-feedstocks, enabling recycling of waste oils, and opening pathways for future carbon capture and utilization (CCU) applications.

IndianOil's projects at Paradip, Panipat, Gujarat, Barauni, and Bongaigaon exemplify this future—transforming refineries into highly integrated, flexible, and low-carbon complexes. These upgrades not only strengthen refinery margins but also align with India's goals of sustainability, industrial growth, and energy independence. By 2047, the most competitive refineries will be those that achieve near-zero residue, switch flexibly between fuel and chemical production, and integrate seamlessly into hydrogen and circular economy value chains.

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10 Global Refinery Performance Benchmarks and Best Practices A Case Study of BPCL Mumbai Refinery

Shri Anukalp Jain, Senior Manager-Energy, Mumbai Refinery

Bharat Petroleum Corporation Limited

The ongoing decade will be remembered as a time where global community faced the dual challenge of maintaining economic growth while acting decisively on climate change. At the core of this effort lies the energy industry, which is both a key enabler of development and a significant source of greenhouse gas (GHG) emissions.

The petroleum refining industry, due to its energy-intensive processes and large carbon footprint, is an important player in ensuring a just and sustainable energy transition. Across the world, refineries are being asked to do more than just process crude —they are being called upon to redefine how it is to be done, with minimal environmental impact. Climate action today is no longer optional; it is an operational, strategic, and ethical imperative.

While the global energy matrix is evolving rapidly with growing contributions from renewable sources, petroleum products remain the dominant source of energy worldwide, particularly in transportation, petrochemicals, and industrial heating. Projections suggest that even by 2035, oil will constitute a major share of energy consumption, particularly in developing economies. This reality reinforces the importance of ensuring that petroleum refining processes are required to be as energy-efficient and environmentally responsible as possible. The focus must shift from not only increasing capacity to also optimizing existing assets, reducing emissions, and integrating new technologies that enable sustainable operations.

At Bharat Petroleum Corporation Limited (BPCL), energy efficiency is not merely a compliance requirement, it is a strategic priority aligned with India's climate commitments and BPCL's sustainability goals. Recognizing the link between energy optimization and climate impact, BPCL Mumbai Refinery (MR) has adopted energy efficiency as a cornerstone of its operations. The Refinery's vision is to emerge as one of the most energy-efficient refineries globally, while also achieving the goals of reducing carbon emissions and conserving natural resources. Efforts are focused on systematic energy management, achieving benchmark performance globally, and deploying the best available technologies.

Mumbai Refinery is the flagship manufacturing Business Unit of BPCL, located strategically in the heart of Mumbai. The refinery began operations in 1955 with a nameplate capacity of 2.2 Million Metric Tonnes Per Annum (MMTPA). Over the decades, it has undergone multiple expansions and technological upgrades to reach its current capacity of 12.0 MMTPA. The configuration today includes two crude processing trains, an array of secondary processing units, and state-of-the-art off-site facilities. Despite urban constraints and legacy infrastructure, BPCL MR has consistently improved its throughput and efficiency. This transformation from a mid-century plant to a modern, high-performing refinery reflects BPCL's long-term commitment to operational excellence.

Benchmarking performance against the global best is essential to drive continuous improvement. BPCL Mumbai Refinery has been participating in Solomon Associates' Refinery Benchmarking Study since 2012. Solomon's Energy Intensity Index (EII) is widely regarded as the gold standard for assessing refinery energy performance, normalized for complexity and throughput. In 2012, MR was placed in Quartile 4 (Q4), indicating higher energy intensity relative to its peers. Through continuous improvements, implementation of varied energy conservation schemes, new projects, and technology upgrades, the refinery progressed to Quartile 2 (Q2) in the 2022 study cycle. This remarkable ascent is a reflection of meticulous planning and relentless execution.

However, BPCL Mumbai Refinery is not resting on its laurels. It has now set its sights on achieving Quartile 1 (Q1) status in the Solomon EII by FY 2025-26—a feat that shall make it the first Indian PSU refinery to do so. Achieving Q1 status would place MR among the top 25% of refineries worldwide in terms of energy efficiency. The roadmap includes targeted energy conservation projects, technological investments, system integration, and robust performance monitoring—all geared towards one objective: to be counted among the global elite.

A defining moment in BPCL MR's energy journey occurred in 2015, when two aging crude distillation units were replaced with a modern, energy-efficient crude unit. While the overall nameplate capacity remained unchanged, the replacement led to significant improvements in energy consumption, heat integration, and operational reliability. This project was a strategic investment in future-ready infrastructure and marked a step-change in MR's energy performance trajectory. It enabled the refinery to process a wider variety of crudes while consuming less energy per barrel—a classic win-win for both business and environment.

Additionally, in response to India's push for 100% Bharat Stage-VI (BS-VI) compliant fuels, BPCL MR commissioned several new units during the period 2017 to 2023 including Isomerization Unit (ISOM), Diesel Hydrotreater (DHT), Gasoline Hydrotreater (GTU) & Kerosene Hydrotreater (KHT). While these units enhanced product quality and ensured regulatory compliance, they also increased the refinery's overall energy demand. However, MR successfully managed this trade-off by optimizing auxiliary consumption and minimizing energy losses. One of MR's most commendable achievements is its lowest specific steam and water consumption among Indian PSU refineries. Despite capacity additions and stricter quality norms, steam, power, and fuel usage remained tightly controlled. The refinery also boasts one of the lowest Fuel & Loss Percentage (F&L%), reflecting exceptional operational discipline. These results are a direct outcome of structured energy monitoring systems, investment in recovery mechanisms, implementation of constructive technologies and continuous personnel engagement.

BPCL MR's approach to energy management is systematic and comprehensive, inclusive of technology, human capital, and governance. Key initiatives include:

- **Furnace Efficiency Monitoring:** Continuous optimization of excess oxygen and stack temperatures to improve combustion efficiency.
- **Focus on Significant Energy Users (SEUs):** High-energy equipment is prioritized for monitoring and optimization.
- **Energy Conservation Scheme Implementation Framework:** Projects are executed with clear ownership, timelines, and metrics.
- **Energy Champion Concept:** Each unit has a designated Energy Champion responsible for driving awareness and improvements.
- **Regular Monitoring and Review:** Energy parameters are analyzed periodically, with findings escalated in Management Review Meetings to ensure apex-level focus.
- **Steam Trap and Leak Management:** Dedicated teams are in place to survey and rectify leaks, ensuring thermal losses are minimized.

By ensuring the above, MR has emerged as a pioneer in technological innovation. With global-first initiatives such as the commercial operation of Double Divided Wall Columns, and nation-first implementations like 100% conversion of steam tracing in offsite lines to electric heat tracing and widespread use of Epoxy-coated Fibre Reinforced Plastic (EFRP) fan blades, MR is actively redefining what is possible in refinery energy management. The adoption of the following advanced technologies has played a critical role in enabling the refinery to significantly reduce energy intensity - while maintaining high product quality and operational reliability:

1. **Divided Wall Column (DWC):** MR is the first refinery in the world to operate a Double Divided Wall Column in its LOBS (Lube Oil Base Stock) unit—an innovation that improves separation efficiency while reducing energy use.
2. **Steam Tracing-to-Electric Tracing Conversion:** The first Indian PSU refinery to convert 100% of steam tracing to electric heat tracing in offsite pipelines, reducing steam losses and improving energy performance.
3. **Epoxy Coated Fibre Reinforced Plastic (EFRP) Fan Blades in AFCs:** Replacement of conventional fan blades with EFRP blades in all Air Fin Coolers (AFCs) has enhanced efficiency and reduced power consumption.
4. **Condensate and Flash Steam Recovery:** Recovery systems are installed in all process units, maximizing energy reuse.

Looking ahead, BPCL Mumbai Refinery's ambition to enter Q1 of Solomon EII marks a significant milestone, not only for the refinery itself but also for India's public sector refining industry. The roadmap to achieve this includes a strategic pivot towards decarbonization, with bold plans such as the integration of renewable power, green hydrogen production, and electrification of steam-driven equipment. These initiatives represent an essential bridge between traditional refining operations and the low-carbon future that India and the world are collectively striving for. To realize this vision, BPCL MR has outlined a set of forward-looking initiatives that will serve as the foundation for this transition, including:

1. **Shift to Renewable Power:** Plans are in place to reduce reliance on fossil-fuel-based captive power generation and integrate renewable electricity sources.
2. **Green Hydrogen Integration:** The refinery aims to facilitate on-site green hydrogen production and utilization, reducing carbon intensity of hydrogen-dependent processes.
3. **Electrification of Rotating Equipment:** Large compressors and pumps currently driven by steam turbines will be transitioned to electric motor drives, thereby reducing the refinery's overall steam demand.

These actions are not only expected to reduce energy intensity but also align MR with national and global net-zero targets.

At BPCL MR, digitalization is playing a pivotal role in energy conservation journey. Tools like Advanced Process Control (APC), Optimizers and Digital Twins are enhancing decision-making, optimizing process variables, and enabling predictive maintenance. These technologies are not only improving energy efficiency but also boosting plant reliability and economic performance.

Mumbai Refinery's commitment to energy conservation and emissions reduction stands out not only in terms of performance metrics but also in the refinery's deeply institutionalized approach to achieve excellence. Its rapid transition from Quartile 4 to Quartile 2 in the Solomon Energy Intensity Index (EII) is a testament to this evolutionary journey, marked by continual interventions, focused leadership, and operational discipline. Mumbai Refinery, now, stands at the juncture of achieving Q1 performance. This is strengthened by the fact that March 2025 performance (EII – 78.6; Q1 entry point as per Solomon 2022 Study Cycle – 77.6) was the best in MR's history. The structured framework for energy management, supported by Energy Champions, periodic reviews, and targeted schemes, ensures that energy conservation is not just a one-time campaign but an embedded part of refinery's culture.

What emerges from this case study is how BPCL is keen to transition towards efficient and sustainable operations. Mumbai Refinery's success reaffirms that with the right vision, technology, and execution, it is entirely possible to meet rising energy demands while minimizing energy consumption and environmental impact. As BPCL continues to invest in people, processes, and clean technologies, the refinery is well-positioned to be a flag-bearer of India's energy transition, inspiring others in the sector to follow suit and scale greater heights of sustainable performance.

11 Fuels to Feedstocks: Integrated Refinery Complexes as Strategic Enablers of India Vision 2047

Engineers India Limited

Crude oil continues to play a significant role in India's energy mix, particularly in the transportation and industrial sectors, accounting for approximately one-fourth of the total primary energy consumption. Energy security remains the top priority for countries around the world, including India, which is heavily dependent on crude oil imports to meet its energy requirements amidst the changing geopolitical landscapes in the oil-exporting nations.

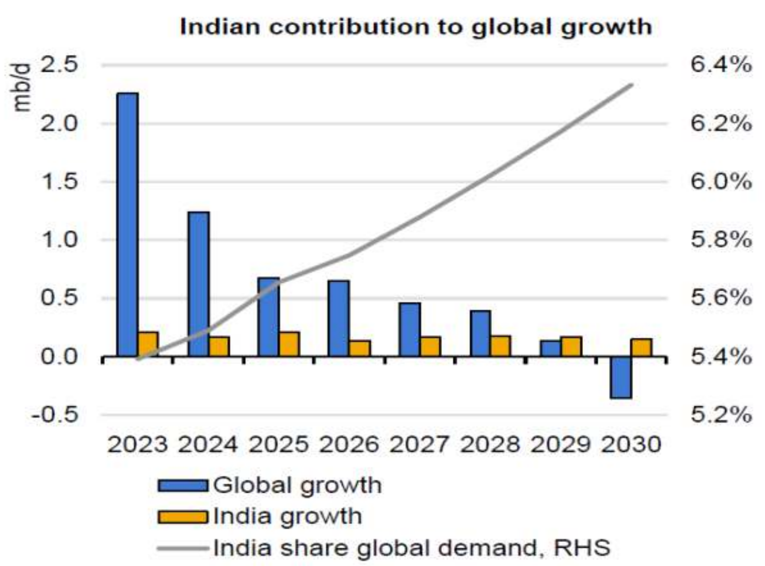
Exhibit: Dual Feed Cracker Unit (DFCU) OPaL, Dahej

The crude oil demand is further expected to be driven in India by the rapid urbanization, industrial growth, increasing mobility, improved access to clean cooking fuels, among others, in the years to come. Simultaneously, India is poised for a robust expansion in its petrochemical sector, fuelled by rising demand from automotive sector including electric vehicles, packaging, construction and infrastructure, solar energy infrastructure, lifestyle products, and household appliances etc.

Crude oil and Products growth Scenario

According to IEA estimates, diesel will remain the single largest contributor to oil demand growth in India, accounting for nearly half of the domestic increase and over one-sixth of total global oil demand growth through 2030. Demand for jet fuel is also expected to rise significantly, with an average annual growth rate of approximately 5.9%. In contrast, gasoline demand is projected to decline gradually due to the growing adoption of electric vehicles in the passenger transport segment.

Globally, petrochemical feedstock is emerging as a key driver of crude oil demand. In India, however, crude oil demand is expected to be driven by both fuel consumption and rising petrochemical feedstock requirements.



Further, a modest anticipated growth of white distillate amidst changing energy landscape and steadily rising petrochemical products demand scenarios mandate for new refinery configurations with more focus on petrochemical products. Several new technologies are also being explored for the conversion of crude oil to petrochemical products. The new refinery configurations are also anticipated to provide flexibility of operation to the owners to address the changing product supply and demand scenario during the energy transition.

At present, domestic production focused towards Bulk/ Commodity Petrochemical (Polymer)/ Per capita consumption of Polymer in India (~12 kg) is low compared to global average. India's Population at around 1.4 billion entails that 1 kg increase on instant indicator results in additional Polymer demand of ~1.4 MMTPA. Net Import of top Petrochemicals in India in year 2023 was around 5.6 MMTPA with an approximate import value of Rs 57,400 Crores. (Source DCPC). Therefore, the demand growth in India for Bulk/ commodity Petrochemical will continue to be healthy. India is expected to require around 12-15 world-scale petrochemical Complexes as per various analyses carried out by multiple agencies, including MoC&F.

Economic sourcing of Petrochemical feedstock and production of base olefins like Ethylene and Propylene remains the key challenge for India. Multiple feedstocks like Condensate, Propane, Butane, Ethane and Naphtha are expected to be utilized for Olefin Production through Steam Crackers and Propane Dehydrogenation Units. However, declining Gasoline demand coupled with robust demand of Diesel and Petrochemicals makes a strong business case for Integrated Refinery Petrochemical Complex.

Further, biomass from forestry products, agricultural residues, and organic waste is also promising as a source of bio-based chemicals, with the advancement in Technologies for Biomass Conversion.

The Business Case for Integrated Grassroot Refinery & Petrochemical Complexes

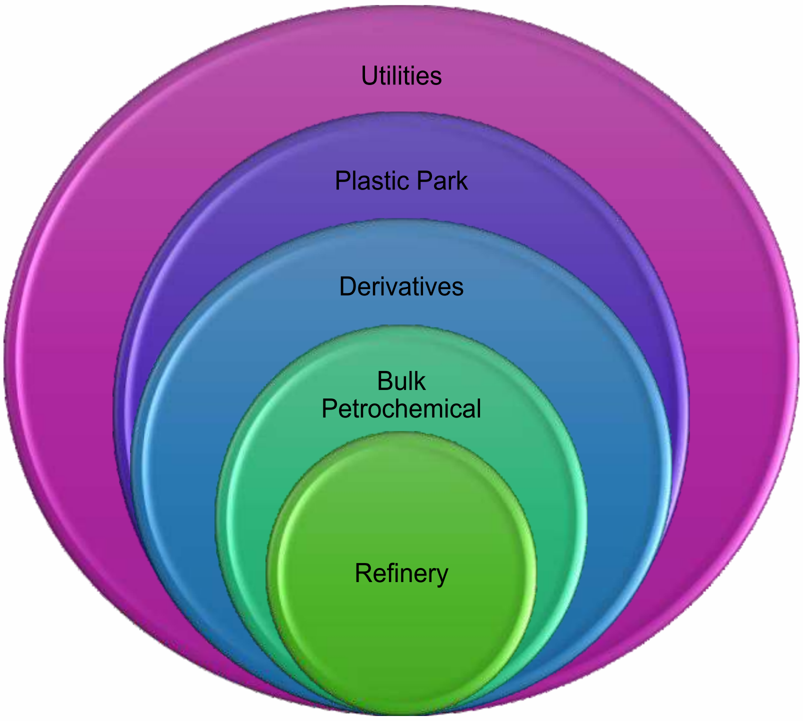
The current Refining Capacity of India stands at around 258 MMTPA which is expected to grow around 310 MMTPA by 2030. India ranks 4th globally in terms of Crude oil refining capacity and is self-reliant in refining products, with notable exports of refined products. However, there is a major shortfall in the Petrochemical segment, necessitating significant quantities of imports in this segment.

Petrochemicals play a vital role in economic growth & development as one of the pillars of the material industry and provide critical inputs enabling other sectors to grow as well. The chemical industry contributes about 6% to India's GDP, generating employment for over five million people. Hence, with the GDP growth tracking a continuous upward trajectory is expected to propel the Petrochemical products growth in the coming years.

Petrochemical monomers i.e. Ethylene and Propylene and intermediates must be manufactured in order to develop specialized chemicals. These petrochemical intermediates are required to produce specialized chemicals, which are then used to make consumer goods and technological products. The main polymer intermediates are ethylene oxide, propylene oxide, polyols, phenol, styrene, and rubber derivatives. India stands as Asia's third-largest economy with annual petrochemicals consumption between 25 million MT and 30 million MT, exhibiting a per capita consumption significantly lower than developed nations. This gap presents ample opportunities for demand growth and investment. The size of the Indian chemicals and petrochemicals could potentially reach $1 trillion by 2040.

A robust primary Energy and Petrochemical demand at the same time is the compelling idea towards Integrated Complexes, wherein the operations of a conventional oil refinery and a petrochemical plant are combined. This approach makes the best use of feedstocks and byproducts for the production of chemicals and fuels to optimize the value obtained from crude oil. Compared to individual facilities, integrated complexes can increase efficiency and profitability by pooling resources and utilities. Depending on the location of the complex, renewable energy sources can be utilized to buttress the energy requirement for the complex.

The Petrochemical Intensity Index (PII) measures the percentage of crude oil converted into petrochemicals rather than fuels within a refinery. It's a key metric for evaluating a refinery's integration with petrochemical production. New Grassroot Integrated Refinery Petrochemical complexes can have Petrochemical Intensity Index of ~30% which can be achieved utilizing proven downstream technologies.



Refinery Configurations for these new complexes is a major challenge since these refineries coming up in transition era are expected to be nimble towards shifts in fuel quality, cyclical petrochemical demands, spread of light and heavy crude and taking advantage of alternate feedstocks. Refinery/Petrochemical Operators will also be required to take pre-emptive actions about measuring, monitoring and reducing carbon emissions and find cost-effective ways to reduce their carbon footprint to be future-ready and leverage the benefits of lower emissions in ESG and Financial terms.

Strategic push for Growth beyond fuels in India

India produces ~30 MMTPA of Indigenous crude oil and a modest 34-36 BCM of Natural Gas. However, this is set to change with advances in discovery of crude oil near Andaman with expected reserves of 184,440 crore litres of crude oil. This discovery shall have a significant impact on global energy flows and Indian economy is expected to reach 20 trillion USD. Crude oil as a source of Energy and Petrochemical feedstock shall provide impetus for setting up a hub of manufacturing complexes in India fuelled by strong demand.

Existing Refineries in India have either executed integration with world scale petrochemical complexes or evaluating synergies for the same. Indian Oil's Panipat Refinery and HMEL's GGSRP are quintessential in this category having executed integration of world scale petrochemical complexes with the existing refinery. In addition, Paradip Refinery of Indian Oil is implementing a petrochemical complex adjacent to its existing refinery. This complex also benefits from naphtha management of other IOCL refineries.

Also, HPCL's HRRL Project is one of the highest petrochemical intensity grassroot integrated refinery cum petrochemical complexes in India. It has a petrochemical intensity of around 26% and is configured to diversify the products based on the prevailing fuel and petrochemical market demand. Propane Dehydrogenation Units by GAIL and Petronet LNG, under execution are expected to cater towards Polypropylene demand in a cost-optimal manner.

EIL has played a key role in the implementation of mega petrochemical complex projects in India and would continue to deliver its engineering and project management excellence towards achieving India's petrochemical vision 2047.

Conclusion

Global Energy trade flows, i.e. worldwide exchange of energy resources, such as fossil fuels, nuclear energy, and renewable sources, among nations, are affected by elements such as supply and demand, geopolitics, economic conditions, and technological progress. In addition, petrochemical trade patterns are intricate and ever-changing, influenced by elements such as local production capabilities, consumption needs, and international trade regulations.

Indian Refiners are already on a path of adopting a blend of organic and inorganic strategies, transitioning beyond fuels towards deeper integration of refineries with chemical and petrochemical production, enabling the country to achieve energy security and self-reliance in petrochemicals, fully aligned with India Vision 2047.

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Techno-commercial review of E-SAF production through Direct Air Capture

Shri Karthick R, Chief Manager (Innovation Center), Technical Services

Mangalore Refinery and Petrochemicals Limited

1. Introduction and Background

The aviation sector faces increasing pressure to decarbonize, with Sustainable Aviation Fuel (SAF) emerging as a critical solution to reduce greenhouse gas emissions. The Power-to-Liquid (PtL) pathway, which synthesizes liquid hydrocarbons from renewable electricity and CO2, is gaining attention as a sustainable alternative to biomass-based SAF production methods, such as Hydroprocessed Esters and Fatty Acids (HEFA) and Alcohol-to-Jet (AtJ). Unlike these pathways, PtL does not compete for limited biomass resources, potentially offering an unlimited feedstock through captured CO2 and renewable electricity. However, the pathway's sustainability hinges on the carbon intensity of its inputs, and its high production costs pose significant challenges. This paper provides a comprehensive analysis of the PtL pathway, focusing on its technological maturity, economic constraints, and competition for renewable energy resources.

2. SAF production routes and their production cost

2.1. Hydroprocessed Esters and Fatty Acids (HEFA)

Hydroprocessed Esters and Fatty Acids (HEFA) pathway, approved under ASTM D7566 Annex A2 in 2011, is one of the most mature routes for SAF production. The process involves the catalytic hydrotreatment of lipid-based feedstocks to remove oxygen, followed by hydrocracking and isomerization steps to yield paraffinic kerosene suitable for blending with conventional jet fuel at levels up to 50% by volume. Typical operating conditions include temperatures of 250–350°C and pressures of 30–80 bar. The hydrotreatment stage commonly employs sulfided NiMo or CoMo catalysts on alumina supports, while isomerization is facilitated using noble metal catalysts such as Pt or Pd.

HEFA-compatible feedstocks include vegetable oils (e.g., palm, soybean, and rapeseed, representing a global supply of approximately 220 million metric tons), used cooking oil (11–13 million tonnes), animal fats such as tallow (12–15 million tonnes), and emerging oilseed crops like Carinata and Camelina. Jet fuel yields from HEFA typically range from 15% under standard operation, up to 70% with advanced isomerization catalysts. However, increased selectivity towards jet fuel may reduce the total liquid yield to 85–90%. Co-products consist of naphtha (10–15%), diesel (15–70%), and gaseous fractions including propane and other light hydrocarbons (5–10%).

With a technology readiness level (TRL) of 9, HEFA is commercially deployed by producers such as Neste and World Energy, though current capacities are skewed towards renewable diesel production. Key challenges include the limited availability of sustainable lipid feedstocks, competition with both food uses and diesel markets, and the need for extensive pre-treatment of waste oils to remove impurities such as free fatty acids.

2.2. Gasification with Fischer-Tropsch (FT) Synthesis

The thermochemical gasification route combined with Fischer–Tropsch synthesis represents a flexible pathway for SAF production, approved under ASTM D7566 Annex A1 (2009) and Annex A4 (2015). In this process, biomass feedstocks are gasified at temperatures between 800–1000°C and pressures of 20–30 bar to produce synthesis gas (CO and H_2). This syngas is subsequently converted into hydrocarbons via FT synthesis, operated at 200–350°C and 20–40 bar, using Fe- or Co-based catalysts. Post-synthesis hydrocracking and alkylation are employed to enhance the jet fuel fraction.

Relevant feedstocks include municipal solid waste (MSW), forest residues, agricultural residues, and lignocellulosic biomass such as woody materials.

The process yields a jet fuel fraction of approximately 40–60%, accompanied by diesel (30–40%), naphtha (10–20%), and waxes (5–10%). Effective syngas cleaning is essential to prevent catalyst poisoning. Although FT synthesis itself is considered TRL 9, the integrated gasification and syngas cleanup systems remain at TRL 6–7. Fulcrum BioEnergy's commercial-scale facility (2022) exemplifies this integration, using MSW with FT liquids co-processed at Marathon Petroleum.

Challenges include the high capital intensity of gasification units, technical complexity arising from feedstock variability, and logistical difficulties in transporting low-energy-density, high-ash biomass. Research into bifunctional FT catalysts for higher jet selectivity is ongoing, but ASTM approval remains a prerequisite for commercial deployment.

2.3. Alcohol-to-Jet (AtJ)

Alcohol-to-Jet (AtJ) pathway, codified in ASTM D7566 Annex A5 (isobutanol, 2016; ethanol, 2018) and Annex A8 (2023, C_2–C_5 alcohols), enables SAF production from alcohol intermediates through a series of catalytic transformations. The process includes dehydration (150–300°C, 1–10 bar, typically using zeolite catalysts), oligomerization (200–400°C, 10–30 bar, via acid or metal oxide catalysts), and final hydrogenation (200–300°C, 20–50 bar, using Ni or Pt catalysts).

Feedstocks for this route include ethanol (derived from corn, sugarcane, or cellulosic biomass), isobutanol, and other light alcohols. Methanol-to-jet variants are currently under ASTM review. Notably, LanzaJet's Freedom Pines facility, commissioned in 2024, is the first commercial-scale AtJ plant. Typical jet fuel yields range from 60–80%, contingent on alcohol type and process optimization. Co-products include naphtha (10–20%) and light gases (5–10%). Ethanol used in this route can be produced through conventional fermentation or more innovative syngas fermentation (e.g., by LanzaTech) and enzymatic cellulosic processes.

The ethanol- and isobutanol-based AtJ routes have reached TRL 8–9, while methanol-based systems and cellulosic ethanol production remain at TRL 6–7 and TRL 5–6, respectively. Economic viability is challenged by high ethanol prices, especially for second-generation sources, and intense competition with bioethanol applications in road transport. Although sugarcane ethanol offers a low carbon intensity (CI), its scalability is constrained by land and water limitations.

2.4. Power-to-Liquids (PtL)

Power-to-Liquids (PtL) technologies synthesize liquid hydrocarbons using renewable electricity, CO_2, and water as primary inputs. Electrolysis—either alkaline or proton exchange membrane (PEM)—operates at 50–80°C and 20–40 bar to generate hydrogen. This is combined with captured CO_2 via the Reverse Water Gas Shift (RWGS) reaction (600–900°C, 1–10 bar, Ni or Cu catalysts) or through co-electrolysis in Solid Oxide Electrolyzer Cells (SOECs, 700–850°C, 1–5 bar) to produce syngas. Subsequent conversion occurs via FT synthesis (200–350°C, 20–40 bar, Fe/Co catalysts) or methanol synthesis (200–300°C, 50–100 bar, Cu/ZnO catalysts), followed by AtJ processing.

Feedstocks are limited to renewable electricity and captured CO_2, derived from industrial point sources or direct air capture systems. Jet fuel yields range from 40–60% via FT and 50–70% via methanol-to-jet pathways. Co-products typically include diesel (20–30%), naphtha (10–20%), and residual methanol (5–10%). Due to conversion inefficiencies across multiple steps, overall system energy efficiency is limited to 30–40%.

While individual FT units are TRL 9, integrated PtL systems, particularly RWGS and SOEC configurations, are still at TRL 5–6. Demonstration projects, such as Sunfire's pilot facility, highlight incremental progress. However, the high capital cost of electrolyzers and the price volatility of renewable electricity remain major barriers. Furthermore, competition for clean electricity with other sectors and the need for low-CI CO_2 sources present additional sustainability and scalability concerns.

2.5. Co-processing

Co-processing involves blending small quantities of bio-intermediates (typically 5%) such as lipids or FT liquids into conventional petroleum refining units. This pathway, approved under ASTM D1655 (2018 for lipids; 2020 for FT liquids), allows for the integration of renewable carbon into existing hydroprocessing infrastructure. Operating conditions range from 250–350°C and 30–200 bar, utilizing NiMo or CoMo hydrotreating catalysts.

The process accommodates feedstocks including used cooking oil, tallow, and FT liquids derived from biomass gasification. Jet fuel yields depend on the carbon chain length and nature of the bio-intermediate but generally constitute 2–4% of total product output. Diesel (60–70%), gasoline (20–30%), and light gases (5–10%) are the predominant co-products. With a TRL of 9, co-processing is commercially practiced in several refineries. However, the current ASTM limit on blend ratios restricts SAF output. Efforts to increase permissible blending levels up to 30% are ongoing, which would significantly improve overall SAF yields.

2.6. Direct Thermochemical Liquefaction

Thermochemical liquefaction technologies convert solid biomass into liquid intermediates through processes such as fast pyrolysis (400–600°C, 1–5 bar, non-catalytic or zeolite-based), catalytic pyrolysis (400–500°C, zeolite catalysts), and hydrothermal liquefaction (HTL, 250–350°C, 100–200 bar, generally non-catalytic). The resulting bio-oil or biocrude is upgraded via hydrotreatment (250–350°C, 30–80 bar, NiMo catalysts) to meet jet fuel specifications.

Acceptable feedstocks include sewage sludge, municipal solid waste, and lignocellulosic residues such as forestry and agricultural waste. Post-upgrading, jet fuel yields typically range from 30–50%, alongside diesel (30–40%), naphtha (10–20%), and solid co-products like biochar (10–20% for pyrolysis processes). However, upgrading efficiency losses and feedstock heterogeneity remain technical challenges.

With TRL values around 6–7, thermochemical liquefaction is under active development. Notable initiatives include pilot demonstrations by Alder Renewables and BTG-neXt. Despite technical promise, ASTM certification and large-scale commercial validation are still pending. Economic barriers include complex upgrading requirements, inconsistent feedstock composition, and high capital costs associated with reactor systems.

3. e-SAF production by RWGS-FT route

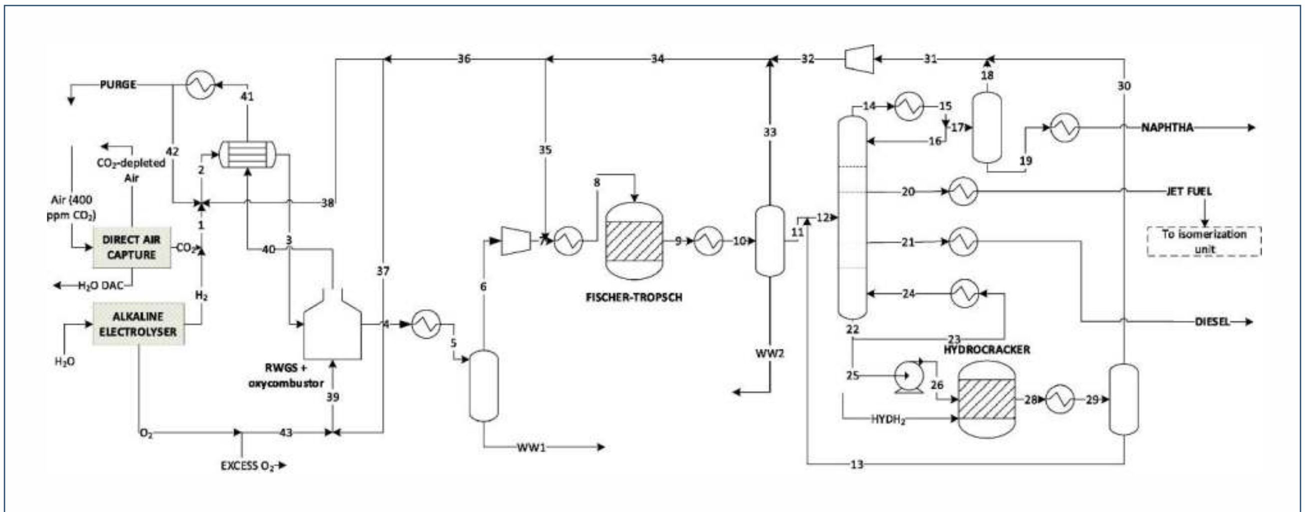


Figure 1: PtL pathway to SAF production by Rojas-Michaga et al. (2023)

The PtL process depicted in above represents a synthetic aviation fuel production pathway that integrates renewable electricity, atmospheric CO_2, and water to produce sustainable drop-in jet fuels. The design is based on a techno-economic and life cycle model developed by Rojas-Michaga et al. (2023) and simulated using Aspen Plus. The plant comprises five major unit operations: Direct Air Capture (DAC), Alkaline Water Electrolysis, Reverse Water Gas Shift (RWGS), Fischer–Tropsch (FT) Synthesis, and Hydroprocessing.

3.1. CO_2 and H_2 Generation

Atmospheric CO_2 is captured using a Vacuum-Temperature Swing Adsorption (VTSA) system developed by Climeworks. This system employs APDES-NFC sorbents, operating under cyclic heating and vacuum conditions to selectively desorb CO_2 and water. The purified CO_2 stream (Stream 1) is directed to the RWGS unit. Hydrogen (Stream 2) is generated via alkaline electrolysis using deionized water and electricity derived from offshore wind. The electrolyzer also produces oxygen (Stream 43), which is partially fed into the oxy-combustion section of the RWGS reactor and partially purged.

3.2. Syngas Production via RWGS

The RWGS reactor combines CO_2 and H_2 to produce carbon monoxide and steam, forming a syngas mixture (Stream 6). The reactor operates at high temperature (~850°C), with in situ oxy-combustion providing necessary heat. Excess water from this step is purged (Stream WW1). Heat recovered from this unit is also used to regenerate the DAC beds, enhancing overall thermal integration.

3.3. Fischer–Tropsch Synthesis

Syngas is fed to a multi-tubular Fischer–Tropsch reactor (Stream 6 → FT Reactor). The reactor, packed with a cobalt-based catalyst, operates at 20–25 bar and moderate temperatures (220–240°C), converting syngas into a broad spectrum of hydrocarbons. Products are cooled and separated (Streams 9–11), yielding aqueous waste (WW2) and a hydrocarbon mixture (Stream 12).

3.4. Product Separation and Upgrading

The FT product is fractionated in a distillation column into naphtha (Stream 30), jet fuel (Stream 21), diesel (Stream 24), and a heavy wax fraction (Stream 22). The waxes are hydrocracked in a fixed-bed reactor (Block 23) and recycled into the separation column to enhance middle-distillate yields. Jet fuel may optionally undergo isomerization to meet ASTM freezing point requirements.

3.5. Integration and Recycling

Unconverted light gases are partially recycled (Stream 36) or purged to avoid inert accumulation (Stream 41). Water recovered from FT and DAC units is reused in the electrolyzer. The system is designed with a high level of thermal and material integration to improve carbon utilization and energy efficiency.

3.6. Techno-economic analysis

The economic analysis was conducted in 2022 GBP values using a discounted cash flow (DCF) model over a 25-year plant life, assuming a 10% discount rate and 40% tax rate. Key outcomes are summarized below:

Metric	Base Case Value
Total Capital Investment (TCI)	£929 million
Annual SAF Production	21.7 million gallons
Minimum Jet Fuel Selling Price (MJSP)	£5.16 per kg (~£4.37/L)
OPEX Share of MJSP	~67%
Electricity Cost Contribution (to OPEX)	~42%
CO_2 Capture and Electrolysis CAPEX Share	>60% of total CAPEX
Overall PtL Efficiency	25.6% (based on electricity)

A one-way sensitivity analysis was performed to evaluate the influence of uncertain parameters on MJSP. Key findings include:

- Hydrogen Cost: Most influential - reducing from £3.09/kg to £1/kg decreases MJSP by ~40%.
- CO_2 Cost (DAC): A drop from £359/tonne to £50/tonne yields substantial savings.
- Electricity Cost: Each £0.01/kWh reduction leads to a ~£0.24/kg decrease in MJSP.
- Electrolyzer Cost (CAPEX): Reduction from €663/kW (2020) to €444/kW (2030) contributes to ~15–20% savings.
- Learning Curve for DAC: Potential 50% cost decline through technology maturity and scale.

3.7. Scope for Competitiveness Improvement

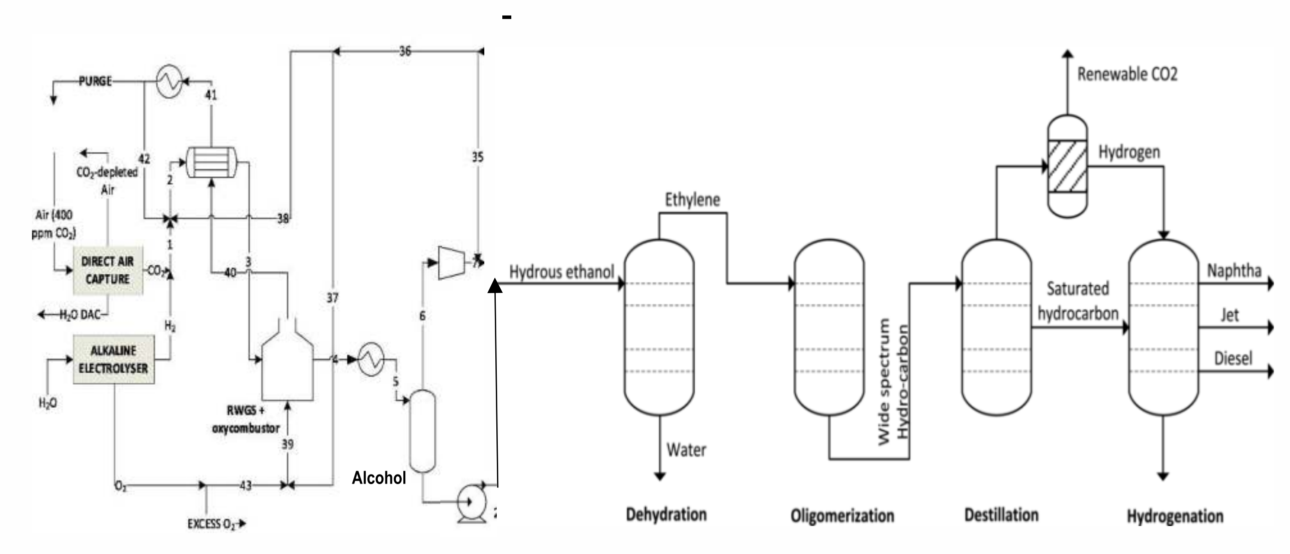
According to McKinsey, industrial point-source capture could cost as little as $25 per tonne of CO2 in some industries, such as bioethanol, and more than $100 in sectors, such as cement production (McKinsey, 2022). Direct air capture (DAC), on the other hand, costs about $250-$600 per tonne of CO2, with differences based on whether a liquid solvent is used ($170-$260/tonne CO2), or solid sorbent ($270-$500/tonne of CO2) (McKinsey, 2022). Although DAC using solid sorbent is at a lower TRL level and requires further development, it has a greater potential for cost reduction while also operating at much lower temperatures and requiring lower energy inputs (McKinsey, 2022).

Another option is the direct conversion of CO2 with H2 into hydrocarbons. However, this approach is challenging and requires a catalyst, such as Fe, that can convert the CO2 to CO while also carrying out the FT synthesis (Panzone et al., 2020).

According to McKinsey, the fuel synthesis process in PtL represents only 12% of the cost, while renewable electricity, hydrogen, and carbon inputs will account for more than three-quarters of the cost by 2030 (McKinsey, 2022). Renewable electricity accounts for about 25%, hydrogen capital costs about 30% and carbon capture about 15-30%, depending on the source of CO2 (McKinsey, 2022).

Other work has suggested that the electrolyzer and electricity costs (including capacity factors (CFs)29 and cost for hydrogen storage) have the biggest impact on the cost of eFuels (Grahn et al., 2022). Also, when "green" electricity is intermittent, hydrogen storage may be needed to enable stable fuel production. With sustained R&D, economies of scale, and regulatory incentives, MJSPs could fall to £2.5–3.0/kg SAF, making PtL a viable long-term solution for decarbonizing aviation.

4. e-SAF production by RWGS-ATJ route



This process represents an integrated Power-to-Liquid (PtL) pathway for Sustainable Aviation Fuel (SAF) production. It combines Direct Air Capture (DAC) of CO_2 and hydrogen production via electrolysis with Alcohol-to-Jet (ATJ) fuel synthesis. This pathway substitutes Fischer–Tropsch synthesis with a catalytic ATJ upgrading process similar to that used by LanzaJet, integrating ethanol conversion through dehydration, oligomerization, and hydrogenation to yield a drop-in synthetic paraffinic kerosene (ATJ-SPK).

4.1. Syngas Generation and Alcohol Synthesis

Direct Air Capture (DAC) extracts CO_2 from atmospheric air using a vacuum-temperature swing adsorption system. Simultaneously, hydrogen is generated from water via alkaline electrolysis using renewable electricity. The high-purity H_2 and captured CO_2 are combined in a Reverse Water-Gas Shift (RWGS) reactor at ~850°C and 1–10 bar to produce a syngas mixture primarily composed of CO and H_2. The syngas undergoes further processing (not shown explicitly in this modified diagram) to synthesize ethanol, for example via catalytic conversion or microbial fermentation. The ethanol is recovered, purified (to 95.6 wt% by azeotropic distillation), and directed to the ATJ section for upgrading.

4.2. Alcohol-to-Jet (ATJ) Conversion Pathway

The ATJ process includes four major catalytic steps: alcohol dehydration, olefin oligomerization, hydrogenation, and product fractionation.

4.3. Alcohol Dehydration

In this step, ethanol is dehydrated over an acid catalyst (typically zeolites or alumina) to form ethylene. The reaction operates at 300–450°C and 1–10 bar. Any unreacted ethanol is recycled or purged. The resulting ethylene-rich stream is separated from water via a knockout drum and phase separator (stream 10).

4.4. Oligomerization

Ethylene is then passed through an oligomerization reactor, where light olefins are catalytically combined into higher molecular weight hydrocarbons in the C8–C16 range, which fall within the jet fuel boiling range. This stage operates at 200–300°C and 10–30 bar using solid acid catalysts like ZSM-5 or Amberlyst-35. The product stream consists of a distribution of linear and branched olefins.

4.5. Hydrogenation

The olefin-rich stream is hydrogenated in a fixed-bed reactor over Ni or Pt catalysts at ~200–300°C and 20–50 bar. This reaction saturates the double bonds to produce paraffinic hydrocarbons. Excess hydrogen is recycled via compression (stream 26).

4.6. Product Separation

The fully hydrogenated stream is directed to a distillation column. Fractionation yields three main hydrocarbon cuts:

- **Naphtha (C5–C8):** Stream 17
- **Jet Fuel (ATJ-SPK) (C8–C16):** Stream 21
- **Diesel-range hydrocarbons (>C16):** Stream 24

The jet fuel product may be routed to an optional isomerization unit to improve cold-flow properties and freezing point compliance with ASTM D7566 Annex A5.

4.7. Techno-economic analysis

The minimum selling price (MSP) of jet fuel from the ATJ process, under 2021 "nth-plant" assumptions:

Pathway	MSP (USD/gal)
Ethanol-to-jet	$4.29
Isobutanol-to-jet	$3.44

For first-of-a-kind (2015) pioneer plants, these figures rise to $5.29/gal and $4.15/gal respectively. Alcohol feedstock cost accounts for approximately 75–80% of total fuel cost, making it the dominant economic factor.

Economic modeling in the study reveals the following cost levers and sensitivity results:

- **Alcohol Feedstock Price:**

A $0.10/kg reduction in alcohol price leads to a $0.40–0.50/gal drop in MSP. For isobutanol, parity with ethanol occurs at ~$755/ton vs. ~$534/ton for ethanol.

- **Conversion Yield Increases:**

Raising jet fuel yield by 10% (e.g., from 60% to 66%) reduces MSP by ~$0.30–0.40/gal.

- **Hydrogen Cost and Usage:**

Reducing H_2 price from $3/kg to $1.5/kg cuts MSP by ~8–10%.

- **Capital Efficiency (Learning Curve):**

Transitioning from 2015 to 2021 design reduces MSP by ~20–25% due to smaller reactors (e.g., reduced recycle for isobutanol) and improved plant integration.

5. Scope for Competitiveness Improvement

While the scope for improvement on CO2 capture and green H2 production and RWGS remains the same as earlier section, further scope is summarized below:

Unit Operation	Required Improvements
CO2 Capture & Green H2	• Same improvements as mentioned in previous section
Alcohol Conversion	• Increase overall alcohol yield to more than 60%
Dehydration	• Higher selectivity catalysts • Heat recovery and integration • Minimize alcohol losses via improved reactor design
Oligomerization	• Better control of chain length distribution • Lower recycle ratios, especially for ethanol • Advanced catalysts for C8–C16 selectivity
Hydrogenation	• Lower catalyst cost (e.g., Ni-based instead of Pt) • Better H_2 utilization efficiency
Separation	• Improved distillation efficiency • Better integration with refinery systems
Feedstock Supply	• Reduced alcohol production cost • Integrated lignocellulosic fermentation pathways

With sustained R&D, economies of scale, and regulatory incentives, MJSPs could fall to $2.0–3.0/kg SAF, making PtL a viable long-term solution for decarbonizing aviation.

6. A note on electricity required for e-SAF production

According to McKinsey, at least 36 MWh is needed to produce 1 tonne of efuel (kerosene plus other products) that is produced via PtL. When using direct air capture, this increases to 45-52 MWh per tonne (McKinsey, 2022), with high-temperature DAC using more electricity. As illustrated in the McKinsey report, the production of 50,000 tonnes of PtL fuel (~60 million litres) will require 1.1 TWh of electricity, which is equivalent to more than 2,700 acres of photovoltaics (McKinsey, 2022). It should also be noted that efuels represent an inefficient use of electricity (only 10-15%) compared to electric vehicles, which have an efficiency of 80% (Kohl, 2022). Consequently, some workers argue that efuels are therefore an inefficient way of using energy and that this energy could perhaps be directed to other sectors where greater emissions reductions could be achieved. Commercialization of the power-to-liquids process still has some technical challenges pertaining to individual processes such as the RWGS reaction and electrolysis. This is also a costly pathway for the production of SAF. Consequently, the main targets of cost reduction are reducing the cost of renewable electricity, reducing the cost of electrolyzers and reducing the cost of direct air capture (McKinsey, 2022).

7. SAF production cost outlook from all production routes

IEA Bioenergy Task 39 SAF report in 2024 presents a detailed techno-economic assessment of multiple SAF production pathways using harmonized assumptions for feedstock costs, yields, capital investment, and minimum selling price (MSP) for both pioneer and nth-of-a-kind commercial facilities. Pioneer Facility refers to a first-of-a-kind commercial facility with high capital and operational costs due to process learning curves, lack of economies of scale, and higher financing risks. Nth Facility represents a mature, replicated facility benefiting from cost reductions through technology learning, supply chain development, and standardized construction practices. These reflect long-term cost expectations under commercial deployment. The report synthesizes this data for several prominent SAF technologies, including Gasification with Fischer-Tropsch (GFT), Alcohol-to-Jet (ATJ), Power-to-Liquid (PtL), HEFA and fast pyrolysis routes. The results are tabulated below. Key observations from the report's futuristic cost landscape is ATJ from corn ethanol is among the most cost-effective SAF routes with an MSP < \$0.90/L. HEFA pathways (already commercial) also demonstrate strong cost viability, with MSPs around \$0.80–\$1.10/L. PtL routes, especially using DAC CO_2, remain the most expensive with MSPs > \$3.5/L in current configurations.

Processing technology	Feedstock	Feedstock cost ($/MT)	Yield	Product slate (%) (jet:diesel: gasoline:other)	TCI (million USD$)		MSP SAF (USD$/L)	
					Nth (total distillate MLPY)	Pioneer (total distillate MLPY)	Nth	pioneer
GFT	MSW	30	0.31	40:40:20	1427.6 (500)	2944 (500)	0.9	1.63
GFT	Forest residues	125	0.18		1207.2 (300)	2488.7 (300)	1.69	3.3
GFT	Agricultural residues	110	0.14		1123.8 (220)	2316.8 (220)	2.0	3.8
ATJ	Ethanol (based on corn)	456	0.60	70:0:30	316.4 (1000)	662 (1000)	0.79	0.87
ATJ	Isobutanol	1110	0.75		649.5 (1000)	1349.8 (1258)	2.35	2.49
HEFA	FOGs	580	0.83	55:26:19	447.7 (1000)		0.8	
HEFA	Vegetable oil	810	0.83		456.4 (1000)		1.1	
Pyrolysis	Forest residues	125	0.28	44:28:16:12	384.4 (134)	794.7 (134)	1.3	2.04
Pyrolysis	Agricultural residues	110	0.27		384.4 (134)	794.7 (134)	1.33	2.08
PtL	DAC CO2	300	0.24	40:40:20	1313.2(400)	2266.1 (400)	3.60	4.02
PtL	Flue gas CO2	50	0.24		1248.7 (400)	2155.9 (400)	2.70	3.14

IEA-Bioenergy Task 39 SAF report has reported the above techno-commercial landscape of SAF based on various open-source scientific studies. Here, GFT = Gasification and Fischer-Tropsch synthesis, ATJ = Alcohol-to-Jet conversion, HEFA = Hydroprocessed Esters and Fatty Acids, PtL = Power-to-Liquids, MSW = Municipal Solid Waste, FR = Forest Residues, AR = Agricultural Residues, FOGs = Fats, Oils, and Greases, DAC = Direct Air Capture, TCI = Total Capital Investment (in million USD, 2017 basis), MLPY = Million Litres per Year (total distillate product), MSP SAF = Minimum Selling Price of Sustainable Aviation Fuel (USD per litre).

8. Conclusion & Summary

The study presents a comprehensive techno-economic and life cycle assessment of sustainable aviation fuel (SAF) production via the Power-to-Liquid (PtL) pathway. The cost structure is dominated by operating expenditures, particularly electricity and hydrogen production, and by the capital intensity of DAC and FT synthesis or ATJ infrastructure. Sensitivity analysis indicates that hydrogen cost, CO_2 capture cost, and electricity price are the most influential parameters affecting economic viability.

Despite these limitations, IEA-Bioenergy Task 39 SAF report concludes that PtL SAF is a critical long-term option for fully decarbonizing aviation, especially in regions with abundant renewable electricity and hard-to-abate emissions. The pathway is particularly valuable for capturing and utilizing CO_2 from hard-to-decarbonize sources or even atmospheric CO_2 through DAC.

To accelerate deployment and improve cost competitiveness, the stakeholders focus has to be on:

- Sustained and focussed R&D on all steps of PtL for e-SAF production
- International collaboration and investment in PtL innovation.
- Large-scale demonstration projects,
- Integration with renewable energy expansion plans,
- Policy instruments (e.g., SAF mandates, carbon pricing, green fuel credits)

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Bongaigaon (IndianOil); Estd. -1974

13

Demonstration of Light Naphtha Isomerization Technology using Indigenous IV-IZOMax$^{CAT®}$ at Bongaigaon Refinery

Shri Pushkar Varshney, Shri Talari Raju, Shri Vimal K Upadhyay, Shri Sulagna Majumdar, Shri Hemant Kumar, Dr Satyen K Das, Shri RK Kaushik Singha, Dr. Alok Sharma

Indian Oil Corporation Limited

Dr. Chaitanya Sampara,

Viridis Chemicals Pvt Ltd

Introduction

With the growth in vehicular population and economic development, the demand for gasoline in India has seen a steady and significant rise. This trend is projected to continue till the year 2035 as indicated in Figure 1. Further, stricter fuel quality regulations necessitate cleaner and more efficient gasoline. The Light Naphtha Isomerization (ISOM) process is one of the key refinery processes contributing to the production of high-octane, low-aromatic gasoline blending stream for meeting the stringent gasoline specifications. This process converts low-octane light straight run naphtha into a high-octane gasoline blending stream. In this process, the octane number increases by conversion of the straight chain paraffinic hydrocarbons to their respective isomers, whose octane is higher than that of straight chain hydrocarbons. The feed to the ISOM process may also comprise naphthenes and aromatics. Aromatics, mainly Benzene in the feed, get saturated and thereby help in managing benzene content in the overall gasoline pool.

Precious metal catalysts such as the ISOM catalyst (platinum-based) used in petroleum refineries in India have been traditionally imported from foreign technology providers and manufacturers. If these high technology materials can be developed and manufactured in India, it not only provides a monetary advantage to all the refineries but also gives the country a new standing at par with the traditional catalyst providers in the world.

To solve this problem statement, Indian Oil R&D, which specializes in Process Development and Licensing, jointly with Viridis Chemicals Private Limited, a MSME company that utilizes molecular level modelling to innovate new catalytic materials, developed a new nanoparticle catalyst that is highly efficient for Light Naphtha Isomerization.

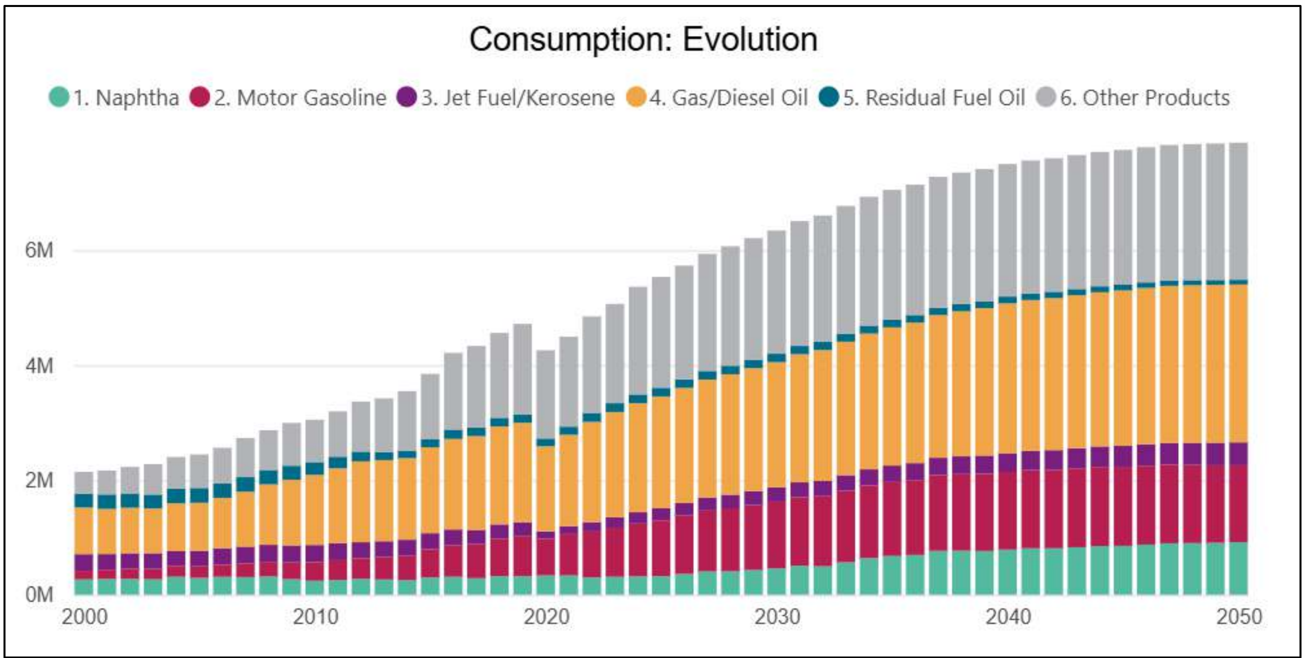

Figure 1 : Consumption of various petroleum products in India, past data and projection[1]

Conventionally, 2 types of catalysts are employed in the ISOM process as under:

a. Platinum (Pt) on chlorinated Alumina support catalyst: This type of catalyst has very high activity and operates at a lower Reactor Inlet Temperature (RIT) (~120 - 140°C). However, it is highly susceptible to even very low levels of contaminants. This catalyst requires continuous chloride dosing and, consequently, a downstream chloride treating facility such as a caustic scrubber.

b. Pt on zeolite support catalyst: This type of catalyst has lower activity and operates at a higher temperature (RIT of 242-262°C). It is very robust with respect to tolerance to the contaminants.

The new Catalyst that has been jointly developed by IOCL R&D and Viridis Chemicals falls into a new third genre of catalysts and can be categorized as 'Pt on Mixed metal oxide support'. This catalyst offers a unique advantage in comparison to the conventional types of catalysts as it possesses better tolerance towards feed impurities compared to the chlorinated alumina catalyst and has significantly higher activity in comparison to the zeolite-based catalyst. Further, it does not require the continuous dosing of chloride, which leads to acid formation (HCl) downstream of the reactor. This process

[1]S&P Global, Commodity Insight Annual Strategic Workbook 2024

advantage facilitates the use of this catalyst in units that do not have the material of construction suitable to handle acids. It also reduces the costs associated for downstream processing of the effluent due to acid generation in the reactors.

IndianOil's Bongaigaon Refinery (BGR) operates 153 kTA ISOM unit for improving the octane number of feed comprising light straight run naphtha and light reformate. This ISOM unit was designed with Pt on zeolite support catalyst considering the non-availability of any feed pre-treating facility and to utilize the then existing idle Xylene Isomerization & Fractionation units for the ISOM project. The jointly developed 'Pt on mixed metal oxide catalyst' was chosen as the target candidate to replace the existing catalyst in order to increase the RON and yield of the isomerate.

Catalyst Development and Background

Lab development

The project started with the development of the catalyst recipe on a lab scale. Different catalyst formulations were prepared at the lab scale in 10-50 g batch sizes and evaluated to assess the performance. Based on the evaluation results, the best formulation is selected for further scale-up. The repeatability of the catalyst performance was also established, and the same was found to be satisfactory.

Catalyst Scale-Up & Pilot Scale Validation

The finalised catalyst formulation was scaled up in two batches of 50 kg size for the support material, out of which platinum loading was done on a 5 kg sample from each batch of support material. The performance evaluation of the samples from both batches was carried out in Isomerization Bench Scale unit with different Naphtha feeds. The Scaled-up catalyst was found to be meeting all the desired performance criteria. A detailed study was done using the pilot scale data to establish its commercial feasibility.

Feasibility study for Bongaigaon Refinery

The scaled-up batch catalyst was also tested for long long-duration run (> 1000 h) using actual BGR feed in a pilot plant to assess the performance and operational stability of the catalyst. Additionally, the catalyst was tested against various impurities, including moisture, CO/CO2, and sulfur, to check its sensitivity towards these contaminants and its effect (both temporary and permanent) on the catalyst activity. It was observed that the catalyst was susceptible to the presence of high moisture in hydrogen (>2 ppmv). Hence, after reconfirmation through long-duration multiple experiments, a hydrogen dryer was proposed for consideration in this technology. The catalyst demonstrated superior tolerance towards feed contaminants in comparison to the traditional Pt on chlorinated alumina support catalyst. The tolerance limits of this Catalyst for various contaminants are given in . A trademark 'IV-IZOMaxCAT®' on the jointly developed catalyst, ready for commercialization, is filed and granted by the Indian Trademark Office.

Table 1: Contaminants limits for IV-IZOMaxCAT®

Parameter Specification	Maximum limit
Fresh Naphtha Feed	
Total Sulfur	5 ppmw
Total Nitrogen	0.5 ppmw
Moisture	5 ppmw
Heavy Metals	1 ppbw
Benzene + Toluene	6 wt%
C7+ Hydrocarbons	10 wt%
Make-up Hydrogen	
Hydrogen Purity	70-80 vol%
Moisture in hydrogen	2 ppmv
Chloride content in hydrogen	0.5 ppmv
CO+CO2 in hydrogen	20 ppmv

Implementation at Bongaigaon Refinery

The ISOM unit at BGR was licensed by IndianOil-R&D jointly with EIL for the production of BS-III & BS-IV quality MS along with benzene saturation in 2011. The Pt on zeolite support catalyst, sourced from a foreign licensor, has been in operation since the commissioning and was due for replacement in 2024. Based on the positive, successful outcome of the feasibility study with BGR ISOM naphtha feed, it was decided to replace the zeolite-based catalyst with IV-IZOMaxCAT®. 23 MT of the Catalyst was manufactured in 12 lots, each of ~2 MT in size. Each lot of the Catalyst is tested against performance and physicochemical properties at IndianOil R&D. Based on satisfactory performance of each Catalyst lot, clearance is provided for the dispatch of the Catalyst to BGR. The overall quantity of the Catalyst used was significantly lower than the previously used zeolite-based catalyst, owing to the superior performance of IV-IZOMaxCAT®. The feed for the Isomerization unit at BGR consists of light straight-run naphtha, along with light reformate. The hydrogen from the Catalytic Reforming Unit (CRU) was used as a make-up hydrogen stream in the BGR ISOM unit. The Catalyst was loaded in May 2024, and the feed cut was done in June 2024 (Figure 2).

The catalyst was successfully demonstrated, meeting all guaranteed parameters during the Performance Guarantee Test Run (PGTR). The performance of the Catalyst during PGTR is given in Table 2.

Table 2: Performance matrix of IV-IZOMax$^{CAT®}$ at BGR

Parameter Specification	Guarantee Values	PGTR Value
Isomerate RON	86	86.7
Isomerate Yield, wt%	94	97.3
Benzene in Isomerate, wt%	Max 0.1	Below detectable limit

Figure 2: Successful commercialization of IV-IZOMax$^{CAT®}$ at BGR ISOM unit

Advantages of IV-IZOMaxCAT® Catalyst

Energy Consumption: ISOM unit's operation at the reactor inlet temperature (RIT) of 135°C with IV-IZOMax$^{CAT®}$, in contrast to the RIT of 242°C with zeolite-based catalyst, results in a significant reduction in energy consumption, as a direct benefit of the lower operating temperature.

Environmental Impact: The catalyst's ability to operate efficiently at lower temperatures can lead to reduced greenhouse gas emissions from the burning of fuel gas in the furnace. This results in a net reduction of CO_2 emissions by 2.5 KTA at the BGR ISOM unit. Furthermore, the reduced operating temperature directly reduces the by-product formation (resulting due to cracking). This leads to an increase in the overall conversion efficiency and reduces the wastage (due to flaring).

Octane Number & yield: IV-IZOMax$^{CAT®}$ has demonstrated an ability to produce high-octane isomerate product with concomitant improvement in its yield exceeding that produced using zeolite-based catalyst. The isomerate octane improves from ~84 to 86, and the product yield improves from ~91% to 97% using IV-IZOMax$^{CAT®}$ in comparison to zeolite-based catalyst.

Benzene Saturation: Enhanced benzene saturation has been achieved, contributing to the overall improvement in gasoline quality.

Economic Benefits: With the increased yield and reduced FG consumption due to the lower RIT of IV-IZOMax$^{CAT®}$ in comparison to zeolite-based catalyst, ₹ 37 crore per annum of additional savings are envisaged at BGR.

Future Prospects

IV-IZOMax$^{CAT®}$ catalyst enables refiners to produce higher quality gasoline blending stream cost-effectively. Given its substantial advantages over zeolite-based catalysts, this technology has the potential to replace 112 zeolite-based catalyst ISOM units globally, representing an estimated market of ~3000 MT of catalyst.

Conclusion

The IV-IZOMAX$^{CAT®}$ at Bongaigaon Refinery ISOM unit is a true showcase of indigenous technology as all the activities, from catalyst development to commercialization in the ISOM unit, are based on the efforts by IndianOil and Viridis. The successful demonstration of IV-IZOMAX$^{CAT®}$ technology has not only added a new feather in the cap for IndianOil as 'Technology Provider' but also given confidence to the Refining industry in India as a whole to adopt indigenous technologies in line with the true spirit of “Make in India”. The catalyst offers numerous advantages, including superior product RON, energy efficiency, operational savings, and environmental benefits. The successful implementation at BGR serves as a compelling case study, demonstrating the catalyst's potential to enhance the production of high-quality gasoline.

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Petrochemical Intensity of Future Refineries and Crude-to-Chemicals

Shri Rajesh Rawat, Head Olefins Business &
Shri Amit Chaturvedi, President,
Petrochemicals Operations;

Reliance Industries Limited

Crude oil refineries, traditionally, have focused only on fuels sector – be it transportation sector or heating fuels for both industrial and personal applications. Not long ago, one of the biggest concerns of experts in this industry, used to be depleting crude reserves. This was expressed in years of oil remaining in difference reservoirs all over the world. But exploration & development of new reserves along with huge focus on renewables and their continuously rising usage because of environmental concerns has resulted in slowdown in growth of fossil fuel consumption. Thus adding years of residual oil. Development in shale oil recovery, horizontal drilling and fracking made such reserves throwing new suppliers to the oil market. In recent times concerns are more on the sustainability of oil demand instead of supply. With improved efficiencies in mobility fuels as well as boost in Electric vehicles sales have started seeing stagnation or decline in its growth rates. Impact on Gasoline demand is already being felt and its not long before technology starts impacting HSD consumption also. China reported peaked its gasoline demand towards end of 2024 as more than half of personal vehicles sold in the country were Electric Vehicles. Exponential improvements in battery technologies and sharp reduction in their costs have made Electric Vehicles affordable. Demand declines for gasoline and in some cases also diesel have been reported from countries like Japan as well as European nations. Oil experts have already started projecting mid 2030s as global peak oil demand. In other words, biggest challenge for the refineries industry is expected to be management of situation arising because of impact on transportation fuel demand.

Refinery economics is measured in terms of Gross Refinery Margins (GRM) and is function of demand supply of refinery products and more so of the complexity of the refinery in case of specific unit. Petrochemical prices are typically one order higher than fuels, which in many cases are feeds for petrochemical units. Naphtha, LPG, Off gases are common Petrochemical feedstocks. Major commodity petrochemicals include

- Olefins – Ethylene, Propylene and Butadiene/ Butene derivatives
- Aromatics – Benzene, Toluene and Xylenes derivatives as basic chemicals.

The downstream derivative petrochemical industries from these basic chemicals are Polymers (Plastics), Elastomers (Rubbers), Polyesters (Fabrics, PET bottles & films) and Solvents (Paints, resins, etc) all of which have shown good demand growth typically linked to GDP of the country / region. These products are mainly materials used in applications like packaging, infrastructure like pipes (for water & sewage movement), profiles, furniture, irrigation, automobiles (body and tyres), clothing, upholstery and many similar uses which enhance quality of life of common man. With rising global economic growth, demand of these lifestyle products continues to grow and likely to stay on this path for years to come.

Raw material for the petrochemicals is sourced from Refinery: Off-gases, LPG and Light Naphtha are key raw material for Olefins production and Heavy Naphtha or Reformate is the raw material for Aromatics. Traditionally petrochemical plants were built close to the refineries or near ports for ease of raw material supply. Refinery integration with Petrochemicals, especially if co-located, results in value addition of Hydrogen from crackers into refinery, value addition of refinery off gases in crackers and also provides multiple feed options for petrochemicals. It also opens up opportunities of process/ heat integration for the combined entity thereby adding significantly to bottom line.

Global Petrochemical majors like Exxon, Shell, Total, etc conventionally also had presence in refining and upstream oil exploration. Such companies had wider visibility of upstream and downstream businesses and were the early and logical integrator of the two businesses and industries. Refinery – Petrochemical integration journey started with Propylene production from Fluidised Catalytic Cracker Units (FCCs) with Propylene yield improving from around 3-4% levels in early units to 20% plus propylene production with High severity operation and technological development in its catalyst. The other prominent integration is in adding Aromatics plants at the refinery complex to add value to the reformate stream. In the refinery, reformate is used to blend in gasoline pool but in petrochemical unit the stream enhances its value by extracting its components namely Benzene, Toluene and Para / Ortho Xylene. Going further in the integration journey is when off-gases from refinery stream is used as petrochemical feed and cracked to produced olefins like ethylene, propylene, butene & butadiene. This integration has led to improved profitability for refinery.

Petrochemical Intensity refers to percentage of crude converted into petrochemicals. Traditional refineries when forward integrated to petrochemicals would convert 10-15% of their crude oil processed to petrochemicals mainly via propylene and aromatics. The trend is now gaining pace to increase this intensity further with new units built at 40-60% petrochemical intensity and further in plans to up to around 70% - 80% with Crude to Chemicals projects. Crude Oil to Chemicals (COTC) is basically an integrated refinery designed with Refining and Petrochemical processes to maximize chemical production directly from crude oil, bypassing or minimizing refining fuels products. Saudi Aramco is building Crude to Chemical complexes in Saudi while Sinopec is already operating a few units in China. Lummus today offers technology for such integration as TC2C (Thermal crude to Chemicals).

One of the challenges in crude to chemical complex is its size in terms of petrochemical output. Recently built units with petrochemical intensity of 40-60% are mega scale Aromatics and Olefins Plants. The capacity of such new Para Xylene plant in Asia now constitutes around 7-8% of global demand and hence their shutdown results in significant disruption in the products supply chain. Due to large capacity of a every single unit, commissioning of few such units has resulted in massively oversupplied market in these products. Global operating rates have therefore got depressed resulting in the longest trough in the business cycle. Apart from this, the Capex intensity of these complexes are also very high and hence requires large up-front investments by the respective companies.

Technology too offers challenges especially if we are looking at processing variety of crudes like heavy, sour or acidic. Petrochemical process reactions are sensitive to many impurities like heavy metals, sulphur, etc. Crude to Chemical unit with plans of 70% petrochemical intensity are required to keep developing and enhancing their technology keeping in mind these challenges. Technological development and its implementation takes time and that would see the litmus test of achieving the goals of this integration within the next decade.

Sustainability (circular economy), recycling and decarbonisation pressures will also be one of the challenges for future petrochemical intensive and crude to chemical units. Various processes these units viz High severity catalytic cracking, steam cracking of crude or heavy streams, hydrocracking, reforming, etc are all high energy guzzlers. Environmental impact would continue to put pressure on making them energy efficient and lowering their carbon footprint. Plastic Recycling potentially can impact virgin petrochemical demand.

Going forward, in the long-term petrochemical output as percentage of crude oil throughput is bound to increase as petrochemical demand growth outpaces fuels products demand. Integrated refining and petrochemical will continue to dominate with more refineries diversifying downstream and further building complexes from Crude Oil to Petrochemicals without or minimal fuels products. This is a strategic shift for companies in the hydrocarbon business which we will witness over the next decade. This would potentially transform the refinery companies and diversify them into new downstream businesses.

Disclaimer: The views, opinions, and statements expressed in this article are solely those of the author(s) in their personal capacity.

15 Predictive Maintenance and Asset Integrity in Smart Refineries

Shri Jayanti Vagdoda,
Vice President (Maintenance)
Nayara Energy Limited

Oil & Gas sector has grown rapidly in India fueling the energy requirements of 1.4 billion people. Refineries and Petrochemical complexes continue to be backbone of Energy security and provide feedstock to many small & medium scale industries contributing significantly to Industrialization of Indian economy and generating employment. Process Industry being a confluence of mostly all streams of Engineering & other Streams and requires skilled manpower for Operations and upkeep of Industrial Hubs. Refineries and Petrochemical Complexes are expanding with growing energy needs, adding value to economy.

Refineries and Petrochemicals complexes have been embracing technological advancements and keeping pace with market requirements to meet growing demand of energy in the country, Specialty chemicals and new materials. Safe, Efficient & Reliable operations of many of these large-scale Refineries and Petrochemical Complexes which are benchmarked consistently in Quartile 1 in majority of parameters requires them to consistently improve their performance overtime by investing in themselves. Development of Systems, Processes and Procedures along with integration of Technology is critical for Refineries & Petrochemical complexes to become Smarter & Agile and transform into World Class Manufacturing facilities.

Characteristics of Smart Refineries:

A smart Refinery uses Plant digitalization, data-driven decision making and extensive simulation in addition to conventional Refining operations for maximizing the value creation. Reliability and availability of equipment's plays a vital role in Safe and Sustainable Refinery Operations.

Below are the key foundation pillars in transformation of Refinery to Smart Refinery:

- **Visionary Leadership**

  Visionary leadership involves inspiring and motivating others to pursue a long-term vision, focusing on future goals and making significant changes. It's characterized by a clear understanding of the future, innovation, and a desire to create a positive impact, often challenging existing ways of doing things.

- **Strong Data Management**

  Strong data management involves implementing processes and strategies to ensure data is accurate, consistent, secure, accessible, and readily usable for business purposes. It encompasses aspects like data governance, quality, security, and access control, ultimately driving better decision-making and business outcomes.

- **Skilled Resource**

  A "skilled resource" refers to an individual who possesses the necessary knowledge, skills, and experience to effectively perform a job or task. They are often trained, well-educated, and capable of working independently and efficiently. Skilled resources are vital for organizational success and can contribute to the overall development of a country.

- **Systems and Infrastructure**

  A digital refinery leverages digital technologies to integrate and optimize refinery operations, including IT and OT systems. This involves creating digital twins of assets, using advanced analytics, and implementing automation to improve Efficiency, Reliability, Process safety and Overall Safety.

Asset Integrity Eco System:

Classification of Mechanical Static & Rotary Equipment's and Electrical & Instrumentation systems is important for a Smart Refinery. The processes for maintenance of every system and its upkeep are critical for Process Safety and Reliability of Refinery Operations.

Equipment classification and data availability:

To establish an Asset centric system, equipment details with micro data availability is very important. Structure databases enable analysts to take key strategic decisions. Four major categories can be created to cover majority of the equipment's i.e. Static, Rotary, Electrical & Instrument. Each category is further classified into two sub-levels of Class and Type. For example Rotary Category can be further classified as Pumps and Compressor (Class) and Overhung Centrifugal Pump (Type). Maintenance and Spares Strategies are developed based on these classification.

- **Effective Maintenance Strategy implementation:**

  Maintenance of Systems and Equipment's is categorized into four sub groups for better implementation

  a. *Preventive Maintenance:*

     Preventive Maintenance (PM) is maintenance that is regularly performed on equipment to reduce the probability of failure and identify potential failures in advance. This is generally applicable to equipment having a standby.

  b. *Predictive Maintenance:*

     Predictive Maintenance (PdM) is maintenance that monitors the performance and condition of equipment during normal operation and support the decision making for its corrective maintenance and reliability improvement. Rotary and Electrical Equipment are covered in Predictive Maintenance.

→ **Rotary Equipment:**

Following activities are covered under Predictive Maintenance (PdM):

i. Online Condition Monitoring (Vibration & Temperature Measurement)

   Critical Assets based on high maintenance cost and Operation priority are covered. These system captures and displays the data 24x7 and Alarms and equipment tripping along with diagnosis charts that can help for prediction of fault well in advance and tripping can be set to protect it. System-1 of M/s GE for Online Vibration and Bearing Temperature measurement have been installed in all Single Line Super Critical Assets.

ii. Off-line Vibration Monitoring

   The equipment which are classified under Super Critical, Critical and Semi-Critical category have been included for predictive maintenance. Its monitoring frequency is mainly driven by the criticality.

iii. Lube oil Analysis

   Lube oil is like a blood to equipment, which reduces friction, removes the heat and avoids metal to metal contact. Lube oil properties (Viscosity, Viscosity Index, Moisture, Total Acid Number (TAN), Flash Point, etc.) affect equipment reliability and hence are being measured periodically. Information of equipment wear and tear can be obtained from wear particle from the lube oil. Wear Debris Analysis, Spectrography, RPVOT (Rotating Pressure Vessel Oxidation Test) are the test being performed. Equipment sump size and criticality is the selection criteria for covering any equipment lube oil under monitoring plan. Monitoring compliance is being measure monthly to ensure coverage of defined equipment vibration measurement.

iv. Look, Listen & Feel (LLF) Practice

   LLF Rounds are taken for equipment which are being monitored in MTBF:

   - Centrifugal Pumps
   - Reciprocating Compressor
   - Axial Fin-fans

Equipment which are in continuous operation, specific LLF sheets for Centrifugal Pumps, Reciprocating Compressors and Axial Fin-fans have been prepared and being filled by Plant Maintenance Technicians.

→ **Electrical Equipment:**

a. Health assessment of Transformer and Transformer oil through periodic testing.

- Oil testing: Dissolved Gas analysis, Breakdown Voltage (BDV), PPM, Furan test, Oil screen testing.
- Transformer tests: Online partial discharge test, Magnetic balance.

Based on these tests, a health index for the transformer is prepared, and necessary maintenance plans are implemented. Additionally, online moisture removal from transformer oil is performed.

b. Health assessment of High Tension (HT) Cable / HT Switchgear.

Health assessment of HT cables and switchgear includes Online Partial Discharge tests which detect early issues and eliminate problematic components in the power system.

c. Health assessment of Battery System.

Health assessment of plant batteries involves bi-monthly condition monitoring of AC/DC UPS and its battery bank. Periodic discharge tests are conducted to assess the residual life of the batteries. Based on preventive maintenance parameters and discharge tests, replacement schedules are determined.

d. Reliable source of power availability.

Ensure uninterrupted electrical system performance when any incoming power supply fails by seamless power transfer to motor bus through Fast Bus Transfer schemes. Reliability governance of the power system protection requires routine checking of numerical relays and their operation, testing of relay and control circuits through primary and secondary injection tests along with unit protection scheme checks.

e. Motor Condition and Reliability Evaluation Program

Motors are critical assets of the electrical network, being responsible for driving all rotating and reciprocating machines. Their safe, reliable & efficient operation is essential. Due to their dynamic nature, they are much more prone to failures than static equipment. The best way to prevent such failures and maximize their efficiency is to use motor testing services that combine several Online and Offline diagnostic techniques like Electrical Signature Analysis, Partial Discharge Analysis, TanDelta and Capacitance Analysis to assess their condition.

f. Integrated and Intelligent Electrical Protection System

In this project, we established a centralized remote access and management tool for protection relay management. This tool can track, monitor, and automatically validate relay settings, generating validated setting files that authorized personnel can upload to relays via OEM software. The tool includes an advanced relay health assessment to prevent failures.

Benefits:

- Prevent mal-operation of protection systems due to incorrect relay settings or erroneous protection schemes.

- Enhance root cause analysis efficiency for electrical incidents.
- Aid compliance with international power system protection standards like NERC.
- Validate changes in relay settings for modifications in electrical network configurations.

c. *Corrective Maintenance:*

Unscheduled repairs affecting equipment availability are restored with high priority and its maintenance history is captured in ERP system like SAP to have data base for time bound RCAs (root cause analysis) and defined path forward.

d. *Turnaround Maintenance:*

Extensive Inspection and Maintenance of Refinery Units / Equipment's is carried out during perioding Turnarounds. Frequency of Turnaround of Refinery is decided based on Plant Physical conditions, Healthiness of Catalystic systems, Business & Statutory requirements Generally, Turnaround frequency varies from 3 to 5 years depending upon the configuration and robustness of the Refinery.

Usage of Advanced Predictive Maintenance Methodologies:

- **Reliability Centered Maintenance (RCM):**

Reliability methodologies like Reliability Centered Maintenance (RCM) & Asset Strategy Management (ASM) has started giving results in optimizing the maintenance cost and solutions to repetitive failures.

Reliability centered maintenance (RCM) is a corporate-level maintenance strategy that is implemented to optimize the maintenance program of a company or facility. The final result of an RCM program is the implementation of a specific maintenance strategy on each of the assets of the facility. The maintenance strategies are optimized so that the productivity of the plant is maintained & improvement in Reliability using cost-effective maintenance techniques.

There are four principles that are critical for a reliability centered maintenance program.

a. The primary objective is to preserve system function

b. Identify failure modes that can affect the system function

c. Prioritize the failure modes

d. Select applicable and effective tasks to control the failure modes

- **Risk Based Inspection (RBI):**

The inspection department at Nayara Energy Limited has experienced a significant transformation through the digitization of its operations. By incorporating advanced inspection technologies, such as corrosion sensors, Inspection Management (IM), Thickness Monitoring (TM), and Risk-Based Inspection (RBI) through GE APM, the company has revolutionized inspection processes. These tools provide precise and efficient evaluations of asset conditions, optimizing inspection procedures both during in-service periods and turnaround intervals, thereby enhancing efficiency and saving time. Additionally, Nayara Energy Limited has developed an in-house tool for tracking inspection requests and managing QA/QC contractor audits as part of the Refinery QA/QC Inspection & Record Management System. Furthermore, we have developed the RPMS tool for managing Integrity Operating Windows (IOWs).

a. **Corrosion Monitoring through online probes & sensors:**

At Nayara Energy, we are monitoring corrosion using various online probes, including Electrical Resistance (ER) probes, Field Signature Method (FSM), and Permasense sensors.

ER Probes: Reduction in the element's cross section due to corrosion results in a corresponding increase in the element's electrical resistance. This principle is utilized to monitor the corrosion activity of fluid in ER systems. It can also be retrieved in an online condition for ease of maintenance.

FSM: It is based on electrical conductivity. The technique involves passing a controlled

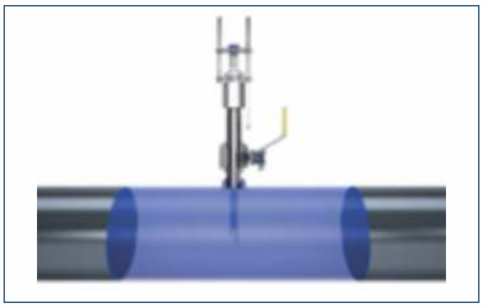


Fig. Schematic of ER probe system.

excitation current through the structure to establish a unique electric field pattern. This is non-intrusive sensing pins which are distributed over the areas to be monitored and detect changes in the electrical field pattern.The resulting voltage is measured for a fixed pin pattern and any change in conductivity will cause a change in the field pattern, i.e., Uniform metal loss will cause increase in field pattern / strength.

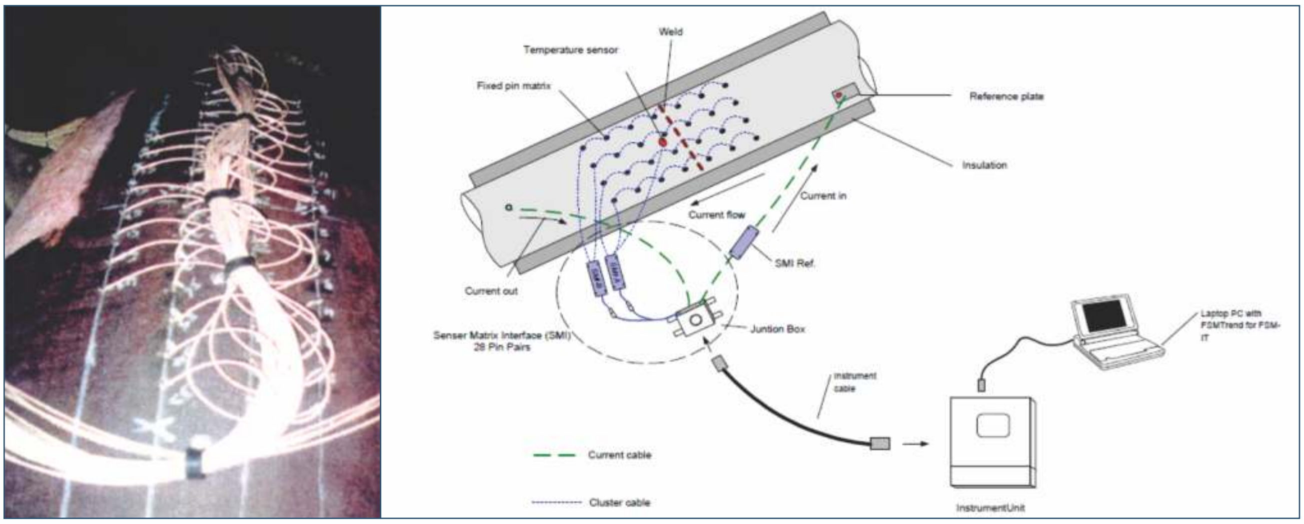


Fig. Pin matrix & schematic for FSM system.

Permasense: These sensors works based on well-proven Ultrasonic principles but unique in that they mounted on stainless steel waveguides, Permasense's GT W210 sensor gives reliable data up to 600^{o}, It is useful for measuring the actual thickness of systems.

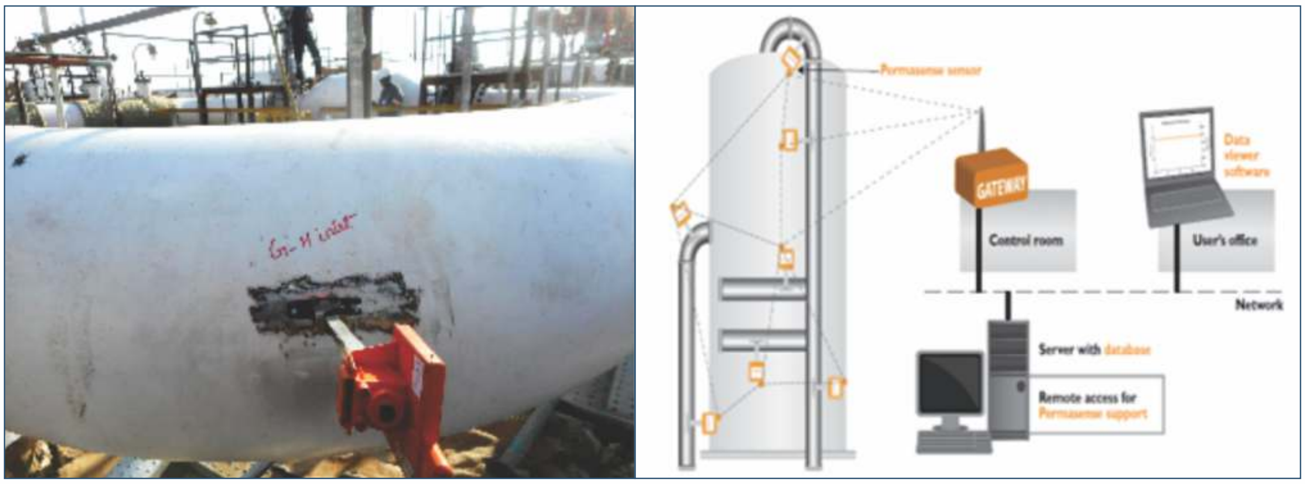


Fig. Site installation & schematic for Permasense system.

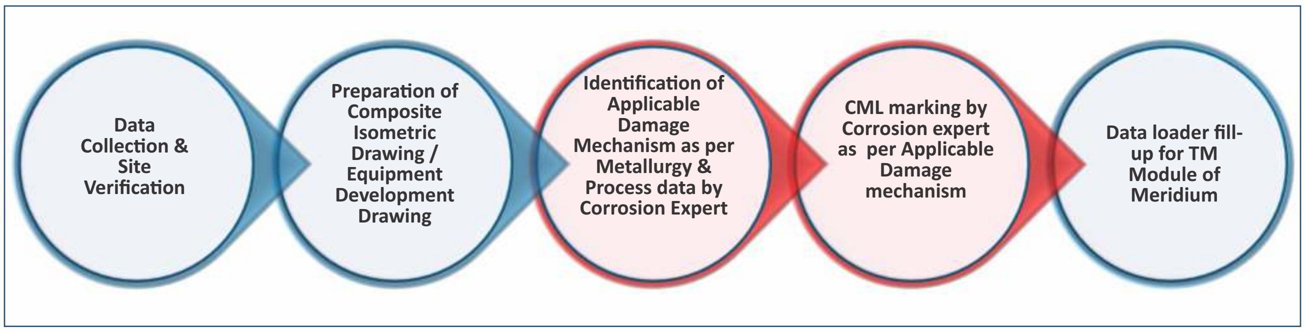
Corrosion Coupons: This traditional technique, is highly effective for directly measuring metal loss, allowing for the calculation of general corrosion rates through the weight loss method. Additionally, the coupon surface is examined for pits, microbial growth, and deposit composition.

Fig. Coupon installation and corrosion coupon rack setup.

b. Data Analytics and Reporting:

Digitalization facilitates the collection and analysis of extensive data, yielding valuable insights into asset performance management within the Inspection Management and Thickness Monitoring module of GE APM. Through Inspection Management, we can efficiently track all inspection plans and maintain comprehensive inspection records. The processing of inspection recommendations via recommendation management through SAP enhances monitoring capabilities. Additionally, the ease of data retrieval and the maintenance of historical inspection records contribute to its user-friendliness.

Earlier inspections were conducted at random locations, providing information solely about the current condition, with no data available for corrosion rate or thickness trending. The Thickness Monitoring Module of GE APM is a tool designed for trending thickness readings and assessing remaining life. To utilize the benefits of the TM module, it is necessary to identify Corrosion Monitoring Locations (CMLs) for all static assets and piping. We have therefore standardized and digitized CMLs using the following methodology.



- **Root Cause Analysis:**

  Equipment or Process failures are rigorously analyzed using various techniques. Availability of various digital data and logbooks are important source to identify the problem and its analysis provides an insight to avoid repetition in similar Processes and Equipments. RCA process involves a Multi-disciplinary expert team which helps in identifying the real causes of any failures and recommendations are to be implemented in a time bound manner.

- **Training and Skill Development:**

  Training and Skill development programs help employees learn and acquire new skills and gain the professional knowledge required to meet the Organization & Individual Growth. Engineers and Front-Line Work force are trained by experienced Internal and External Subject Matter Experts with practical demonstrations.

Summary and Pathforward:

A robust, reliable and sustainable Maintenance & Inspection culture can be developed by adoption of proven technologies and advanced systems for continuous improvement of Asset Integrity. Data Historians, ERP integration (like SAP), RBI & RCM, RCA & System Failure analysis and Standardization of Material are essentials elements for a best performing Refinery & Petrochemical Units.

Smart Refiners are the one which Digitally transform with adoption of new Technologies in their journey towards Operational Excellence. Digitalization and Automation of Processes and Equipments is key for Asset Integrity, Maintenance and Inspection, Process Safety and Efficiency improvement.

Transformation with use technologies for complete digitalization of Process & Equipment monitoring with implementation of Artificial Intelligence (AI) and Machine Learning (ML) applications simultaneously in identified areas for Safe Operations & GRM improvement, Failure prediction, Unplanned Equipment breakdown and reduced Maintenance expenditures. Adoption and Integration of Digital Technologies with existing systems and training of Internal resources will define a Smart Refinery in future.

16 Advancing the Green Ammonia Value Chain, Green Methanol and Enabling Sustainable Aviation

Mr. Ralf Weishaupt and Mr. Christoph Krinninger, Business Development, Green Energy ,
Clariant Germany

Shri Aravind Narayanam, GM – Sales and Technical Services, Process Catalysts,
Süd-Chemie India

Catalysts are key to powering the global shift to cleaner energy, making it possible to produce low-carbon ammonia, green methanol, and sustainable aviation fuels. These next-generation solutions help decarbonize sectors like transport, power, and chemicals - building on what we already have while paving the way for a greener future. With decades of experience, Clariant/Süd-Chemie is proud to support this journey by developing innovative catalysts that make sustainable energy a reality.

The following are key areas where catalysts are playing a vital role in advancing the transition to cleaner, more sustainable energy solutions:

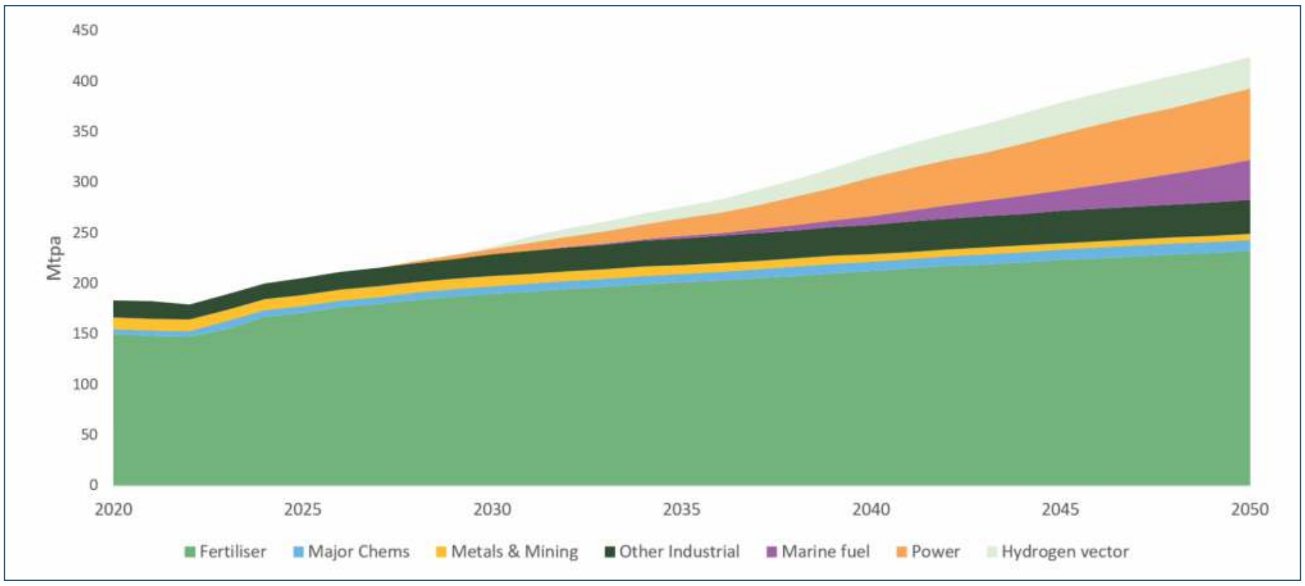
- Catalysts to Facilitate the Green Ammonia Value Chain
- Catalysts to Unlock Green Methanol
- Catalysts for a Sustainable Future of Flying

Catalysts to Facilitate the Green Ammonia Value Chain

The Future Market of Low-Carbon Ammonia

Low-carbon ammonia is poised to become a cornerstone of the global energy transition. As the world seeks to decarbonize various sectors, ammonia's unique properties position it as a versatile energy carrier with significant growth potential. The market is expected to expand beyond its traditional use as a fertilizer feedstock, with new applications such as ammonia as a marine fuel, a hydrogen carrier for long-distance transportation, and a fuel for power generation.

Expected ammonia demand:



Source: Wood Mackenzie, Lens Hydrogen, 2025

Green Ammonia Production

Traditional ammonia production using the Haber-Bosch process is carbon-intensive, accounting for around 1.8% of global CO_2 emissions. Green ammonia production eliminates these emissions by using hydrogen from water electrolysis powered by renewable electricity and nitrogen from air separation.

Key challenges:

- Fluctuating feed due to intermittent renewable sources
- High energy consumption needing reduction
- Catalysts that perform under variable conditions
- Operation at lower pressures to improve efficiency

Clariant/Süd-Chemie's AmoMax™ Series: Enabling Green Ammonia Production

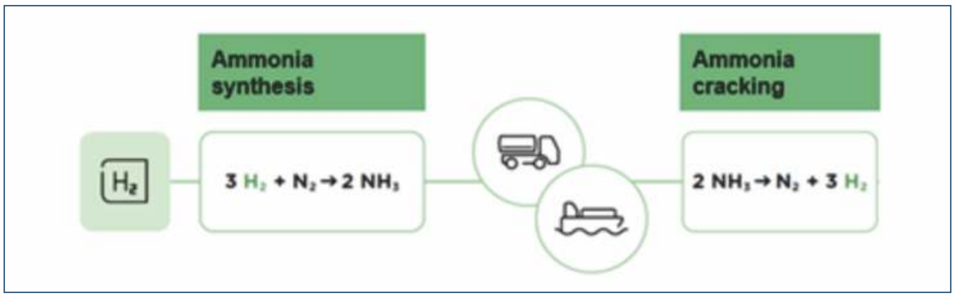
AmoMax ammonia synthesis catalysts address these challenges with:

- Higher activity for efficient synthesis
- Lower operating pressure requirements
- Enhanced water and oxygen resistance
- Stability under fluctuating feed conditions

With over 120 references globally, AmoMax catalysts are trusted in many green ammonia projects.

Ammonia Cracking: Unlocking Hydrogen at Point of Use

Ammonia cracking technology plays a pivotal role in the hydrogen economy. Since hydrogen is most economically produced in regions with abundant solar and wind resources - often far from industrial centres- ammonia serves as an ideal hydrogen carrier. Converting hydrogen to ammonia for transport and cracking it back at the point of use addresses this logistical challenge.



Ammonia cracking decomposes NH_3 into H_2 and N_2, essential for using ammonia as a hydrogen carrier.

Scale and Location Considerations:
Centralized Large-Scale Crackers:

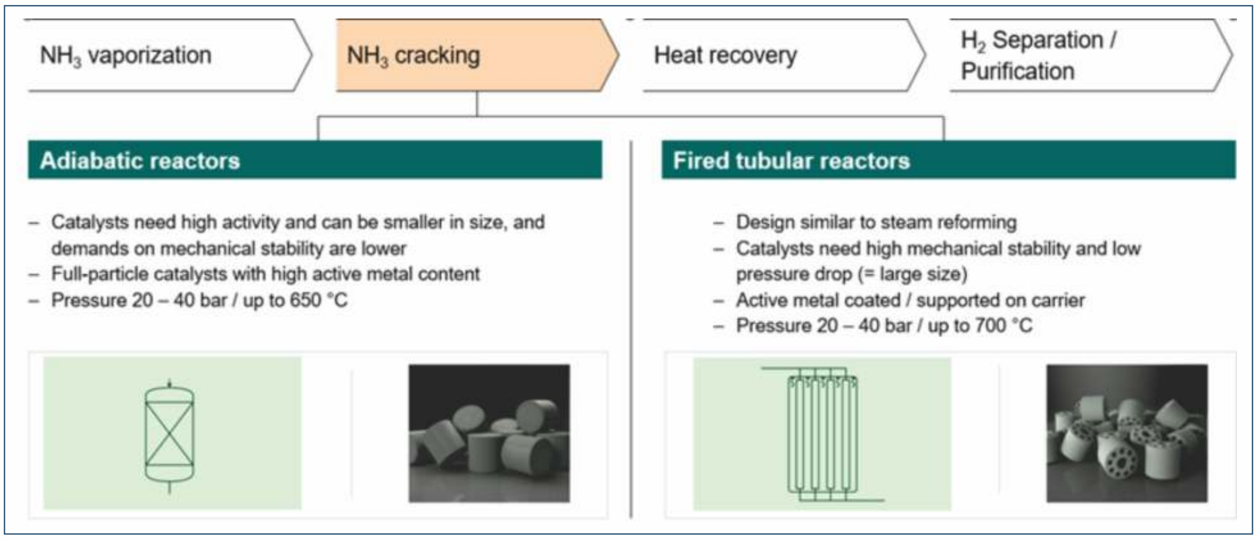
- Over 1000 MT/day capacity
- Located near ports and industrial hubs
- Serve industrial hydrogen and grid injection
- Require high-temperature nickel-based catalysts

Decentralized Small-Scale Crackers:

- Up to 100 kg/hr capacity
- Urban and refuelling station locations
- Support local hydrogen generation
- Require low-temperature ruthenium-based catalysts

Clariant/Süd-Chemie's HyProGen DCARB Series for Large-Scale Cracking

HyProGen DCARB catalyst series for efficient large-scale ammonia cracking:



- *HyProGen 820/821 DCARB:* Ideal for adiabatic reactors in industrial applications
- *HyProGen 830 DCARB:* Proven for reformer-type high-temp reactors in demanding conditions

These catalysts enable centralized hydrogen production for industrial clusters and energy grids.

HyProGen DCARB 850 for Small-Scale Cracking

For decentralized use, HyProGen DCARB 850 provides:

- High activity at low temperatures
- Excellent low-pressure performance
- Compact design ideal for urban stations
- Greater overall efficiency

It's especially suitable for hydrogen refuelling and distributed energy systems.

Green Methanol

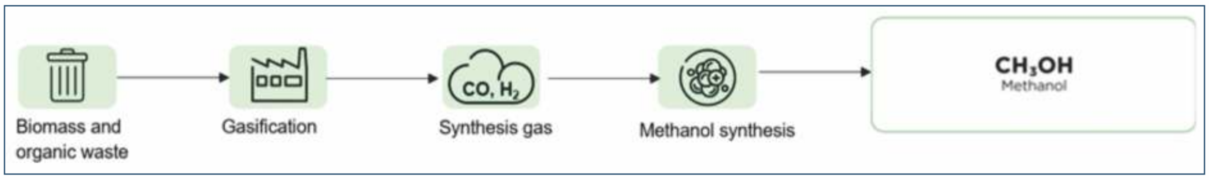
Renewable or green methanol is emerging as a critical component in the global energy transition, offering a sustainable alternative to conventional fossil-based methanol. Thanks to its versatility as a liquid energy carrier, green methanol is forecasted to grow substantially over the next two decades, providing a practical pathway to decarbonization across multiple sectors.

This carbon-neutral fuel can be used in marine shipping, road transportation, and power generation, while also serving as a valuable feedstock for the chemical industry. Its ability to be stored and transported using existing infrastructure makes it particularly attractive as a bridge to a more sustainable future.

At Clariant/Süd-Chemie, we have over 50 years of expertise in methanol synthesis and a clear commitment to developing innovative catalysts for the energy transition. We're proud to be at the forefront of this revolution, having our catalysts already operating in commercial-scale green methanol lighthouse projects.

Bio-Methanol

Bio-methanol is produced from renewable biomass sources, offering a sustainable alternative to fossil-based methanol. The production process involves:



Feedstock Preparation:

Bio-methanol can be produced from various biomass sources, including agricultural residues, forestry by-products, biogas from landfills, sewage, and municipal solid waste (MSW).

Gasification:

The biomass undergoes gasification, converting it into synthesis gas (syngas), a mixture primarily consisting of hydrogen, carbon monoxide, and carbon dioxide.

Purification of Synthesis gas: The purification is a crucial part of the process because biomass and waste sources contain numerous non-typical impurities and poisons (such as heavy metals, As, S, Cl, and others), which can deactivate the methanol synthesis catalyst. Clariant has extensive experience and a wide portfolio of purification catalysts and adsorbents, including the ActiSorb series.

Methanol Synthesis:

The syngas is then converted into methanol using specialized catalysts. MegaMax catalyst technology is particularly well-suited for biomass-to-methanol projects, providing the highest activity and enhanced stability to maximize lifetime productivity.

Clariant/Süd-Chemie offers the ActiSorb series catalysts for the purification of the syngas and the MegaMax series for methanol synthesis. The catalysts have been selected for several bio-methanol lighthouse projects, for example in China and Europe:

Taonan Green Methanol Project (China)

- China's first biomass gasification-to-green methanol project
- Production capacity: 250,000 TPA (two phases by 2027)
- Feedstock: Farm waste combined with wind power
- Construction of first phase began in March 2024
- Expected start-up: First half of 2025
- Uses Clariant/Süd-Chemie's MegaMax catalyst technology

Repsol Project (Tarragona, Spain)

- Production capacity: 240,000 tons per annum
- Feedstock: Municipal waste
- Final Investment Decision (FID) reached in January 2025
- Planned start-up: 2029
- Will utilize Clariant/Süd-Chemie's catalyst technology

E-Methanol

E-methanol represents an alternative pathway to sustainable methanol production, utilizing renewable electricity and capturing carbon dioxide. The production process includes:

Green Hydrogen Production:

Renewable electricity powers water electrolysis to produce green hydrogen, a critical component that distinguishes e-methanol from conventional production methods.

Carbon Dioxide Capture:

CO_2 is captured either from industrial point sources, BECCS, or directly from the air through DAC technologies.

Methanol Synthesis:

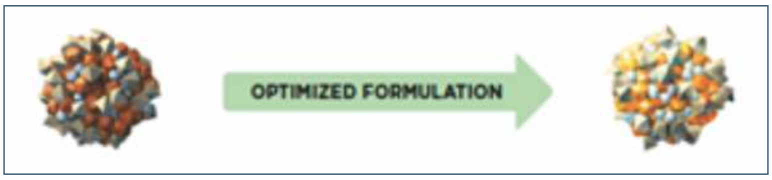
The captured CO_2 and green hydrogen are combined in a catalytic reactor to produce methanol. Clariant/Süd-Chemie's MegaMax catalysts have proven highly effective in this application, demonstrating excellent activity and stability despite the challenging conditions of CO_2-to-methanol conversion.

European Energy, Kassø, Denmark

- World's first and largest commercial e-methanol plant
- Production capacity: 42,000 tons per annum
- Feedstock: Biogenic CO_2 and hydrogen from electrolysis
- Uses Clariant's MegaMax 900 catalyst
- Started operations in March 2025
- Key customers include Maersk, Lego Group, Novo Nordisk

MegaMax 900 DCARB: Tailor-Made CO_2-to-Methanol Catalyst

Based on over 55 years of experience, Clariant developed the MegaMax 900 DCARB catalyst for direct e-methanol production from CO_2 and hydrogen.



The optimized formulation with an advanced microstructure provides exceptional physical robustness, increased number of active sites, a high turnover frequency (TOF), and an improved metal dispersion resulting in consistent, high-level performance over extended periods and higher hydrothermal stability than previous catalyst generations.

MegaMax 900 DCARB product benefits

- Higher activity
- Higher mechanical and hydrothermal stability
- Longer lifetime
- Low by-products make

Customer benefits

- Superior lifetime yield (typically 4 years)
- Lower operational costs
- Significant monetary benefits

Sustainable Aviation Fuels (SAF)

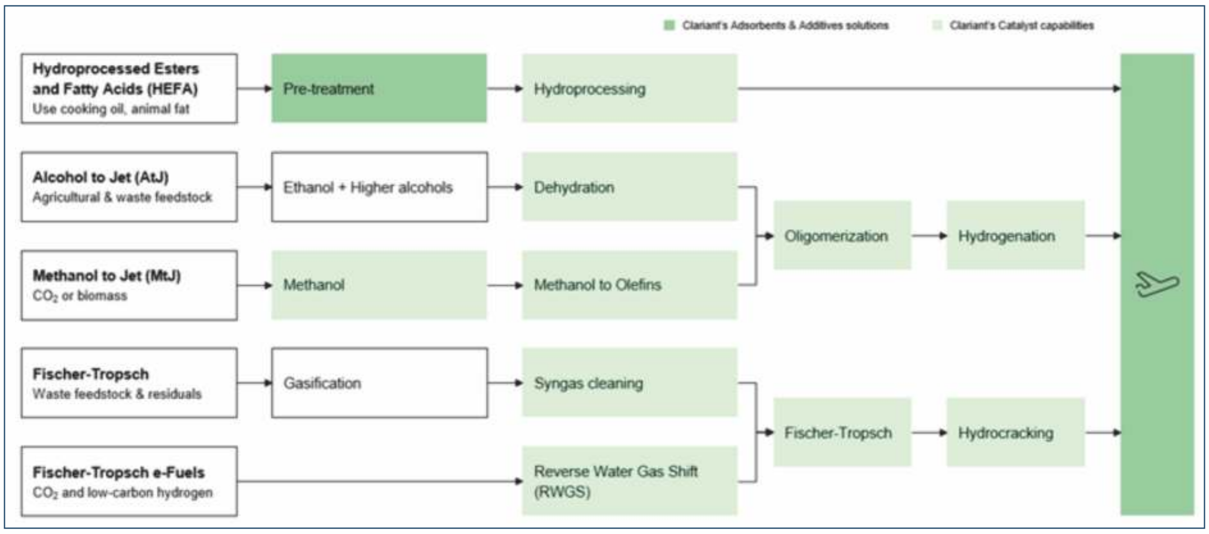
What are Sustainable Aviation Fuels?

As the aviation sector faces increasing pressure to decarbonize, SAFs have emerged as the most viable near-term solution to significantly reduce greenhouse gas emissions while maintaining compatibility with existing aircraft and infrastructure. Unlike conventional jet fuels derived from fossil sources, SAFs are produced from sustainable feedstocks such as waste oils, agricultural residues, and other renewable materials, offering a cleaner alternative that can significantly reduce lifecycle carbon emissions compared to traditional jet fuel.

Different Pathways to Produce SAFs

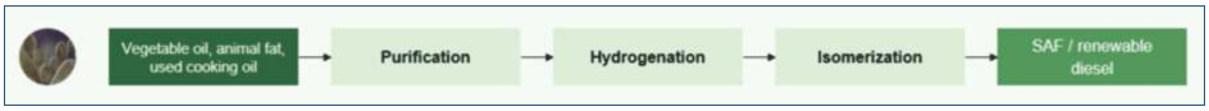
Clariant has developed a comprehensive portfolio of catalytic solutions for the major SAF production pathways:

- The HEFA route is ready now, but feedstock is constrained, preventing further growth in the next decade.
- Beyond 2030, technology readiness of Alcohol-to-Jet route (EtOH-base) and Gasification/ Fischer-Tropsch is expected to serve the growing demand.
- As a long-term solution to produce e-fuels from CO_2 and H_2 via power-to-liquid routes such as Methanol-to-Kerosene and Fischer-Tropsch synthesis.



HEFA Route and Clariant's Catalyst Options

The HEFA pathway is the most widely used commercial process for SAF production, converting bio-based oils and fats into drop-in jet fuel through critical steps:



1. Feedstock Purification with TONSIL™ Series Adsorbents

Process Function: Removes contaminants from raw feedstock that could poison downstream catalysts

Benefits:

- Highly effective adsorbents based on bentonite or attapulgite
- Precisely adaptable to feedstock requirements
- Effectively removes phosphor species, metals, soaps, chlorine, sugars
- Can reduce contaminants to below 1 ppm
- Meets high standards for processing

2. Hydrogenation with HDMax™ Catalysts

Process Function: Removes oxygen from triglycerides and breaks them into hydrocarbon chains

Benefits:

- Specifically designed for hydro-deoxygenation of bio-based feedstocks
- Enables breakdown into straight-chain hydrocarbons
- Optimized for high activity and selectivity

3. Isomerization with HYSOPAR™ Series Catalysts

Process Function: Converts straight-chain hydrocarbons into branched structures

Benefits:

- High isomerization selectivity at high conversion
- Minimizes product loss from cracking
- Improves cold flow properties essential for jet fuel
- Applicable for both bio-based and fossil feedstocks
- Based on Clariant's isomerization expertise

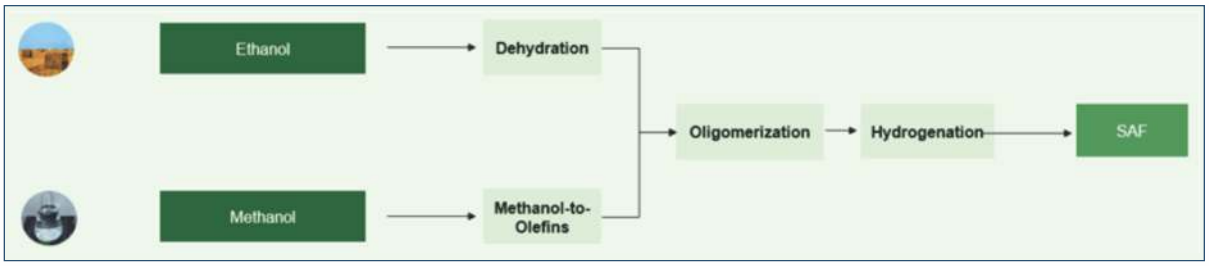
Alcohol and Methanol to Jet Routes

Alcohol-to-Jet (AtJ) Pathway

Utilizes alcohols from fermentation of agricultural residues and waste.

Methanol-to-Jet (MtJ) Pathway

Utilizes methanol derived from renewable sources or captured CO_2.



1. Ethanol Dehydration with ActiSorb 100 Series

Process Function: Converts ethanol to ethylene, the first building block for jet fuel

Benefits:

- Alumina-based catalysts optimized for high ethylene yield
- Enables the first step in transforming bioethanol to jet fuel

Methanol-to-Olefins Conversion

Process Function: Transforms methanol into olefin building blocks

Benefits:

- Clariant catalysts achieve ~95% conversion to SAF-relevant compounds
- Ongoing development for optimization

2. Oligomerization with SAFMax™ Series

Process Function: Builds longer hydrocarbon chains from ethylene or other olefins

Benefits:

- High selectivity for fuel-grade carbon chains
- Proven industrial performance
- Produces high-quality iso-paraffinic diesel/jet fuel
- SAFMax 300 for C2=, SAFMax 900 for C3+=
- Superior mechanical stability and activity

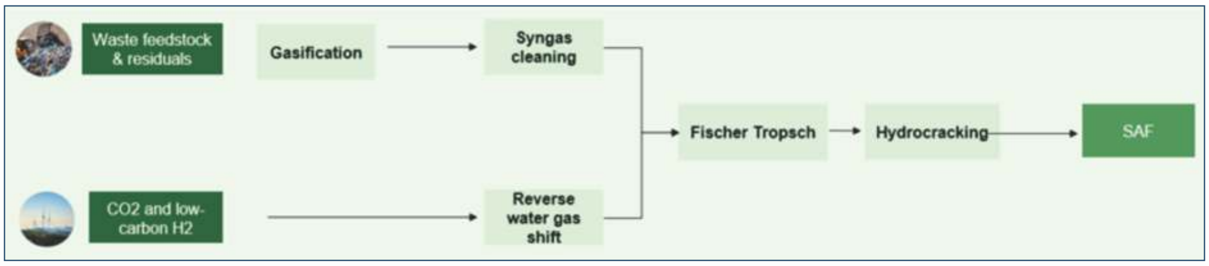
Hydrogenation with NiSAT™ Series

Process Function: Saturates olefins into stable paraffinic hydrocarbons

- Optimized nickel content (<50%wt)
- High poison and sulphur tolerance
- Shorter start-up, lower reduction temps
- Hydrogenates oxygenates and sulphur/nitrogen species

Fischer-Tropsch Pathways

Utilizes waste, residuals, CO_2, and low-carbon hydrogen:



1. Gasification and Syngas Cleaning

Process Function: Converts solid feedstocks into clean synthesis gas

Benefits:

- Clariant's catalysts support the production of SAF from waste feedstock and residuals

- Clariant provides specialized catalysts for syngas purification
- Enables the processing of diverse waste feedstocks into a consistent syngas intermediate

2. Reverse water gas shift

Process Function: Converts CO2 and hydrogen into syngas that gets further processed into liquid hydrocarbons and optimizes their properties

Benefits:

- ShiftMax 100 RE offers effective conversion of CO2 and hydrogen into syngas for e-fuels processes
- High selectivity to avoid methanation, high resistance against coking and high-temperature stability
- ShiftMax 100 RE is operating in INERATEC´s e-Fuels plant in Germany

3. Hydrocracking/Isomerization

HYSOPAR series enables the adjustment of hydrocarbon properties via Isomerization and/or cracking to produce high-quality synthetic paraffinic kerosene

17 Transforming Refineries for the Petrochemical Era

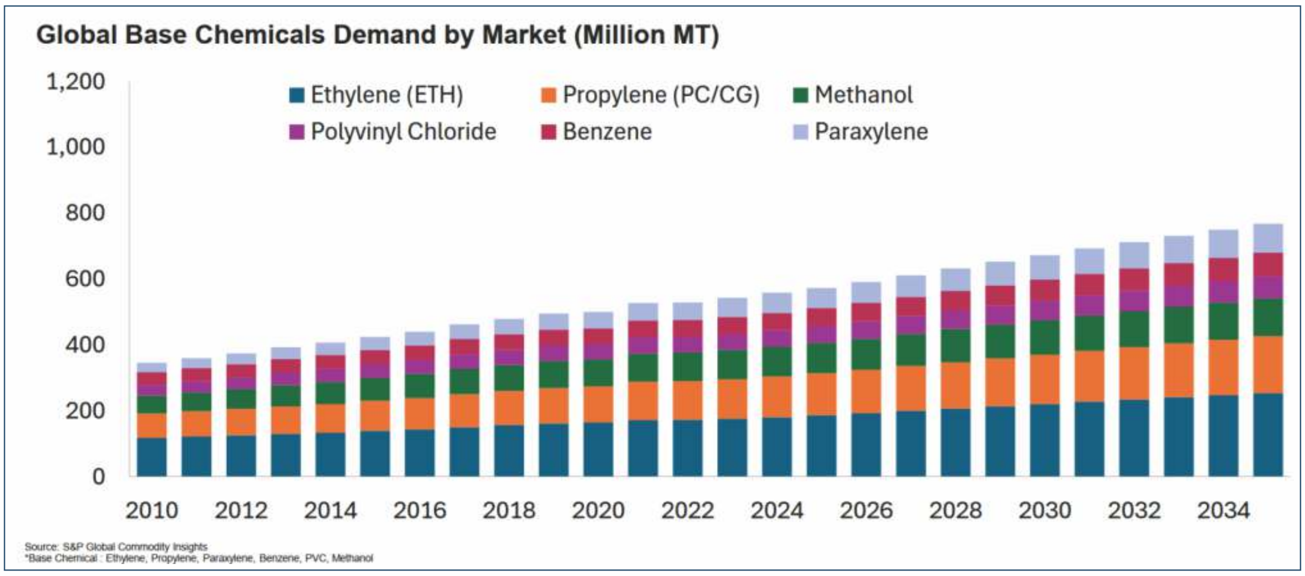
Mr Alexis PAILLIER, Lead Technology Engineer – Chemical Integration

Axens

Introduction: A Strategic Shift in Refining

The global refining industry is at a crossroads. As the world accelerates its transition toward cleaner energy and more sustainable consumption patterns, traditional fuel markets are entering a period of structural decline. Gasoline, diesel, and residual fuel oil—once the cornerstones of refinery output—are now facing diminishing demand, particularly in mature economies. This shift is not merely cyclical; it reflects a deeper transformation in how energy is produced, consumed, and valued.

In contrast, the petrochemical sector is emerging as a bright spot in an otherwise challenging landscape. Forecasts suggest that global demand for petrochemicals will continue to grow at a rate exceeding 4% annually over the coming decade.



Petrochemicals are essential to modern life, forming the building blocks of plastics, textiles, packaging, electronics, and countless other products. As such, they are expected to become the primary driver of crude oil consumption, especially in high-growth regions such as wider Asia.

This divergence in demand trajectories is reshaping the strategic priorities of refiners worldwide. Refineries originally designed for fuel production, with little or no petrochemical integration, are increasingly being shuttered in regions like Europe, North America, Korea, and Japan. These facilities struggle to remain competitive due to shrinking local fuel consumption, limited economies of scale in petrochemical production, and higher labor and regulatory costs.

In response, the industry is embracing a new paradigm: **maximum integration between refining and petrochemicals**. This approach aims to maximize chemical yields and improve profitability by shifting the product slate away from fuels and toward high-value petrochemical intermediates. Over the past decade, this strategy has given rise to a wave of ambitious **Crude to Chemicals (CTC)** projects, such as Hengli and Shenghong. These mega-complexes are designed from the ground up to convert a significant portion—50 to 70%—of crude oil directly into petrochemicals.

However, the path to full integration is not without obstacles. CTC projects typically require massive capital investments, often exceeding $20 billion, and involve long lead times and complex execution. In today's uncertain geopolitical and economic environment, such high-risk ventures are increasingly difficult to justify, especially in regions with limited access to low-cost feedstocks or financing.

As a result, the future of refining will likely follow a two-tiered path. A limited number of new, standalone Crude to Chemicals (CTC) complexes will continue to emerge in regions where the conditions are most favorable—namely, the Middle East, where access to low-cost feedstocks and available capital make such large-scale investments viable, and in countries like China and India, where strong petrochemical demand growth and efficient project execution—both in terms of time and budget—support continued development. However, these projects will remain the exception rather than the rule. For the vast majority of refiners, the focus will shift toward **revamping, repurposing, and expanding existing assets** to increase petrochemical output. This strategy is not only more capital-efficient but also essential for survival in a market where traditional fuel margins are under sustained and growing pressure.

The remainder of this article will explore the practical strategies available to refiners seeking to adapt from optimizing existing units for higher chemical yields, to deploying deep conversion technologies, and finally, to integrating modular petrochemical complexes into existing sites.

Optimizing Existing Assets

For most refiners, the most practical and immediate path toward petrochemical integration lies in the optimization of existing assets. Rather than building entirely new complexes, many are choosing to revamp and repurpose current units to shift product yields away from fuels and toward high-value petrochemical intermediates. This strategy offers a more capital-efficient route to competitiveness and can be implemented incrementally, allowing refiners to adapt to market changes without the burden of massive upfront investment.

One of the most effective levers in this transformation is the **Fluid Catalytic Cracking (FCC)** unit. Traditionally optimized for maximum gasoline production—typically yielding **45–55 wt% gasoline**—FCC units can be reconfigured to boost **propylene yields to 15–20 wt%**, compared to just **3–5 wt%** in conventional FCC operations. This transition—often referred to as moving from "maxi gasoline" to "maxi olefins"—can be achieved through catalyst selection, operating condition adjustments, and hardware modifications.

Another valuable strategy involves the **extraction of aromatics from FCC gasoline**. FCC gasoline contains a significant amount of aromatics such as benzene, toluene, and xylenes (BTX), which are essential building blocks for the chemical industry. By integrating extraction units or upgrading existing separation systems, refiners can recover these aromatics and redirect them into the petrochemical value chain, thereby enhancing the overall profitability of the FCC stream.

Similarly, **VGO hydrocrackers**, which are typically configured to maximize middle distillates like diesel and jet fuel, can be reoriented toward **naphtha production**. In a conventional setup, hydrocrackers may yield **above 80% distillates**, but with process adjustments and diesel cracking, **naphtha yields can be increased above 85%**, making it a valuable feedstock for steam crackers and/or aromatic complexes.

These revamping strategies not only improve product flexibility but also extend the economic life of existing assets. They allow refiners to respond more dynamically to market signals, shifting output toward higher-margin petrochemical products as demand for traditional fuels continues to wane. Moreover, these upgrades can often be implemented within the existing footprint of the refinery, minimizing permitting challenges and construction timelines.

In a market environment where capital is scarce and uncertainty is high, optimizing existing assets represents a pragmatic and strategic step forward. It enables refiners to begin the journey toward petrochemical integration without overextending financially—laying the groundwork for deeper transformation in the future.

Cracking the Heavy End: Deep Conversion for Petrochemical Growth

While optimizing existing assets offers a practical first step toward petrochemical integration, many refiners are also exploring deeper, more transformative solutions. **Deep conversion technologies** are designed to process the heaviest fractions of crude oil—such as vacuum residue and high-sulfur fuel oil—into lighter, high-value products like olefins and aromatics. These technologies not only reduce the production of low-value fuel oil but also significantly enhance a refinery's chemical yield.

One of the most established deep conversion technologies is **H-Oil®**, the original ebullated-bed hydrocracker for heavy feedstocks, licensed by Axens. It typically converts vacuum residue into lighter products, with industrial conversion rates reaching up to **93%**[1], all while maintaining a high stream factor, making it a highly reliable and efficient solution for continuous operation. H-Oil® can be integrated with downstream units—such as fixed-bed hydrocrackers—to produce naphtha and other petrochemical feedstocks. Its flexibility in handling a wide range of feedstocks, combined with its ability to reduce fuel oil production and generate low-sulfur fuel oil (LSFO), makes it a strong candidate for refiners seeking to unlock value from the bottom of the barrel.

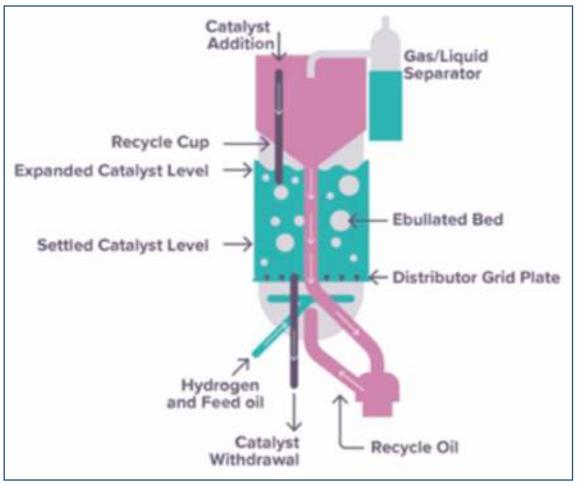


Figure 5: H-Oil® Ebullated Bed Reactor (AXENS technology)

[1]*Commercial Investigation of the Ebullated-Bed Vacuum Residue Hydrocracking in the Conversion Range of 55–93%. ACS Omega 2020 5 (51), 33290-33304*

Another advanced option is **High Severity Fluid Catalytic Cracking (HS-FCC™)**. Developed by an alliance between Saudi Aramco, the King Fahd University of Petroleum and Minerals, ENEOS, Technip Energies and Axens. It operates under more severe conditions than conventional FCC units and HS-FCC™ can convert a larger share of heavy feedstocks into light olefins and aromatics. In some configurations, HS-FCC™ units can achieve **propylene yields of up to 20 wt%**, while also producing valuable aromatics and reducing fuel oil output to near zero. This makes it an attractive solution for refiners aiming to pivot toward petrochemicals without the need to build entirely new complexes.

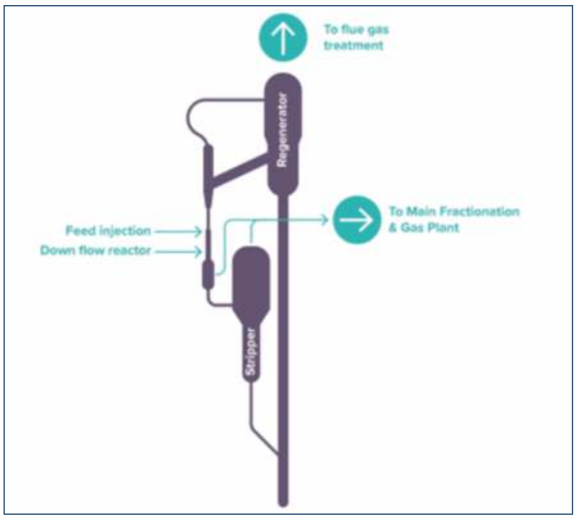


Figure 6: HS-FCC™ Reaction section (AXENS technology)

Case Study: S-Oil Refinery Expansion

A compelling example of deep conversion in action is the **S-Oil Residue Upgrading Complex (RUC)** project in South Korea. As part of its Onsan complex upgrade, S-Oil implemented HS-FCC™ technology. This expansion enabled the refinery to convert low-value residues into high-value petrochemical products, including propylene and BTX aromatics. As a result, S-Oil increased significantly its propylene production and successfully eliminated its high-sulfur fuel oil (HSFO) output, replacing it with a limited volume of LSFO. This shift significantly reduced the refinery's reliance on traditional fuel markets, positioning S-Oil as a more resilient and profitable player in the region.

These technologies, while capital-intensive, offer a strategic advantage for refiners with access to heavy feedstocks and the ambition to move up the value chain. When integrated effectively, deep conversion units can transform a refinery's product slate, reduce environmental liabilities associated with fuel oil, and unlock new revenue streams in the petrochemical sector.

Plug-in CTC Complexes: Modular Integration for Maximum Impact

For many refiners, especially those unable to commit to the scale and capital intensity of full-scale Crude to Chemicals (CTC) projects, a more agile and adaptable solution is emerging: the integration of **plug-in petrochemical complexes**. These modular units are designed to complement existing refinery infrastructure, offering a flexible and lower-risk pathway to increase chemical yields without the need for a complete overhaul.

Unlike traditional grassroots CTC projects, which typically involve long development timelines and substantial capital commitments, plug-in complexes can be deployed more rapidly and with significantly lower investment intensity. Their greatest advantage lies in the **synergies they create with existing assets**. By integrating seamlessly into current operations, these complexes can reuse spare capacity in existing units—such as hydroprocessing, reforming, or utilities—to post-treat the outputs of the new complex. Conversely, they can also be designed to process low-value or underutilized streams from the existing refinery, converting them into higher-value petrochemical products. This two-way integration enhances overall site efficiency, reduces redundancy, and maximizes return on both past and new investments.

A particularly promising innovation in this space is the development of **direct crude-to-chemicals technologies** that bypass conventional atmospheric and vacuum distillation. Technologies like **Catalytic Crude to Chemicals (CC2C™)**—developed by Axens, Aramco, and Technip Energies—enable the direct conversion of crude oil into petrochemical feedstocks through catalytic processes. These systems reduce both capital and energy intensity, and when integrated into existing sites, they allow refiners to scale up chemical production in a phased, demand-driven manner.

Beyond the technical benefits, plug-in complexes offer strategic flexibility. They allow refiners to adapt incrementally to shifting market conditions, diversify their product slate, and reduce exposure to declining fuel markets. Operationally, they benefit from shared site services, logistics, and utilities, which lower production costs and improve energy efficiency.

In a world where capital discipline is critical and transformation is urgent, plug-in petrochemical complexes represent a smart, scalable solution—bridging today's constraints with tomorrow's opportunities.

Conclusion

As the global energy landscape continues to evolve, the refining industry must adapt to remain relevant and profitable. With traditional fuel markets in decline and petrochemicals poised to drive future crude demand, integration between refining and chemical production is no longer optional—it is essential. While a select few players will continue to invest in large-scale Crude to Chemicals complexes, the majority of refiners will need to focus on pragmatic, capital-efficient strategies: optimizing existing assets, deploying deep conversion technologies, and integrating modular plug-in complexes.

These approaches offer a flexible and scalable path forward, enabling refiners to shift their product slate, enhance margins, and secure a more resilient position in the value chain. The transformation is already underway—and those who act decisively will shape the future of refining in the petrochemical era.

Axens holds all the cards to support this transformation, offering a comprehensive portfolio of technologies, expertise, and project experience to help each customer define the most appropriate solution for their specific needs—whether through incremental upgrades or full-scale integration strategies.

Mumbai (HPCL); Estd. -1954

18 Digital Refining: AI, ML, and Digital Twins in Operational Excellence

Shri Pravin Jain, CEO

Tridiagonal.ai

1. Introduction

India's oil refineries have long stood as industrial bedrocks, converting crude into fuels and chemicals that support one of the fastest-growing economies in the world. However, the sector now faces mounting challenges: increasingly complex feedstocks, volatile energy markets, tighter environmental compliance, and a widening knowledge gap due to a retiring workforce. These pressures demand a fundamental shift—not just in technology, but in philosophy.

Digital refining represents that shift. It's the fusion of advanced technologies like **Artificial Intelligence (AI)**, **Machine Learning (ML)**, **Hybrid AI**, **Agentic AI**, and **Digital Twins** with traditional process engineering. Together, these innovations move refineries beyond data collection to intelligent decision-making, enabling **autonomous operations**, **prescriptive maintenance**, and real-time optimization.

But success depends not just on algorithms, but also on human alignment, policy support, and a culture of learning.

This article outlines the strategic imperative of digital refining for India's energy independence and sustainability vision for 2047. Through practical use cases, institutional insights, and scalable best practices, we explore how refineries can build digital depth and national resilience.

2. The Case for Change

Refineries today operate in an environment that is more demanding than ever before. Beyond process complexity, they must deliver on performance, sustainability, and compliance—all while preserving margins.

Operational Complexity Is Rising

The global shift to heavier, sour crudes creates variability in yields and quality. These feedstocks strain existing equipment, increase fouling rates, and reduce catalyst efficiency—leading to shutdowns and higher maintenance costs.

Modern refineries must also handle dynamic blending, tighter recipe controls, and fluctuating energy inputs. Yet many still depend on legacy tools—static models, scheduled reports, and spreadsheet logic—to make critical decisions.

Agentic AI, capable of making decisions and initiating actions autonomously, addresses this by learning continuously and adapting to real-time operational contexts.

Environmental Pressures Are Non-Negotiable

Carbon taxation, ESG mandates, and net-zero targets are now central business considerations.

Refineries must track GHG emissions, sulphur levels, and water usage, often with limited visibility.

Hybrid AI—which blends symbolic reasoning with data-driven ML—can model emissions pathways while complying with policy logic and safety rules, enabling **prescriptive** interventions like adjusting furnace firing patterns or switching utilities automatically.

The Talent Gap Is Real

An aging workforce is exiting with decades of tacit knowledge. Younger engineers bring digital fluency but may lack operational instincts.

Prescriptive maintenance and **digital learning environments** can bridge this divide by turning data into guided action plans—helping less experienced staff make expert-level decisions.

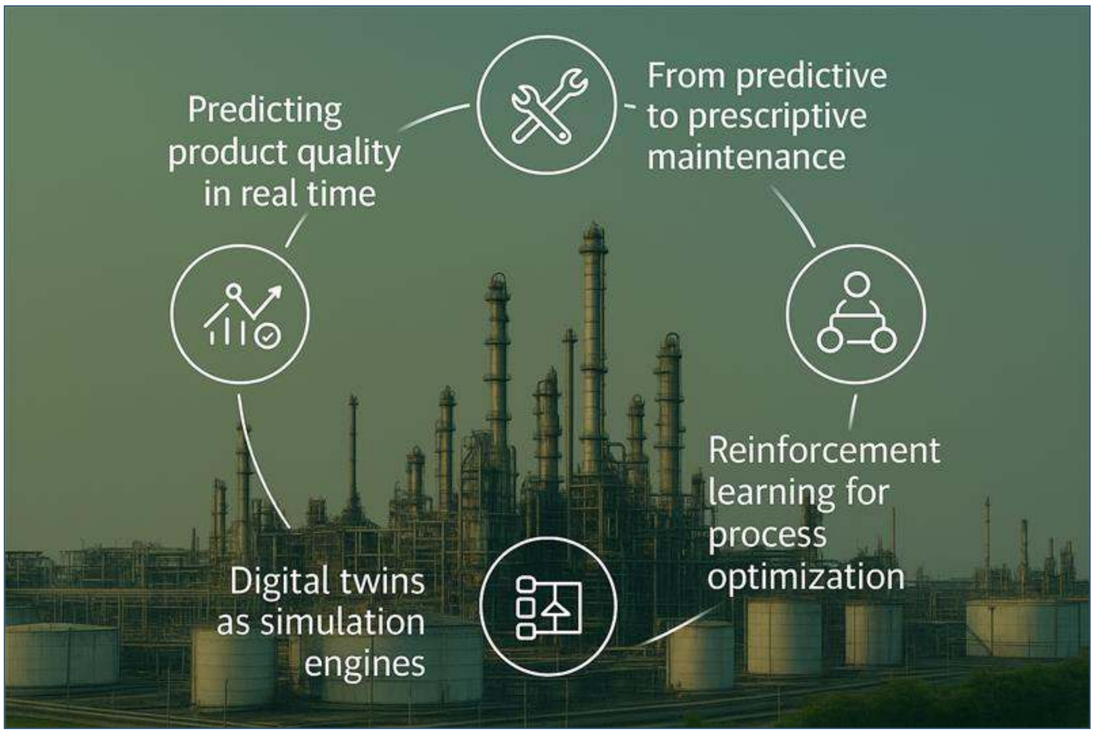
The Policy Push

India's policymakers recognize the digital imperative. At India Energy Week 2025, MoPNG Secretary Pankaj Jain emphasized AI's role in oil and gas transformation. This is aligned with the government's broader vision for a $10 trillion economy, clean energy leadership, and technology-led industrial growth.

In this context, digital refining becomes a national capability, not just a competitive advantage.

The Relevance

The refining process encompasses multiple interconnected disciplines, including mechanical, chemical, thermal, and materials science. This creates a significant challenge in accurately modeling the underlying process principles within a highly complex, high-dimensional parameter space, where numerous variables interact in intricate ways. Usually, this challenge is addressed by experimentation and simulations involving a high degree of expensive manual intervention in modeling. A promising solution for this problem is the incorporation of Artificial Intelligence (AI) and more specifically Machine Learning (ML) techniques in the modeling afford.



AI-Driven Refinery Optimization Cycle

3. AI/ML and Digital Twins: Refinery Game Changers

The promise of digital refining lies in its ability to **sense, decide, and act**—often without human intervention. This is the foundation of **autonomous operations**, where AI agents augment or replace manual workflows.

3.1 Predicting Product Quality in Real Time

In units like the diesel hydrotreating unit (DHDT), hitting ultra-low sulphur specs is non-negotiable. Traditional workflows are slow—sample, test, adjust.

Hybrid AI models, combining physics-informed algorithms with neural networks, now offer real-time sulphur prediction based on reactor conditions. These **soft sensors** close feedback loops instantly—preventing off-spec production and enabling **prescriptive adjustments** to process parameters before deviations occur.

3.2 From Predictive to Prescriptive Maintenance

Rotating equipment like pumps and turbines often fail without warning. ML models trained on sensor data (vibration, temperature, lube oil, current) enable early fault detection.

But the next step is **prescriptive maintenance**—where the system doesn't just flag anomalies but recommends specific actions (e.g., change bearing, reduce load, schedule lubrication). **Agentic AI** can even autonomously raise work orders in CMMS systems and adjust loads to prevent cascading failures.

In one refinery pilot, prescriptive analytics reduced unplanned downtime by 30% and saved over ₹8 crore annually.

3.3 Reinforcement Learning for Process Optimization

Traditional control logic plateaus in complexity. Reinforcement learning (RL) learns through trial, error, and reward, continually refining decisions.

In FCC units or reformers, RL agents explore operating points that maximize profit while meeting emission and energy constraints. Over time, these agents evolve into **virtual operators** that recommend—or even implement—optimal setpoints autonomously.

When deployed in a hybrid architecture, RL outputs are validated against rule-based constraints (safety, quality), ensuring compliance with refinery policies.

3.4 Digital Twins as Simulation Engines

A **digital twin** is a dynamic replica of an asset or process that ingests real-time data and simulates physical behavior (e.g., fluid flow, chemical reactions).

This enables operators to test "what-if" scenarios—like a new crude slate or catalyst switch—without risking plant stability. **Hybrid twins**, combining first-principles models with AI inference, increase accuracy and reliability.

In training and safety analysis, twins enable immersive simulations. In operations, they serve as a **sandbox for autonomous agents** to test and learn safely.

4. What's Holding Us Back

Despite the potential, full-scale implementation remains uneven.

Data Quality and Infrastructure

AI models need accurate, labeled, contextual data. Many plants still deal with:

- Faulty sensors
- Incomplete logs
- Siloed databases

A robust data pipeline—real-time, high-frequency, and interoperable—is essential for **agentic systems** to function effectively and make trusted decisions.

Organizational Silos and Culture

Digital transformation cannot be owned by IT or analytics alone. Success requires shared accountability between operations, maintenance, and leadership.

Agentic systems should not be seen as threats but as **collaborators** that assist human teams. Cross-functional squads, digital champions, and domain-data translators are key enablers.

Explainability and Trust

Refinery professionals must **trust** AI recommendations—especially in safety-critical decisions. Black-box models often create skepticism.

Techniques like **SHAP values**, causal inference, and visual dashboards can demystify AI logic and increase adoption. Hybrid AI also adds transparency by incorporating physical laws and business rules into the model.

5. Building Digital-Ready Refineries

Transforming pilots into platform-wide systems requires strategic investments across people, processes, and platforms.

Talent and Role Redesign

New roles are emerging:

- **Digital Production Engineer**
- **Prescriptive Maintenance Analyst**
- **AI-Operations Integrator**
- **Autonomous Systems Supervisor**

Training must include both core engineering knowledge and digital fluency (Python, SQL, AI tools, systems thinking). Academic partnerships and internal bootcamps can accelerate this upskilling.

Technology Architecture

An effective digital refinery stack should:

- Integrate DCS, MES, LIMS, and ERP systems

- Enable **edge and cloud computing**
- Support API-based data flow
- Allow AI agents to act with clear safety overrides

Modular, interoperable architecture will outperform monolithic solutions.

Governance and Safety Framework

Who validates the models? Who overrides the AI? How is failure managed?

These questions require a governance layer with **digital ethics**, version control, and audit trails. A **central Digital Center of Excellence (CoE)** can define standards, while embedded digital leads execute change on the ground.

6. Looking Ahead to 2047

India's vision for energy security, clean growth, and global leadership aligns closely with digital refining. As the country marches toward its centenary of independence in 2047, refineries must transform into digital-first, low-carbon, and resilient systems that serve as engines of national development.

This transformation will not occur overnight, it requires continuous investment in digital infrastructure, human capital, and cross-sector collaboration. But the roadmap is clear: intelligent operations driven by data, supported by domain knowledge, and aligned with policy and environmental goals.

Imagine a refinery where:

- Every asset, from compressors to heat exchangers has a real-time health score updated every hour using **prescriptive analytics.**
- Emissions are not just reported, but automatically corrected through AI-guided control loops.
- Operators use voice commands and augmented reality to troubleshoot equipment, supported by real-time insights from digital twins.
- Carbon footprint per barrel processed is cut in half through intelligent energy management.
- Shift reports are generated automatically, reviewed collaboratively, and validated through model-driven audits.
- Digital twins simulate hundreds of "what-if" scenarios daily to prepare for disruptions in feedstock, power, or logistics.

This level of autonomy, foresight, and precision will not only improve safety and sustainability, but also establish India as a reference model for emerging economies grappling with similar industrial challenges.

India's Global Opportunity

India's unique combination of:

- A young digital-native workforce
- Deep refining expertise
- Frugal innovation mindset

- Thriving AI startup ecosystem

makes it an ideal candidate to **export digital refinery systems** to Asia, Africa, and the Middle East.

Solutions like cloud-native digital twins, agent-based optimization engines, and **low-cost prescriptive maintenance platforms** can define India's next industrial export wave.

By 2047, Indian refineries can evolve into global hubs of operational intelligence—where AI doesn't replace humans but **elevates human insight into enterprise-wide foresight**.

7. Conclusion

Digital refining is more than an upgrade, it's an evolution in how industrial energy systems think, act, and improve. It blends scientific principles with computational intelligence to create refineries that are not just efficient, but adaptive.

To realize this vision, India must focus on foundational data practices, skilled talent, robust infrastructure, and institutional trust. Digital transformation must be supported by leadership vision, transparent governance, and cross-disciplinary collaboration between operations, engineering, and data teams.

Just as control rooms redefined refineries in the 20th century, **agentic and autonomous systems** will lead the 21st-century transformation.

Let us remember: the refinery of the future is not just a place, it's a platform. A platform where physical processes, human intelligence, and machine cognition converge. Where decisions are not delayed, risks are not hidden, and opportunities are not missed.

With the right intent and investment, Indian refineries can serve as global benchmarks delivering profitability, sustainability, and sovereignty in equal measure.

“Digital tools don't replace human insight, they amplify it. The refinery of the future is a blend of intuition, intelligence, and infrastructure working in harmony.”

Visakh (HPCL); Estd. -1957

19

Maximizing Refinery Margin Through SDA and DCU Integration: Enabling Molecular Management in Bottom-of-the-Barrel Conversion

Mr. Haeil Jo, Technology Manager, ROSE®

KBR

Maximizing refinery margin requires ensuring that the right hydrocarbon molecules are processed in the most suitable conversion units—a concept known as **molecular management**. Traditionally, this is achieved by separating vacuum gas oil (VGO) and vacuum residue (VR), directing lighter cuts to the **Fluid Catalytic Cracking Unit (FCCU)** or **Hydrocracking Unit (HCU)** and sending heavier fractions like VR to the **Delayed Coking Unit (DCU)**.

However, **Solvent Deasphalting (SDA)** introduces a more refined molecular management approach. Unlike distillation, which relies on boiling point differences, SDA is based on molecular type, separating hydrocarbons according to polarity and solubility. When integrated upstream of DCU, SDA significantly enhances refinery flexibility, product yield, and margin.

Understanding Molecular Types in Residue

Residue streams, such as atmospheric or vacuum residue, are composed of complex hydrocarbon structures, typically classified into four molecular types:

1. Saturates

- **Structure:** nonpolar hydrocarbons, including both straight/branched alkanes (paraffins) and cycloalkanes (naphthenes)
- **Properties:** Low molecular weight, high H/C ratio, low density, and low boiling point. Chemically stable and less reactive
- **Role:** Provide fluidity and reduce viscosity in residue
- **Ideal Conversion:** Hydroprocessing, FCC, or lube oil production

2. Aromatics

- **Structure:** Mono- or polycyclic aromatic hydrocarbons (benzene-ring structures)
- **Properties:** Higher density and reactivity; contribute to color, stability, and coke formation
- **Ideal Conversion or Outlet:** FCC (with pretreatment), hydroprocessing, or bitumen flux

3. Resins

- **Structure:** Intermediate polar compounds with heteroatoms (N, S, O)
- **Properties:** Viscous, act as dispersants for asphaltenes
- **Role:** Critical in stabilizing asphaltenes; imbalance can lead to operational issues in conversion units such as Ebullated Bed
- **Ideal Conversion or Outlet:** Low-conversion modern hydroprocessing, Ebullated Bed, DCU (for anode-grade coke), or road bitumen

4. Asphaltenes

- **Structure:** Large, complex, highly polar molecules with fused aromatic rings and high metal content
- **Properties:** Very high boiling points; insoluble in paraffinic solvents
- **Role:** Primary contributors to viscosity and coke formation
- **Ideal Conversion or Outlet:** Slurry hydroprocessing, DCU, solid fuel, or road bitumen blending

SDA Technology Fundamentals

Solvent Deasphalting (SDA) is a liquid–liquid extraction process using light paraffinic solvents—typically propane, butane, or pentane—to selectively dissolve and separate hydrocarbon molecules. When residue is mixed with a solvent:

- **Lighter hydrocarbons** dissolve into the solvent phase to form **Deasphalted Oil (DAO)**.
- **Asphaltenes and heavy contaminants** (metals, sulfur, CCR) precipitate and are removed as the **asphalt phase**.

The selection of solvent impacts the separation:

- **Propane** yields the cleanest DAO (rich in Saturates)
- **Butane** allows for partial recovery of aromatics
- **Pentane** recovers some resin, increasing DAO yield

SDA thus offers a high degree of selectivity in routing molecules based on their chemical structure—not just boiling point.

KBR's ROSE® SDA Technology

SDA has been used in refining for over 70 years, initially to recover lube base oils. However, conventional SDA units—based on distillation—were limited in efficiency. In the 1950s, **Kerr-McGee Corporation** developed a supercritical version of SDA, later commercialized as **ROSE® (Residuum Oil Supercritical Extraction)**. This innovation improves energy efficiency by recovering solvent above its critical point.

KBR acquired ROSE technology in 1995 and has since licensed:

- **76 ROSE units worldwide**
- **Over 1.7 million barrels per stream day (bpsd)**
- **More than 90% market share in supercritical SDA**

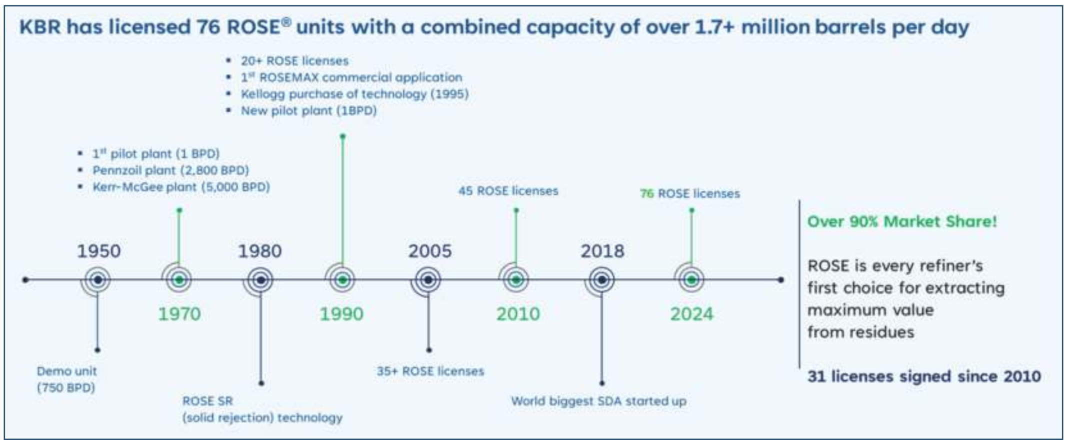


Figure 1 ROSE® Technology Timeline

SDA + DCU Integration: A Molecular Management Approach

Routing paraffinic and aromatic-rich fractions directly to the DCU results in low-value products—such as gas, coke, or low-quality naphtha/distillate. These molecules are better suited for high-yield conversion in FCC or HCU. Integrating **ROSE SDA** before DCU enables:

- Recovery of high-value DAO for FCC or hydroprocessing
- Concentration of asphaltenes and resins into the DCU feed
- Improved overall product yield and refinery margin

Case Study: SDA + DCU Integration

A case study was performed using **PetroPlan™ modeling** for a 200,000 BPD refinery processing a 50:50 AH:AL crude blend, assuming WTI at $70/bbl. Key results include:

- **18% reduction in petcoke production**
- **Increased middle distillate yield**
- **Annual benefit: ~$97 million**
- **TIC: ~$230 million (New ROSE, HCU/DCU modification)**
- **Payout: < 3 years**

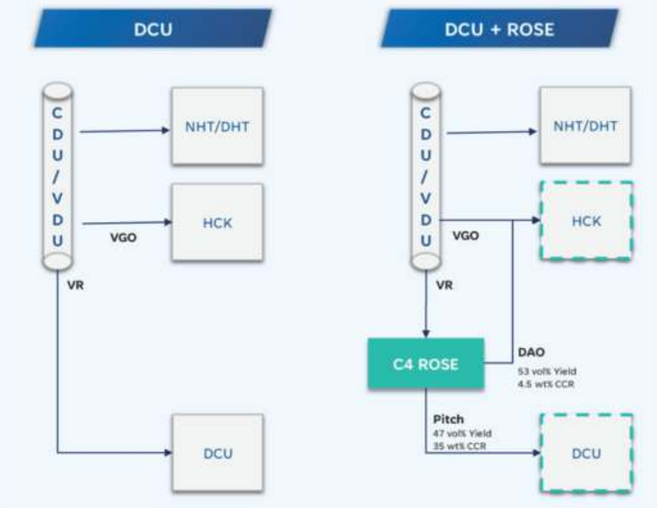


Figure 2 DCU+ROSE case study configuration

Throughout				
Process	**DCU**	**DCU+ROSE**	**Delta**	
VDU	93	93		
HCK	67	82	+15	
DCU	42	20	-22	
ROSE	-	42		
Economics				
	Stream	**Delta**	**Price**	**MM$/yr**
Products	Naphtha, BD	-3,048	$70 /bbl	-74.7
	ULSD/Jet, BD	+7,559	$90 /bbl	+238.1
	VLSFO, BD	+509	$75 /bbl	+13.4
	Coke, T/D	-367	$100 /T	-12.9
	LPG, T/D	-30	$550 /T	-5.7
Consumption	Net FG Con, T/D	+161	$400 /T	-22.6
	H2 Con, T/D	+59	$1,500 /T	-31.0
	STM & BFW	-	-	-4.9
	Power, MW	+2.6	$120/MWh	-2.6
	Sum	**-**	**0**	**+97.1**
Capex	**Item**		**Investment, MM$**	
	ROSE, New		130	
	HCR, DCU Revamp		100	
	Sum		**230**	

Simply Pay-Out <3 years

Table 1: Case study results

Additional Integration Benefits

DCU/VDU Debottlenecking

ROSE SDA allows refiners to bypass some AR around the VDU or operate the vacuum unit at higher pressure, reducing the load while recovering HVGO through DAO. Additionally, with reduced DCU coke yield, refiners may allocate capacity for processing additional residue or alternative feedstocks such as **waste-derived oils or plastic waste.**

Enhanced Anode-Grade Coke Quality

Anode-grade coke quality depends on minimizing saturate content in DCU feed. SDA removes saturates upstream, improving carbon structure and meeting stringent anode-grade coke specs—particularly valuable for integrated refineries or those targeting the graphite electrode market.

Conclusion

SDA is a powerful tool for **molecular management** in bottom-of-the-barrel conversion. By separating paraffinic and aromatic molecules from resins and asphaltenes, ROSE SDA enables optimal routing of each molecular type to the process unit best suited for maximizing value. When integrated upstream of DCU:

- **High-value DAO** is recovered for premium conversion
- **Coke yield is reduced**
- **Product slate is improved**
- **Refinery flexibility increases**

With proven performance, global adoption, and strong economics, SDA + DCU integration is a compelling path forward for refiners seeking to optimize their residue upgrading strategy.

20

Hydrogen in Refineries: Enabling Clean Fuel Production through Integration and Co-processing

Shri Amrish Kumar, Sr. Engineer R&D; Ms. Sukla Roy, Chief Manager Process & Technology & Shri Shyam Kishore Choudhary, Associate Vice President - Process & Technology

Technip Energies

Abstract

This article explores the evolving role of hydrogen in modern refineries, emphasizing its pivotal function in achieving decarbonization targets and enabling clean fuel production. With over 96% of current hydrogen production relying on conventional, carbon-intensive methods, the imperative for sustainable alternatives and efficient recovery becomes critical. We analyze the strategic importance of integrating hydrogen-centric networks within refineries, focusing on the maximization of hydrogen recovery from refinery off-gases (ROG) and the strategic blending of green hydrogen. The article discuses key technologies for hydrogen recovery and purification, highlighting their operational advantages. Furthermore, it elucidates how leveraging internally generated off-gases for high-purity hydrogen production not only enhances refinery self-reliance and reduces operational costs but also significantly mitigates CO2 emissions. The discussion extends to the advancement of low-carbon hybrid hydrogen solutions and the indispensable role of hydrogen in facilitating the co-processing of

renewable feedstocks for "drop-in" biofuels. Ultimately, this work positions hydrogen as a strategic enabler for refineries to transition into key players in the clean energy landscape, balancing operational excellence with environmental stewardship and ensuring future fuel security.

1. Introduction

Hydrogen (H_2) production is a key focus area to decarbonize the refineries to meet net zero target. Greater than 96% of hydrogen manufactured today is through conventional steam methane reforming (SMR), releasing the Carbon dioxide (CO_2) directly into the atmosphere. This grey H_2 has a price of $1.50-2.00/kg. Along with carbon capture, blue hydrogen is estimated to double the grey hydrogen cost, while green hydrogen is a staggering price increase up to around $4-8/kg. To mitigate this increased H_2 cost implications in various production and decarbonization initiatives within the refinery, modern refineries are finding the increased importance of economically recovering unused hydrogen wherever possible. Refineries are evolving into hydrogen-integrated networks, where hydrogen is produced, recovered, and redistributed across units. Retaining the conventional hydrogen production infrastructure, refineries are trending to maximize hydrogen recovery from refinery off-gas (ROG) and blending green hydrogen (from electrolysis) with conventional hydrogen sources to meet the decarbonization goals.

Refinery contributes more than 4% of Global CO_2 emission. Refinery off-gas (ROG) is a valuable byproduct stream that often contains significant amounts of valuable hydrocarbons and hydrogen, generally used as fuel or flared as excess gas. Combustion of ROG contributes about 30-40% towards total CO_2 emission of a refinery. Recovering the hydrogen in ROG is becoming increasingly important for both economic and environmental reasons. It reduces significant amount of direct CO_2 emission by generating clean fuel as well as decreasing intake of fossil fuel to produce hydrogen from the refinery itself and reducing hydrogen purchases through merchant suppliers, creating a circular hydrogen economy. On the other hand, use of hybrid low carbon hydrogen integrating blue hydrogen and green hydrogen further strengthens the pathway to cleaner refining operations

2. Refinery Block Flow and Key Off-Gas Streams

A typical petroleum refinery's block flow diagram illustrates the sequence and interconnections of its primary processing units along with typical off gas sources (**Figure 1**).

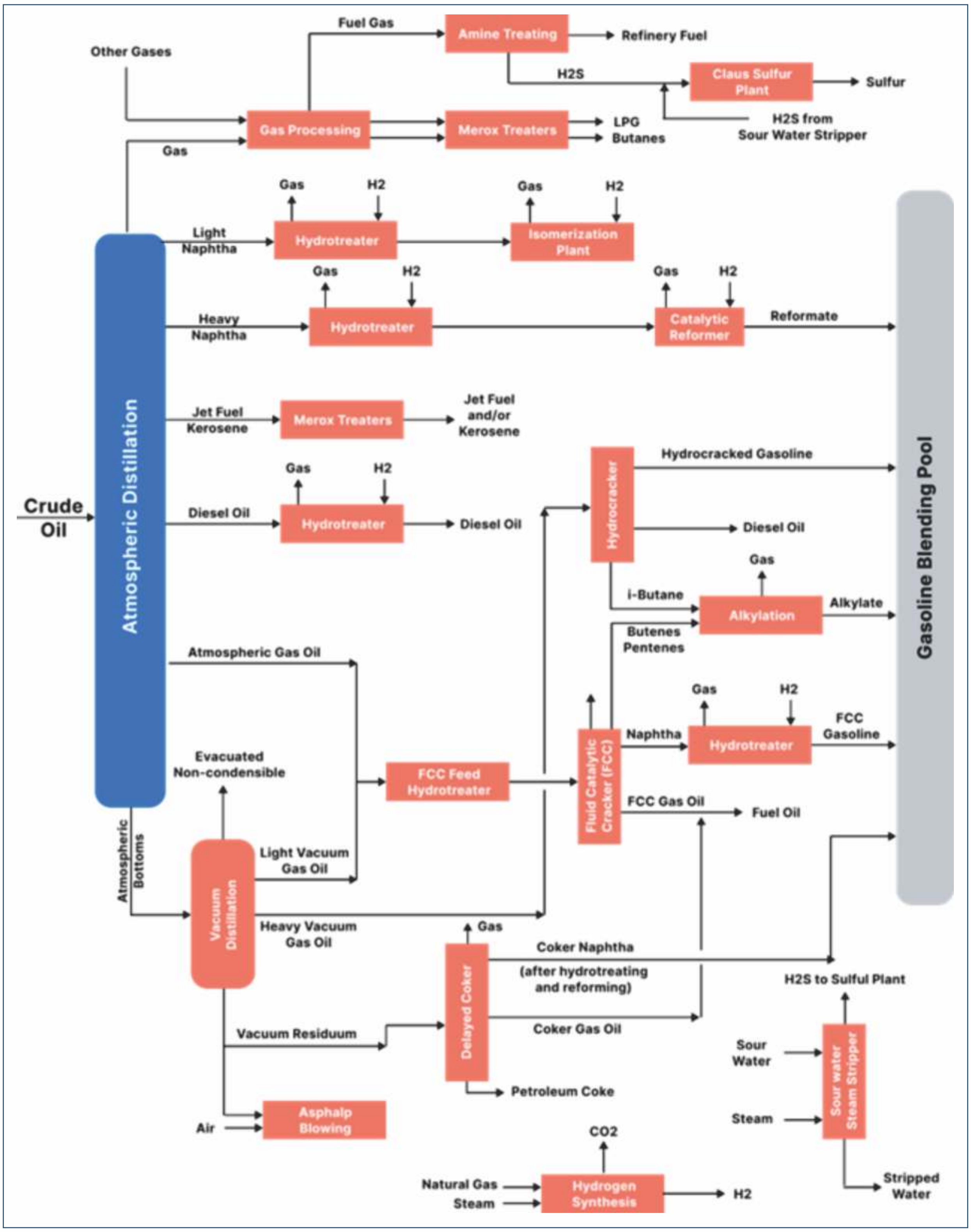


Figure 1: Typical refinery block flow with major off-gas streams

2.1. Major Sources of Refinery Off-Gases

As depicted in the refinery block flow (**Figure 1**), several key conversion units contribute to the refinery's internal off-gas streams,

- **Fluid Catalytic Cracking (FCC) Unit:** A major conversion unit that generates significant off-gas rich in light hydrocarbons and olefins.

- **Coker Unit:** Produces off-gas from cracking heavy residues, containing light hydrocarbons and H2S.
- **Catalytic Reforming Unit (CRU):** Primarily a hydrogen producer, it also generates light hydrocarbon by-products (off-gas) that contribute to the fuel gas balance.
- **Hydrotreating and Hydrocracking Units:** These units consume hydrogen but also produce light hydrocarbons and impurities like H_2S and NH_3, contributing to the refinery's off-gas pool.

Typical off-gas generation from these and other various refinery units is provided in **Table 1**.

Table 1: Refinery units and their typical off-gas generation

Unit Name	Unit Capacity (T/hr)	Off Gas Generation (T/hr)
AVU	375	0.375
NHTU	26.25	0.139
Coker	65.1	5.208
RFCCU	212.5	7.8625
DHDT	412.5	1.5675
HGU	2.8	1.2
Isomerization	31.6	0.6004
NHDT	46.9	0.214

The amount of hydrogen from the main ROG stream in a refinery may be seen in **Table 2**. The remaining streams are hydrocarbons ranging from CH_4 to C_6+, some of which represent a benefit to the refinery and can also be recovered. The composition of the ROG varies, depending on the composition of the crude from which it was originated and the processes to which it has been subjected. Traditionally, a significant portion of these gases is routed to the refinery's fuel gas system to fire furnaces and boilers, contributing to the refinery's energy self-sufficiency. However, with increasing hydrogen demand for decarbonizing the refinery, these off-gases have also become valuable feedstocks for internal hydrogen production.

Table 2: Typical conditions of refinery off-gases

Typical ROG Source	Pressure (barg)	vol% H_2
Delayed coker off-gas	~10	15-30
Hydrocracking HP off-gas	40-125	60-85
Hydrodealkylation off-gas	25-28	50-75
Catalytic reforming	20-30	68-88
Catalytic cracking off-gas	~20	~18
Hydrotreater off-gas	20-50	60-80

The imperative for hydrogen recovery from off-gases is further underscored by their significant contribution to a refinery's overall CO_2 footprint. As illustrated in **Figure 2**, the primary contributors to refinery CO_2 emissions typically include furnaces and boilers (Power plant, ~25%), crude distillation unit (CDU, ~21%), fluid catalytic cracking (FCC) units (~14%), hydrogen manufacturing (SMR/HGU, ~13%), and other utilities (20-50%). Furthermore, off-gases are routed to furnaces and boilers as fuel and often flared the excess amount, contributing significantly to their large emission share. Therefore, efficient recovery and utilization of hydrogen from these off-gas streams directly mitigate the CO_2 released by these high-emitting processes, playing a vital role in reducing the refinery's overall carbon footprint and enhancing environmental performance.

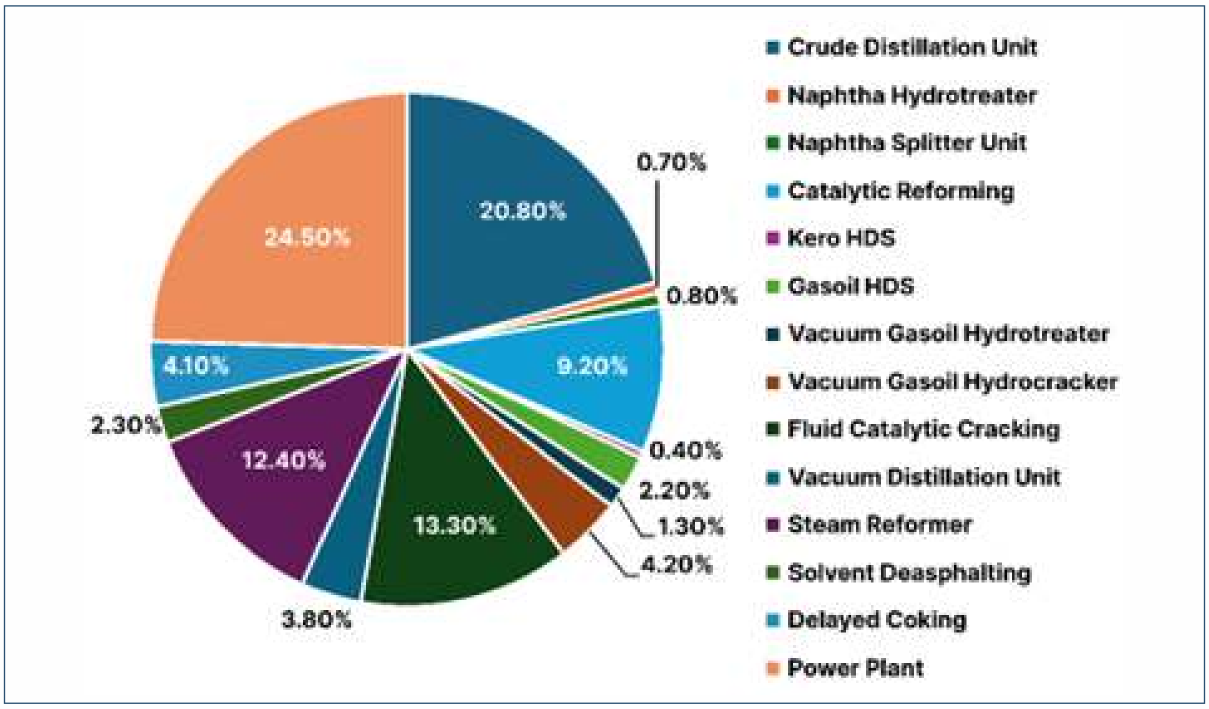


Figure 2: Typical CO_2 emissions contributors in a refinery

3. Hydrogen Production from Refinery Off-Gases

Rather than purchasing hydrogen from external sources, strategic utilization of internally generated off-gases into high-purity hydrogen production significantly enhances a refinery's self-reliance and reduces operational costs. Integrating hydrogen from off gases along with reduced capacity dedicated Steam Methane Reformer (SMR)/Hydrogen Generation Unit (HGU) in refineries enhances the reliance on internal hydrogen production to meet growing demand. Reduces the need for flaring excess off-gases or burning them as low-value refinery fuel, reducing overall refinery greenhouse gas emissions.

3.2. Key Technologies for Hydrogen Recovery and Purification

Several key technologies are employed for hydrogen recovery and purification from ROG mixed gas streams:

- **Pressure Swing Adsorption (PSA):** This technology utilizes specialized adsorbent materials (e.g., zeolites, activated carbon) that selectively adsorb impurities (CH4, CO, CO2, N2, H2S) from the hydrogen stream at high pressure. As pressure is released in a cyclic process, the impurities are desorbed and vented as tail gas, leaving behind high-purity hydrogen. PSA is a well-established and highly efficient method for producing ultra-pure hydrogen.

- **Cryogenic Separation:** This method relies on differences in the boiling points of gases. The off-gas stream is cooled to very low temperatures, causing impurities with higher boiling points (like hydrocarbons, CO2) to condense and separate as liquids, leaving hydrogen as a gas. This technology is highly effective for bulk separation of hydrogen from significant quantities of hydrocarbons.
- **Membrane Separation:** This technology employs semi-permeable polymeric or inorganic membranes that selectively allow hydrogen to permeate through them more rapidly than other gases. The driving force is the partial pressure difference across the membrane. Membrane systems offer energy-efficient recovery, particularly for streams with lower hydrogen concentrations or as a pre-purification step.

Table 3: Comparison of various hydrogen purification techniques, highlighting their key parameters and suitability for different process conditions

Parameter	Membrane Separation	Pressure-Swing Adsorption	Cryogenic Distillation
H_2 Purity	90%-98%	99.9+%	95%-99%
H_2 Recovery	85%-95%	75%-92%	90%-98%
H_2 Product Pressure	< Feed pressure	Feed pressure	Feed/Low pressure
Feed Pressure	300-2,300 psig	150-600 psig	>75-1,100 psig
H2 Feed Content	>25-50%	>40%	>10%
Byproduct Capability	Poor	Poor	Excellent
H_2 Capacity	1-50+ MM scfd	1-200 MM scfd	10-75+ MM scfd
PretreatmentRequirements	Minimum	None	CO2, H2O removal
Capital Cost	Low	Medium	Higher
Scale Economics	Modular	Moderate	Good
Startup Time	Minutes	Minutes	Hours

All three processes are efficient for high hydrogen content and high-pressure feeds but are not efficient for low hydrogen content and low-pressure feeds. When hydrogen content is less than 50% in the ROG feed, placing membrane before PSA will help to enhance recovery of hydrogen in order to generate a stream that is poorer in heavy hydrocarbons and is strongly adsorbed in the PSA, making it difficult to desorb and reducing production. Further cooling/condensation of heavy hydrocarbon before feeding to PSA can optimize the H_2 recovery.

3.3. PSA: A Preferred Purification Method

Impurities in the hydrogen feed can quickly deactivate sensitive catalysts in hydrotreating and hydrocracking units, leading to reduced efficiency, increased operating costs, and even potential unit shutdowns. Therefore, PSA units and other advanced purification technologies are strategically placed within the hydrogen network to ensure the consistently high purity levels required by these critical catalytic processes.

PSA is widely recognized and frequently employed in refineries for upgrading off-gas streams to high-purity hydrogen. Its preference is attributed to several operational advantages while producing high purity hydrogen from off gas:

- Hydrogen with purity levels exceeding 99.9% (often 99.999%) is achievable by PSA
- Effectively handle feed streams with varying hydrogen concentrations and impurity profiles, making them suitable for diverse refinery off-gases
- PSA technology is mature, robust, and offers high operational reliability with relatively simple automation,
- PSA often presents a more cost-effective solution compared to other technologies
- The PSA process produces a "tail gas" stream, which retains significant heating value and is routed to the refinery's fuel gas system to fire furnaces and boilers, contributing to the refinery's internal energy demands and minimizing waste.

4. Hydrogen Integration within the Refinery Block Flow

To fully harness the potential of hydrogen, refineries are moving toward integrated systems that optimize both hydrogen production and its utilization.

4.1. Refinery Off-gas (ROG) to Hydrogen Integration

Before sending Refinery off-gas as obtained from different sources (as mentioned in section 2.1) to hydrogen recovery system:

- Amine units remove H_2S from refinery off gases.
- Lean oil recovery (LOR) recovers C3–C6 hydrocarbons, mostly C3–C4, from off-gas streams improving purity of the off-gas stream. The hydrocarbon-rich oil goes to a stripper, where the hydrocarbons are recovered. Recovered hydrocarbons can be sent to existing SMR/HGU as feed.
- Sometimes off-gas rich in heavy hydrocarbons is passed through condenser and separator system, where separated heavy hydrocarbon condensate is routed to existing SMR HGU as feed upstream of feed purification section. H_2 rich off gas from separator is fed to Hydrogen PSA to recover Hydrogen.

The hydrogen purification (> 99.9% refinery grade) is achieved using a PSA process. The unit comprises of a number of adsorbers, which are all in a different phase of the cycle. At the end of the adsorption step the hydrogen remaining in an adsorber is used for re-pressurization and purging of the other adsorbers in order to increase the hydrogen recovery.

Tail gas from PSA is used as fuel in the Reforming Section. Also tail gas can be compressed and sent to refinery fuel headers to use as fuel in fired heaters, etc.

Feedstock for SMR: H_2 content in ROG can vary as per Table 2. When % H_2 is less than the option for blending ROG along with gaseous feed like Natural gas and feeding into existing SMR will replace part of the natural gas feed. Though it requires checking suitability of the scheme with respect to ROG composition, this integration lowers the carbon footprint of hydrogen production along with added cost advantage.

Once produced and purified, hydrogen is distributed and consumed across various refinery units, forming a critical internal "hydrogen network." This integrated approach (refer to **Figure 3**) ensures an efficient and reliable supply to processes that are highly dependent on hydrogen for their operation and product quality.

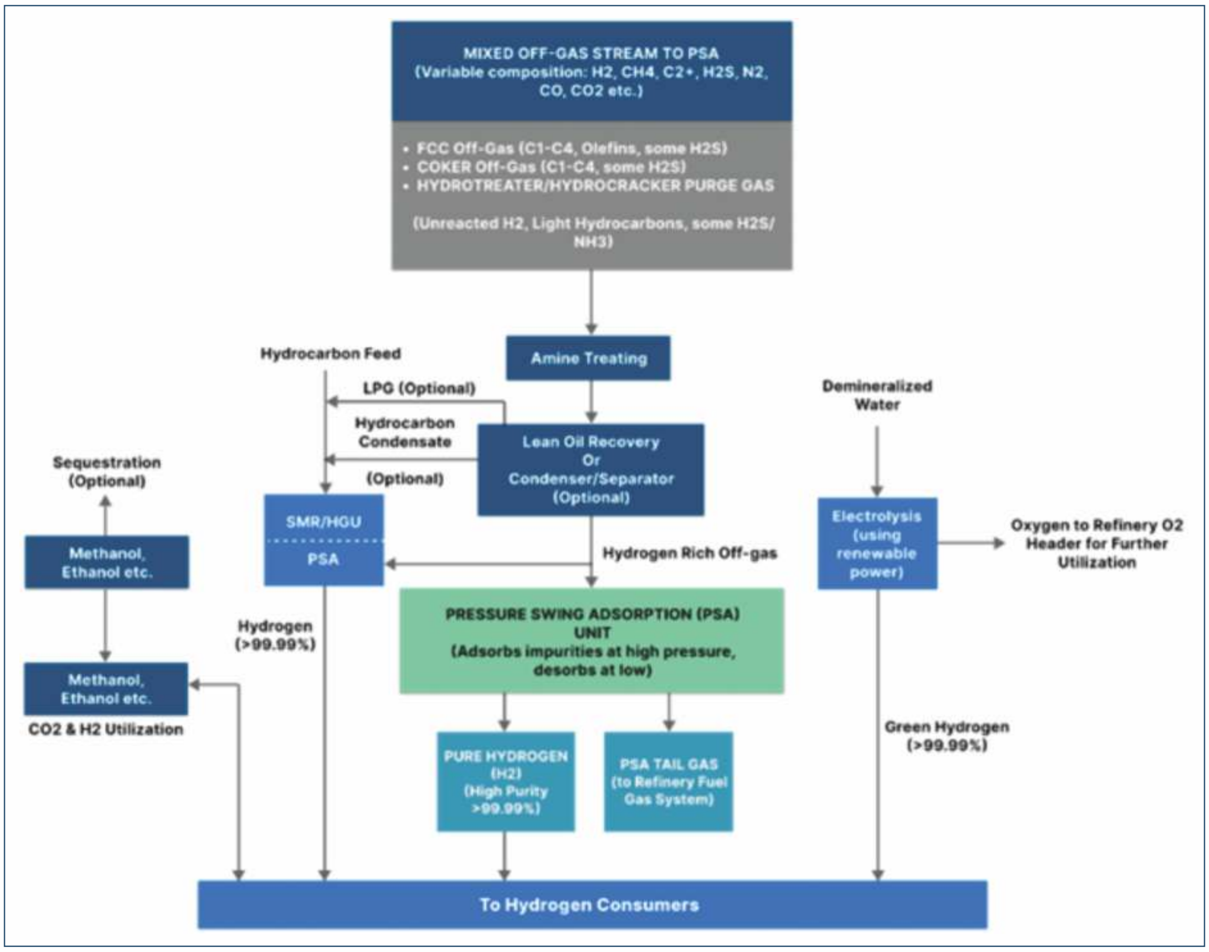


Figure 3: Integrated refinery block flow for hydrogen recovery and utilization

4.2. Advancing Towards Low-Carbon Hybrid Hydrogen

The push for decarbonization has led refineries to reconsider how hydrogen is produced and deployed. Hybrid hydrogen can be produced by combination of multiple hydrogen production or utilization methods to optimize efficiency, reduce emissions, or enhance flexibility. Integrating green hydrogen produced via electrolysis powered by renewable energy, offers a pathway to significantly reduce emissions within the refining sector. Studies suggest that substituting green hydrogen for conventional hydrogen in hydrotreating units alone could mitigate approximately 22% of the sector's CO_2 emissions. Combining green hydrogen, blue hydrogen (conventional H_2 coupled with carbon capture and storage or utilization) and hydrogen recovered from ROG—are becoming central to refinery decarbonization strategies. Converting the captured CO_2 to synthetic fuel in combination with hybrid hydrogen is a new trend in refinery to reduce carbon footprint further.

4.3. Enabling Co-processing of Renewable Feedstocks

A crucial and rapidly emerging application of hydrogen within the refinery block flow is its indispensable role in co-processing renewable feedstocks. Integrating bio-feedstocks like vegetable oils or animal fats with conventional petroleum streams in existing hydrotreating units (such as a Diesel

Hydrotreater) requires a significant amount of hydrogen. Hydrogen actively reacts with the oxygenates present in these bio-feedstocks (e.g., fatty acids, triglycerides), effectively removing oxygen as water and simultaneously transforming them into paraffinic hydrocarbons. These resulting hydrocarbons are chemically identical to conventional diesel or jet fuel components, leading to the production of "drop-in" biofuels that can be seamlessly blended without requiring modifications to existing infrastructure or engines. Simultaneously it is reducing the requirement of fossil based crude oil reducing carbon footprint. The reliable availability of internally generated hydrogen facilitates this transition, enabling refineries to contribute directly to decarbonization efforts and diversify their product portfolio without necessitating entirely new, large-scale processing units.

5. Major Hydrogen Application

The purified hydrogen streams are primarily routed to the following key units that are fundamental to modern clean fuel production:

- **Hydrotreating Units:** In hydrotreaters, hydrogen reacts with sulfur, nitrogen, and oxygen compounds present in various feedstocks (e.g., diesel, naphtha, kerosene) to form hydrogen sulfide (H_2S), ammonia (NH_3), and water (H_2O), respectively. This process is crucial for improving fuel specifications, directly linking hydrogen consumption to environmental mandates for cleaner fuels.
- **Hydrocracking Units:** Significant hydrogen consumers, particularly in refineries aiming to maximize middle distillate yields (jet fuel, diesel) or process heavy, contaminated feedstocks. Hydrogen is consumed for removing impurities like sulfur and nitrogen, breaking down heavy molecules (cracking), for saturating the newly formed hydrocarbon fragments. This ensures the production of high-quality jet fuel, diesel, and gasoline components.
- **Catalytic Reforming Unit (CRU):** While being a net producer of hydrogen, the CRU itself operates under a hydrogen-rich atmosphere. A portion of the hydrogen produced is typically recycled back to the reactor section. This internal recirculation helps to suppress coke formation on the catalyst, maintain catalyst activity, and ensure stable operation, thereby minimizing the need for fresh hydrogen makeup.
- **Reforming and Isomerization:** Enhancing fuel quality through improved octane ratings.
- Co-processing advancement also utilizes hydrogen to produce different bio- or synthetic fuels.

Integration will enhance hydrogen production further within the refinery, opening up utilization of hydrogen as clean fuel as well as production of hydrogen derivatives:

- **Hydrogen is an abundant and clean alternative fuel** with immense potential to reduce CO_2 emissions across various industrial and energy sectors. In heating applications, hydrogen offers a cleaner alternative to natural gas. For example, oil tanks in cold climates use natural gas-fueled heating tubes to maintain high temperatures for separating oil, water, and solids. Hydrogen can replace Natural gas for the same purpose.
- Synthetic fuel Hydrogen can be utilized with captured CO2 to produce valued products like methanol, ethanol, etc.

6. Conclusion

Hydrogen is no longer a passive utility in the refining process—it has evolved into a strategic lever for transformation. Hydrogen's strategic deployment in refining presents a unique opportunity to align operational excellence with decarbonization goals. Through thoughtful integration and co-processing, refineries can evolve into key players in the clean energy landscape, without sacrificing economic performance or fuel security.

By strategically leveraging internally generated off-gases for hydrogen production, refineries can achieve more sustainable operational goals and economic advantages. By implementing advanced recovery technologies, refineries can optimize their hydrogen usage, reduce costs, and contribute to environmental goals. As the demand for cleaner fuels continues to grow, the importance of efficient hydrogen recovery will only increase. Furthermore, integrating low-carbon hydrogen technologies in refineries is a feasible strategy for achieving CO2 reduction goals in both the short and long term. The robust internal hydrogen supply chain is now pivotal for the co-processing of renewable feedstocks, positioning refineries as key players in the production of sustainable, low-carbon fuels. Co-processing represents a balanced approach that combines the best of both fossil-based processes and renewable energy, setting the stage for a cleaner and more resilient fuel production paradigm. As technological innovations continue to drive down costs and as market and policy frameworks evolve, the integration of low-carbon hydrogen will be pivotal in shaping the future of sustainable fuel production.

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21 The Strategic Role of E-Fuels in India's 2047 Vision

Shri Krishna Mani,
Director- Sustainability Centre of Excellence

Honeywell Technology Solutions

Introduction

The world is currently facing a multitude of challenges, including geopolitical instability, supply chain disruptions, high inflation, trade tariffs, and frequent climate change-induced events that are impacting economic stability. Amidst this, India is experiencing robust economic growth, with a consistent GDP growth rate of 6-7% over the past decade. India has become the fourth largest economy in the world, with a GDP of ₹ 331.03 lakh crore[1]. Home to 1.4 billion people, India's demographic dividend is expected to drive and sustain significant economic momentum over the coming decades, leading to large-scale capital investments, accelerated growth in manufacturing and services, and improved GDP per capita.

India has traditionally been mindful of resource utilization and has been at the forefront of addressing climate change. Recognizing the potential impact of climate change on its future growth, India has committed to achieving net zero emissions by 2070. This vision is supported by a robust action plan outlined in the recently submitted Long-Term Low Carbon Development Strategy (LT-LEDS), which balances economic and social development goals while upholding the pledge to climate resiliency through mitigation and adaptation approaches[2].

Impact of Climate change

Climate change impact is affecting every region on the planet in diverse ways. India is no exception. In India, habitats of six hundred million people are in hot spots for extreme weather events. In the last decade alone, India has witnessed several tropical cyclones impacting millions of people and has incurred significant monetary damages. Air pollution has also emerged as a serious environmental problem due to substantial dependance on anthropogenic energy sources. This condition is further aggravated due to local geographical and meteorological conditions. Half of India's population lives in regions with fewer than two hundred clean air days a year[3]. This underscores the need for scale and urgency in action to reduce greenhouse gas emissions (GHG).

India's GHG emissions Profile

India's annual production of total GHG emission is 2.83 Gt CO_2 equivalent (2019), however, the per capita emission is 2.46 tons CO_2 equivalent which is well below the global average (4.79 tons CO_2 equivalent) [2]. India has underpinned its emission strategy based on carbon equity and a just transition that co-creates space for its twin objectives of net zero and inclusive socio-economic growth. In India, power, industry, agriculture, and transport sectors are the major sources (90%) of GHG emissions[4,5].

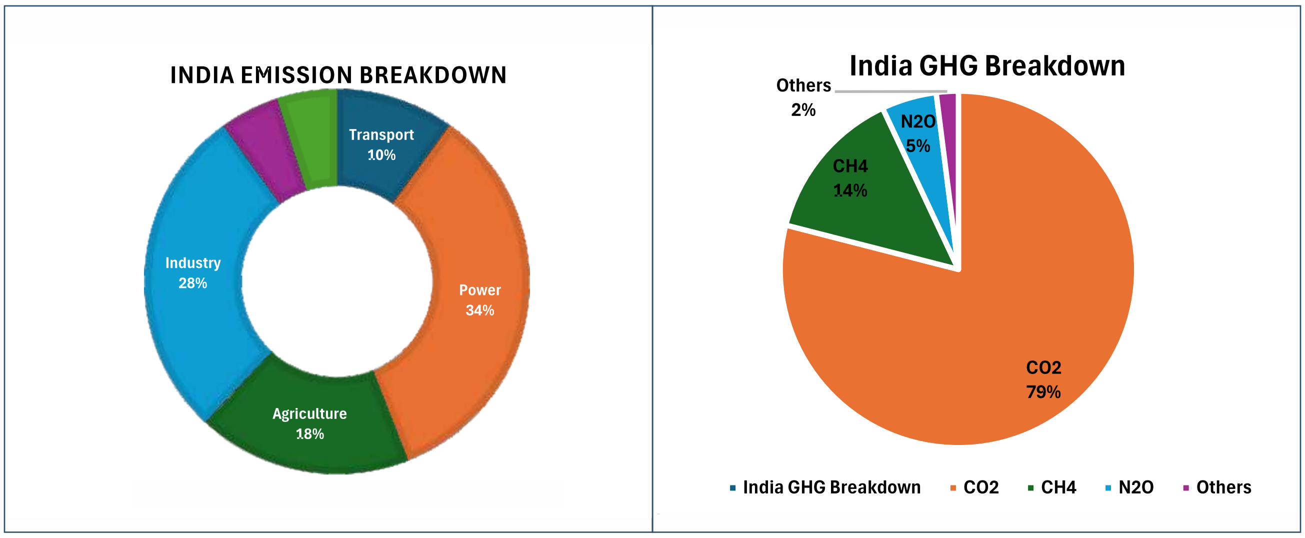


Figure 1: India's emission breakdown

Presently, the energy demand of the economy is met mostly by carbon intensive fuels like coal and oil. In GHG Economic Emission Intensity, a measure to track the energy used for producing a given amount of output (GDP), India stands at 1.5 kg CO_2 equivalent/$ [4]. In the recently submitted Nationally Determined Contributions (NDCs) report, India has vowed to reduce the emission intensity of GDP by 45% in 2030 from 2005 levels and set an ambitious target of adding 50% of cumulative installed electric power capacity through non-fossil-based sources by 2030 [6].

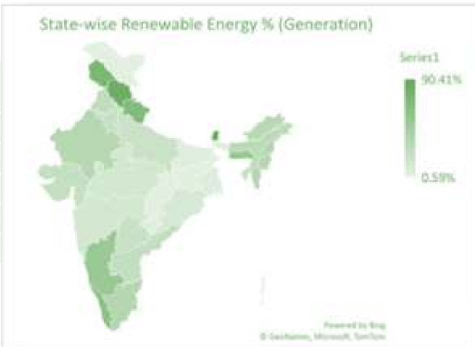
Energy transition accelerators

Energy, security and accessibility: India has high dependence on imported fossil fuels. In 2023, 88% of crude oil, 43% of natural gas and 25% of coal consumed in India were imported. The total crude oil and petroleum product import bill for FY2023-24 was \$156 B [7]. Energy accessibility in India has seen significant improvement over the years, yet challenges remain in terms of affordability and quality. Renewable energy sources such as solar, wind and sustainable liquid fuels can play an increasingly vital role in ensuring reliable, affordable and accessible energy sources that can boost economic activity and improve quality of life. This can also conserve forex outgo.

Sustainable Power

The Indian power and utility sector contributes to 34% of total GHG emissions, and fossil fuels constitute 75% of the total input energy mix[4]. There is a pressing need to decarbonize this sector as it can positively contribute to GHG emissions reductions in other industrial sectors. India has an installed electricity generation capacity of 453 Gigawatts (GW) with 44% generation contributed by renewables [8]. In the near term, implementation of carbon capture technologies, especially the post combustion type, can significantly reduce the emissions from the existing fleet of thermal power generation facilities. India's geography is naturally suitable to produce renewable power. India already has the world's fourth largest wind and solar power installations. Hilly regions and states in the Himalayas hold the current potential for half of the 21 GW [9] of small hydropower in the country. With 7500 km of coastline, peninsular India holds the potential for 75 GW [10] of offshore wind. India already has 42 GW [11] of onshore wind power, with potential to expand to 1164 GW[12]. Forty-six percent of potential wind power can be installed in waste land. With abundant solar incidence, majority of the Indian landscape can produce solar power to the tune of 748 GW assuming 3% of waste lands are covered with solar modules [13]. Low cost of wind and solar power compared to imported fossil fuels and abundance of solar and wind resources make renewable power a cheap source of electricity and India is adding new installations at CAGRs of 35% for solar[14] and 5% for wind[15]. The accelerated decarbonization of the Indian electric grid in the next several decades can enable the adoption of next generation liquid and gaseous fuels (eFuels) that utilize electrical energy as energy source to produce feedstocks such as captured CO_2 and green H_2.

Sr No	Net Zero Electricity States
1	Sikkim
2	Himachal Pradesh
3	Uttarakhand
4	UT of Jammu, Kashmir and Ladakh



Sr No	States with higher % of Non Fossils in Grid	
1	Kerala	70
2	Karnataka	56
3	Meghalaya	53
5	Tamilnadu	42
6	Nagaland	35
7	Rajasthan	34
8	Mizoram	33

Figure 2: India's Low carbon power distribution

Sustainable Mobility

The transport sector plays a key role in economic development and connectivity by facilitating the movement of goods and people, which is essential for trade, labor, commerce, and industry. Sustainable transportation entails the adoption of next-generation propulsion technologies, access to affordable, low carbon energy sources and world class infrastructure such as highways, airports, and ports that reduce the cost of logistics, enhance productivity, and improve the quality of life.

The Indian transport sector contributes 10% of total GHG emissions, with more than three hundred million vehicles on Indian roads and over 68,000 kilometers of railway networks [2,16]. In line with economic growth, passenger demand is expected to increase from 7.3 billion passenger kilometers (BPKM) in 2019-20 to 26.9 BPKM by 2050. Similarly, freight transport is projected to rise from 2.6-billion-ton kilometers (BTKM) in 2019-20 to 20.6 BTKM by 2050[17]. Aviation contributes 5% to transport sector emissions and it is poised to grow multifold due to the burgeoning middle class. By 2050, India is expected to be among the top three consumers of aviation fuel[18].

The wider availability of biomass feedstock, particularly agricultural and forest residues, presents an opportunity to produce sustainable transportation fuels that can effectively decarbonize hard-to-abate mobility segments such as aviation and long-distance surface trucking. Biomass can be converted to fuels either through thermochemical conversion, such as pyrolysis, or through gasification to produce syngas. Syngas can be converted to methanol or Fischer-Tropsch liquids which can be further upgraded to eFuels. Honeywell UOP eFining™ and Honeywell UOP FT Unicracking™ can accelerate the adoption of sustainable mobility. These two pathways eventually can leverage the anticipated deployment of green H_2 and captured CO_2 to produce eFuels and overcome challenges with respect to availability of feeds such as fats, oils and greases.

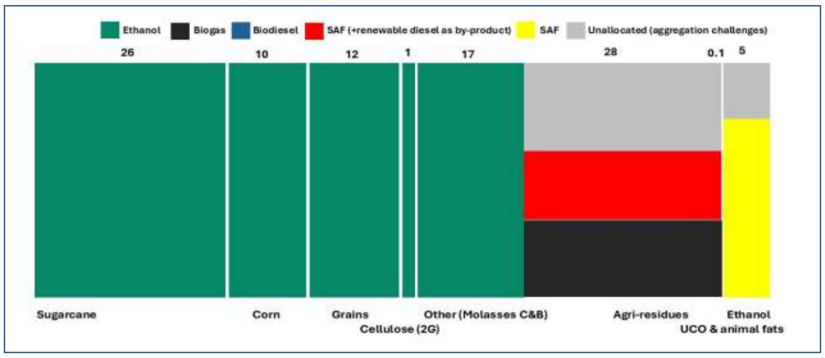


Figure 3: India's feedstock availability for biofuel productions

Industrial Decarbonization

Industrial manufacturing contributes to 28% of India's total greenhouse gas (GHG) emissions. However, the long-term economic growth of India heavily relies on the expansion of domestic industrial manufacturing. Key sectors such as steel, cement, refining, iron, aluminum, and mining are expected to grow through several capital expenditure cycles, leading to both larger investments and higher emissions.

India's Perform, Achieve & Trade (PAT) scheme, which has been implemented across many industry sectors, has been instrumental in driving significant energy efficiencies and emissions reductions.

Recently, the Indian government announced its intention to establish a national carbon market. This market aims to unify the currently fragmented market structures and enable emissions trading across industries. Such a move will accelerate the adoption of carbon capture technologies in industrial segments, paving the way for the availability of CO_2 sources and low-carbon industrial products that are export competitive. The availability of such CO_2 sources would be a trigger point for the emergence of eFuels.

Strategic role of eFuels in achieving Viksit Bharat 2047

Carbon capture from biogenic sources due to the mandated inclusion of biomass in power generation and the evolving green hydrogen capacity auger well for the development of eFuels that can complement biofuels in meeting mounting energy demand by 2047. Indian government through the National Green H_2 Mission (NGHM) has targeted to produce 5 Mt/y (Million Metric Ton Per Annum) of green H_2 by 2030 with an initial outlay of INR 19,744 crore[19]. Currently, 60 MW of green hydrogen production is under construction, and an additional 30,000 MW has been announced[22]. Green H_2 produced through the electrolysis of water by sustainable power can lead to the development of a new class of sustainable fuels known as eFuels. This power-to-liquid technology platform relies solely on the use of renewable energy for capturing CO_2, producing green H_2, and converting both CO_2 and H_2 into liquid eFuels. As a result, a sizable portion of the input renewable energy is converted into the chemical energy of eFuels. Honeywell UOP's ASCC and eFining technologies can capture CO2 from post-combustion sources and produce eFuels via methanol-to-jet pathways, enabling rapid decarbonization in transportation.

Advantages of e-fuels

Climate neutrality and GHG reductions: When produced using renewable electricity and captured CO_2 sources, e-fuels can achieve substantial GHG reductions compared to conventional jet fuel.

Infrastructure compatibility: The drop in nature of the e-fuels allows their direct usage in the existing infrastructure without any new modifications. This is critical for sectors such as aviation where immediate modification is impractical and cost prohibitive. Hence e-fuels facilitate a smooth and less disruptive transition to low carbon transportation.

Reduced resource intensity: Though biofuels produced from fats, oils and greases offer significant GHG benefits compared to their fossil counterparts, they require abundant land, water and fertilizers for crop cultivation. Further, the diversion of oil seeds for fuel production competes with global food security. On the contrast, e-fuels rely on captured CO_2 from industrial emissions, which is a burden free input for fuels and chemical derivatives.

Energy Storage: Renewable energy sources such as solar and wind are inherently intermittent. Co-location of an e-fuel production facility with renewable energy production center can absorb excess renewable energy during periods of high generation and low grid demand.

eFuels Production Triggers

The production of eFuels is a multi-stage process, often conceptualized under the umbrella term "Power-to-X" (PtX) or "Power-to-Liquids" (PtL) technologies. This process involves the conversion of H_2 and CO_2 into various hydrocarbon chains, yielding several types of e-fuels.

Green Hydrogen

Green hydrogen, serving as the primary energy carrier, is produced by splitting water into H_2 and oxygen (O_2) using an electric current, a process known as electrolysis. To qualify as "green," electricity powering this process must originate from renewable or low carbon sources such as wind, solar, or nuclear power. Alkaline water electrolysis, proton exchange membrane electrolysis, anion exchange membrane electrolysis to name a few are being used to produce green hydrogen. It is important to note that green hydrogen production through electrolysis involves energy conversion losses, typically around 20-30%, meaning 70-80% of the electrical energy expended is bound in the H_2 produced. The cost of green H_2 production is a paramount factor influencing the overall economic viability of eFuels. Thus, the eFuel production is heavily dependent on the electrolysis process. Breakthrough in electrolyzer designs and reduction in renewable electricity prices correlate with lower eFuels production cost.

Green H_2 produced has the potential to meet a country's decarbonization needs particularly in long distance trucking, as a scalable reduction agent for chemical manufacturing and as an industrial heating source replacing natural gas. India has the potential to emerge as an export hub particularly for the growing needs in ASEAN region. Honeywell's comprehensive suite of offerings such as catalyst coated membranes that drive electrolyzer performance, Protium for process control and optimization of a production unit, Polybed™ PSA, Polysep™ membranes for purification, liquid organic hydrogen carriers (LOHC) for intercontinental transport and gas grid injection packages for quality and quantity across intra-country pipelines can unlock significant value to investors and make India a world class destination of green hydrogen manufacturing.

CO_2

Carbon dioxide serves as the key feedstock for eFuels, and its origin is a critical determinant of the overall climate impact and sustainability of the final product.

Direct Air Capture: In this pathway CO_2 is directly extracted from the ambient air. This offers an advantage of capturing historic CO_2 emissions and provides circular carbon feedstock. Presently, its implementation requires significant land and low-cost renewable power due to the low concentration of CO_2 (400 wt. ppm) in the atmosphere.

Point Source Capture: Capturing CO_2 from concentrated industrial flue gases such as from power plants, H_2 production facilities, cement plants, steel mills through the usage of physical and chemical scrubbing.

Biogenic CO_2: This refers to the capture of CO_2 which is a byproduct of biofuels production such as from biogas, ethanol, biomass gasification and combustion (bagasse).

Honeywell offers a gamut of technologies tailored to specific industries for the efficient, sustainable and economic capture of CO_2.

Green hydrogen and captured CO2 are typically converted to synthesis gas (mixture of CO and H2) which is then further transformed into different eFuels. The table below depicts some examples of eFuels and their applications.

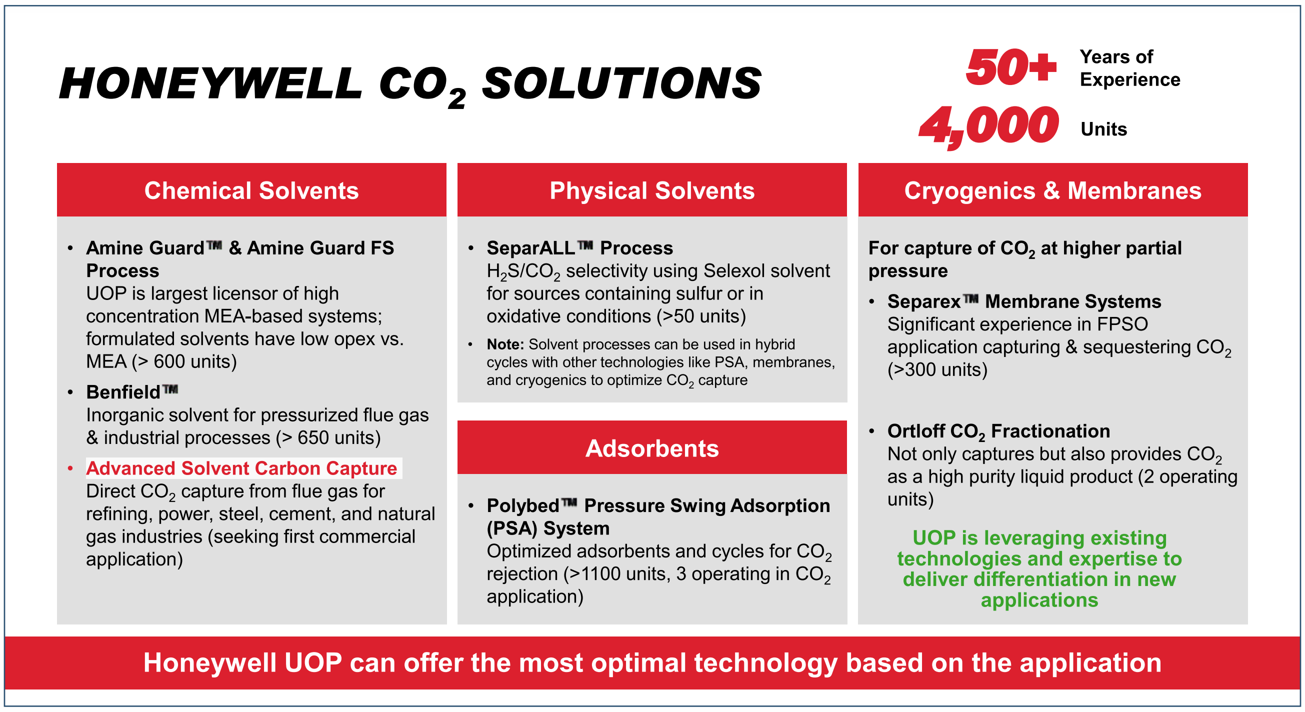


Figure 4: Carbon capture technology options

eFuels	Inputs	Application
eMethanol	Green H2 (water electrolysis), CO2 (DAC, Post combustion sources, biogenic)	Marine fuels, pre-cursor for e-SAF, building block for sustainable chemicals
eAmmonia	Green H2 (water electrolysis), N2 (air separation)	Marine fuels, energy storage, hydrogen carriers and sustainable fertilizer
eSAF	Green H2 (water electrolysis), CO2 (Biogenic, DAC, post combustion sources)	Aviation fuel blend stock
eDiesel	Green H2 (water electrolysis), CO2 (Biogenic, DAC, post combustion sources)	Surface transport and marine fuel applications

eFuels production

Here, we will take a detailed look at how eSAF can be a game changer in decarbonizing the aviation, which is a hard to abate mobility sector. Though there are competing pathways for producing SAF such as from fats, oils, greases and ethanol, eSAF opens opportunities for captured CO_2 utilization and access to lean organic feeds such as agricultural and forestry residues. There are two prominent pathways to produce eSAF, namely Fischer Tropsch and eMethanol.

Fischer Tropsch (FT) pathway

Viable feedstocks for this pathway include synthesis gas derived from biomass, municipal solid waste and biogas. Alternatively captured CO_2 can be converted to CO in a reverse water gas shift reactor to produce synthesis gas that can be fed to Fischer-Tropsch (FT)reactor. Subsequently in the FT process, carbon monoxide (CO) and hydrogen (H_2) are converted into liquid hydrocarbons, lights gases and waxes. Honeywell's Fischer-Tropsch (FT) Unicracking™ technology takes liquid hydrocarbons, waxes, and produces SAF that complies with the strict standards of the aviation industry and results in a lower environmental impact. Honeywell's new FT Unicracking™ process uses a combination of proprietary, commercially proven, highly selective hydrocracking and hydroisomerization catalysts to produce 3-5% more sustainable aviation fuel (SAF), reduce by-product waste and achieve up to 20% cost reduction compared to other commonly used FT-hydrocracking methods. The FT synthetic paraffinic kerosene (FT-SPK) produced is approved under ASTM D7566 and is approximately 90% less carbon intensive than traditional fossil based jet fuels [20].

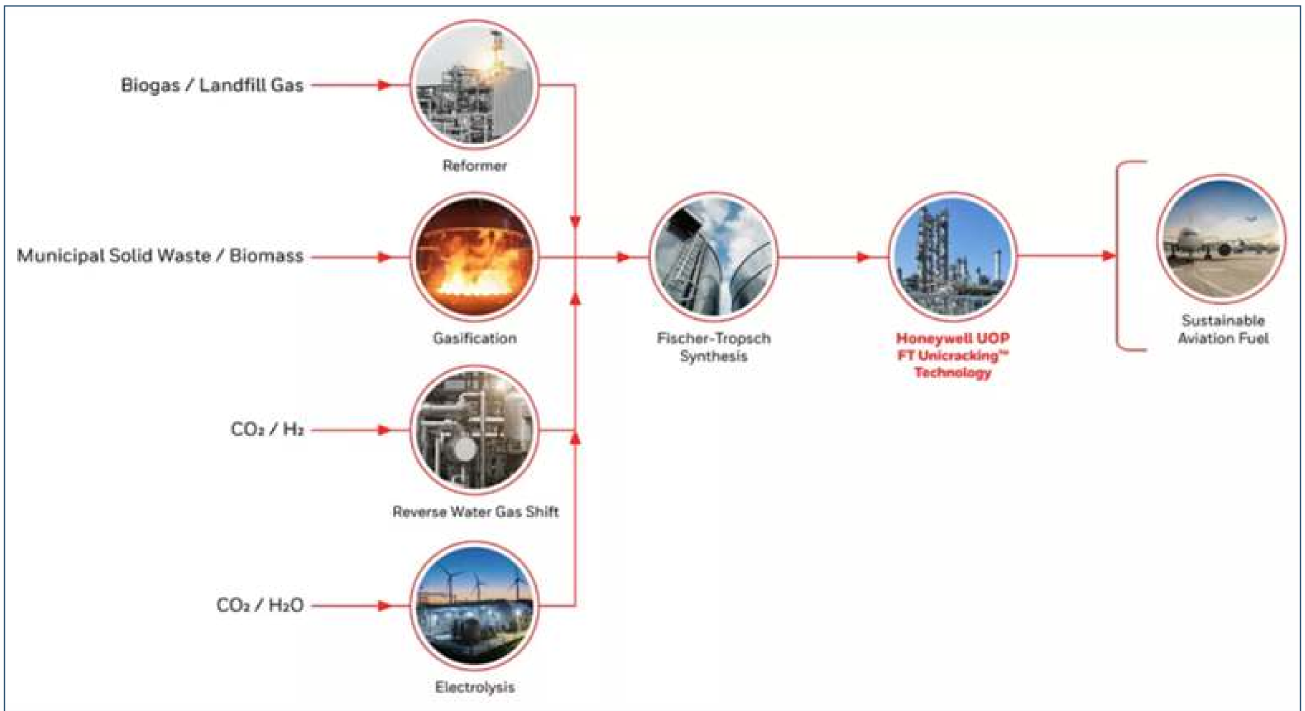


Figure 5: Pathways for Sustainable fuels through FT Unicracking™

This technology is suitable for both new installations and retrofits. This technology, when integrated with existing FT processes, allows for the expansion of feedstocks by enabling new pathways through biomass to liquids (BtL), gas to liquids (GtL), waste to liquids (WtL) or power to liquids (PtL). Honeywell recently announced the formation of a strategic alliance with Johnson Matthey, GIDARA Energy, and Samsung E&A to provide an end-to-end solution with a single point of accountability for converting waste (biomass and municipal solid waste) into SAF. The integrated solution can reduce time between initial engagement and facility start-up by more than 15%, resulting in 5-10% capital cost savings [23].

eMethanol Pathway

eMethanol can be produced commercially from green hydrogen and captured CO_2 including biogenic sources.

Figure 6: eSAF production ecosystem

Honeywell's UOP eFining technology uses eMethanol, a useful, transportable intermediate made from captured CO_2 and green hydrogen to produce eSAF reliably and at scale. This innovative technology achieves high selectivity to jet products through selective recycle flow schemes. UOP eFining has high feed and product slate flexibility and can produce low-carbon-intensity SAF from methanol that is derived from captured CO_2 or from municipal waste. The process features a highly integrated design with minimal CAPEX and plot space.

FEATURES & BENEFITS

- Built on existing commercially proven technology
- Low carbon intensity SAF production
- High SAF yield and selectivity
- Minimized CAPEX and plot space
- Reliable, scalable process steps
- Highly integrated process design
- High-efficiency equipment
- High-value, transportable intermediates enable hub and spoke approach

Honeywell UOP eFining is built on Honeywell UOP's commercially demonstrated methanol to olefin technology (MTO) and decades of experience with oligomerization technologies such as CatPoly, InAlk™, and Catolene™. Honeywell UOP has leveraged learnings from its 37 years of combined MTO operating experience and decades of oligomerization unit designs to develop a highly selective, low carbon intensity approach to jet fuel production. In addition this pathway opens opportunities for green shipping through eMethanol and production of ePetrochemical precursors such as olefins.

Honeywell SAF product meets or exceeds the qualities of aviation fuel required in ASTM D7566 Annex 5. The UOP eFining process successfully converts many types of low-carbon methanol, regardless of the synthesis method, into on-spec, renewable jet fuel. This flexibility gives fuel producers the option to choose the H_2, CO_2, and/or syngas source or even the option to combine multiple feed sources best suits their location and operation goals[21].

SAF PROPERTIES

Properties		Value
Total Acidity KOH, mg/g	Max	0.015
Density at 15°C, kg/m³		730-770
Flash Point, °C	Min	38
Freezing Point, °C	Max	-40
Cycloparaffins, wt%	Max	15
Aromatics, wt%	Max	0.5
Distillation, °C		
T10	Max	205
FBP	Max	300
T90-T10	Min	21

Conclusions

The advancements in eFuels production, as detailed in this paper, highlight the significant potential of this technology in addressing India's energy challenges particularly in the next several decades. By leveraging the adoption of renewable power sources coupled with technology and business innovation in green H_2 and captured CO_2, eFuels offer a sustainable and scalable solution to reduce carbon emissions across diverse industrial segments. The integration of eFuels into the energy systems not only enhances energy security but also contributes to the transition towards a greener and more resilient future. Continued research and development in this field will be crucial to overcoming technical and economic barriers, ensuring that eFuels can play a pivotal role in the Indian energy landscape. Honeywell with its broad suite of eFuels technology portfolio and its strong presence in the country can aid in shaping India as a world class manufacturing hub for next generation eFuels.

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Petrochemical Intensity of Future Refineries and Crude-to-Chemicals

Mr. Pedro M Santos, Senior Director Technology
& Shri Shekhar Tewari, Technology Manager
Chevron Lummus Global

Introduction

As the global energy landscape undergoes a seismic shift driven by sustainability goals, economic pressures, and evolving consumer demands, the refining industry faces a pivotal challenge: how to maximize the value of crude oil while minimizing environmental impact. India too has pledged to achieve Net Zero targets by 2070. This along with the growing domestic demand of energy and polymers has put a tremendous pressure on the industry to seek an optimal pathway of achieving higher petrochemical intensity for existing as well as future refineries. While conventional methods of integrating refineries with petrochemical units provides an improvement in petrochemical intensity, it does so at higher capital expense and higher operating cost leading to significant carbon emissions.

Thermal Crude to Chemicals Technology (TC2C™) is a transformative technical innovation for crude to chemicals conversion developed jointly by Saudi Aramco Technologies Company, Lummus Technology and Chevron Lummus Global (CLG). TC2C™ redefines the traditional refinery model by converting crude oil directly into high-value chemicals, bypassing many conventional steps and unlocking unprecedented efficiency and profitability.

TC2C™ is a modern intensification of traditional processes, by taking the key technological features of commercially proven technologies and fusing them together to meet new processing objectives. The technology integrates desalting, targeted crude separation, crude conditioning, and steam cracking to maximize the yield of high value chemicals. Crude is a mixture of millions of molecules. TC2C™ relies on advanced analytical techniques to first segregate easy to convert and high chemical yielding molecules and then selectively treat the heavier molecules with the optimum addition of hydrogen so that the mixed feed stream cracker (MFSC) section of the TC2C™ produces the optimal chemicals at minimum energy. Lummus' extensive experience in cracking wide range of liquid feeds in MFSC is the foundation for optimizing the front end crude conditioning configuration and tailoring the operating conditions to prepare the feedstocks for steam cracking.

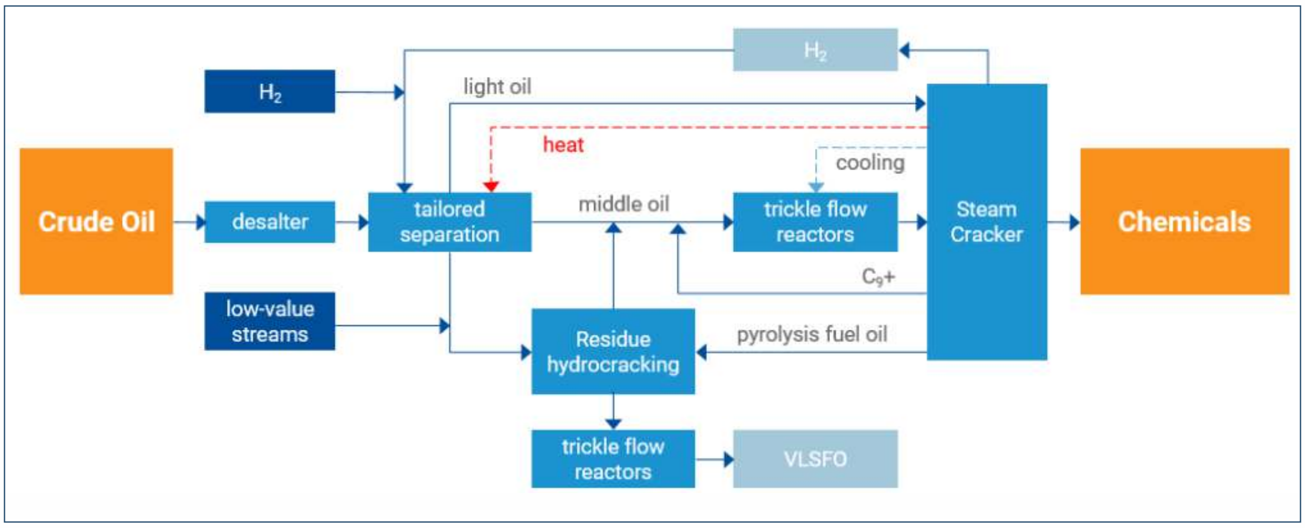
TC2C™ is derived from fundamental research in the areas of process technology, process chemistry, and catalyst technology through a robust, multi-year R&D program. This R&D program led to the development of novel, groundbreaking enhancements for crude to chemicals applications , including these key features, to name a few:

- ✓ Use of new novel proprietary separation devices which eliminates the need for energy intensive, conventional crude atmospheric and vacuum distillation units.
- ✓ Breakthrough hydrocracking catalyst with a tailored mesoporous zeolite for crude to chemicals application
- ✓ TC2C™'s fixed bed and liquid circulation reactors, which are smartly configured to selectively condition crude for MFSC to produce petrochemical building blocks such as ethylene and propylene along with other chemicals
- ✓ TC2C™ also provides the benefit of utilizing the low value orphan streams of refinery and petrochemical complex providing high chemical yield. For instance, Pyrolysis fuel oil is a highly hydrogen deficient material, rich in multi-ring aromatics with low market value, and TC2C™ upgrades this material to high value chemicals products.

TC2C™ as Advanced Refining Approach

Whole crude oil is typically fractionated in a crude oil refinery into a variety of fractions such as naphtha, kerosene, diesel, gas oil (vacuum or atmospheric) and high boiling residuum. Some of these fractions are used as starting feedstock for olefin production in petrochemical industry. Therefore, the starting feedstock for conventional olefin production is first subjected to substantial, expensive and energy demanding refining processes. TC2C™ technology redefines crude to chemicals pathways in an economically viable manner without passing through the conventional refining steps thus providing economically better route for crude to chemical conversion.

TC2C™ is a concept and a technology platform, not a fixed flow scheme. Depending upon the feeds, products and the targeted product slate, the details on the configuration are selected to meet the processing objectives.. One such configuration of TC2C™ is shown below:



In TC2C™, a normal paraffin rich light oil stream is recovered from starting feedstock (wide API range of crudes and/or condensates) using a novel separation device. This approach eliminates heavier molecules from the intermediate stream that is directly routed to the steam cracker. This step uses dilution steam to recover the n-paraffin rich lighter cut. Bottoms from the separation device are routed to another separation device that recovers a middle oil stream which is sent for fixed bed hydroprocessing for contaminant removal and hydrogen addition, using a carefully selected catalyst system. The severity of the reactions are adjusted depending on the feedstock and operating objectives, and optimizes the hydrogen consumption required to optimize the chemicals conversion. Hydroprocessing upgrades the quality of middle oil which results in improved yield of high value products and reduced fuel oil make from steam cracker.

The heaviest portion of the crude, which contains the highest concentration of contaminants such as metals, CCR, and asphaltene, is routed to a liquid circulation (LC) reaction platform utilizing either extrudate or slurry catalyst. The most critical technology component is these residue hydrocracking reactors as they deal with conversion of asphaltenes from crude. The LC reaction section converts the asphaltene and recycle pyrolysis oil from the steam cracker along with other low value stream available from refinery. The remaining unconverted oil is filtered and sent over a fixed bed reactor system to meet IMO-compliant very low sulfur fuel oil (VLSFO) specification (<0.5 wt% S). Products from converted products LC reaction section are further treated in fixed bed reactor which further improves the quality of cracker feed for optimal cracking heater run length and chemicals yield. This system ensures that no heavy polynuclear aromatics (HPNA) reach the steam cracker.

Thus, TC2C ensures that no part of the converted crude is wasted while maximizing the yield of chemicals. While simultaneously ensuing that the reliability of the refinery components matches the reliability of the cracker in terms of on-stream factor.

Key Benefits of TC2C™ for Chemicals and Fuels

One of TC2C™'s most compelling advantages is its ability to convert up to 80 wt% of crude oil into chemicals, including olefins and aromatics. This high yield is crucial in a market where petrochemical demand is outpacing GDP growth, especially in developing economies like India. A comparison of chemicals make of TC2C™ against conventional chemical refinery and naphtha cracker complex is provided below. The comparison is based on generating 2000kTA Ethylene product from the complex along with other incidental products. As evident from this comparison, TC2C™ provides significantly high chemical yield compared to a typical refinery while generating no low value streams such as PFO or LSFO. As compared to the naphtha cracker, TC2C™ provides benefit wrt naphtha vs crude price spread while maximizing the high value products make.

Flowrates in kta	TC2C Complex	Chemical Refinery	Naphtha Cracker
Crude	6262	8355	0
Naphtha	0	0	4806
Ethylene	2000 (32%)	2000 (24%)	2000 (42%)
Propylene	1396 (22%)	1664 (20%)	824 (17%)
Other chemicals	1295 (21%)	2163 (26%)	806 (17%)
VLSFO	567 (9%)	0	0
LSFO / PFO	0	1348 (16%)	248 (5%)
Total chemicals	4691	5827	3630
Total high value products	5258	5827	3630
% Chemicals / High Value Products	75.0 / 84.0	69.7 / 69.7	75.5 / 75.5

By eliminating several energy-intensive refining steps and optimizing hydrogen usage, TC2C™ significantly reduces greenhouse gas emissions. The process is designed to be energy-efficient, aligning with global decarbonization goals and ESG mandates. Comparison of Specific energy and carbon emission is provided below for TC2C complex vs typical refinery and Naphtha cracker is provided below. As evident from the table below, TC2C consumes lowest energy and therefore generates least quantity of carbon emissions per kg of high value chemicals make from the unit.

Specific Energy	TC2C Complex	Chemical Refinery	Naphtha Cracker
kcal/kg ethylene	7243	10075	5156
kcal/kg chemicals	3024	3458	2841
kcal/kg high value products	2553	3458	2841
CO2 emissions			
kg/kg ethylene	1.45	2.09	1.08
kg/kg chemicals	0.61	0.72	0.6
kg/kg high value products	0.51	0.72	0.6

TC2C™ offers 30–40% savings in capital and operating expenditures compared to conventional refining setups. This is achieved through elimination of atmospheric and vacuum distillation units, significantly reduced equipment count, and lower utility consumption. This upfront saving improves the project returns on investment and make the profits sustainable for the operator.

Historically, crude to chemicals complexes have been designed around very light crudes and condensates, which require little to no conditioning prior to feeding into petrochemicals complex. The technology platform breaks through the traditional feedstocks limitations and extends technology solutions/offerings to a wider feed basis with the ability to upgrade the bottom of the barrel and optimize the hydrogen consumption to improve the overall yield of chemicals.

TC2C™ can process a wide API range of crude and condensate feedstocks, including low-value orphan streams such as high sulfur fuel oil, slurry oil and light cycle oil (LCO) from FCC and low-value recycle stream from Mixed Feed Steam Cracker (MFSC). In the development of TC2C™, a major focus area was on the PyOil processing, including testing of different types of pyrolysis oils at a wide range of pyoil proportions in the feed mix to ensure that the concept was robust. Pyrolysis fuel oil is a highly hydrogen deficient material, rich in multi-ring aromatics with low market value. Adding the pyrolysis oil to the liquid circulation reactors where asphaltene conversion takes place, permits higher conversion of asphaltenes, while maintaining product stability.

This flexibility enhances operational resilience and feedstock optimization. This feature also makes it a technology of choice for refiners who are willing to improve their chemical footprint while getting rid of the low value streams.

Integration Benefits of TC2C™

Unlike typical refinery and petrochemicals set up, TC2C™ offers a seamless Integration within the crude conditioning section reactor platforms and between the crude conditioning and steam cracker sections of the unit. This integration allowed the joint team of various SME's to reimagine the process configuration and eliminate processing equipment which is not required to meet the new processing objectives. TC2C™ is designed to tailor the hydrogen content of crude components to create an optimal feed for mixed-feed steam crackers, which boosts the production of ethylene, propylene, and other valuable olefins. Hydrogen generated in the steam cracker can be utilized in the hydroprocessing reactors.

Low value cracker streams such as PGO and PFO can be processed in the crude conditioning fixed and/or ebullated bed reactors to improve the overall chemicals yield. Not only materials such as recycles, hydrogen and utilities are exchanged between crude conditioning section and steam cracker, processing conditions are also optimally utilized within and between these sections which is essential for improved carbon intensity of the process.

TC2C™ utilizes the CLG's commerically proven experience of integrating multiple fixed-bed and liquid circulation reactors in crude conditioning section, enabling selective conditioning of crude and efficient conversion of crude molecules to a full boiling range of feed molecules which can be routed directly to the steam cracker. This intensification reduces the number of processing steps and improves profitability of the unit.

Strategic Implications for Refiners

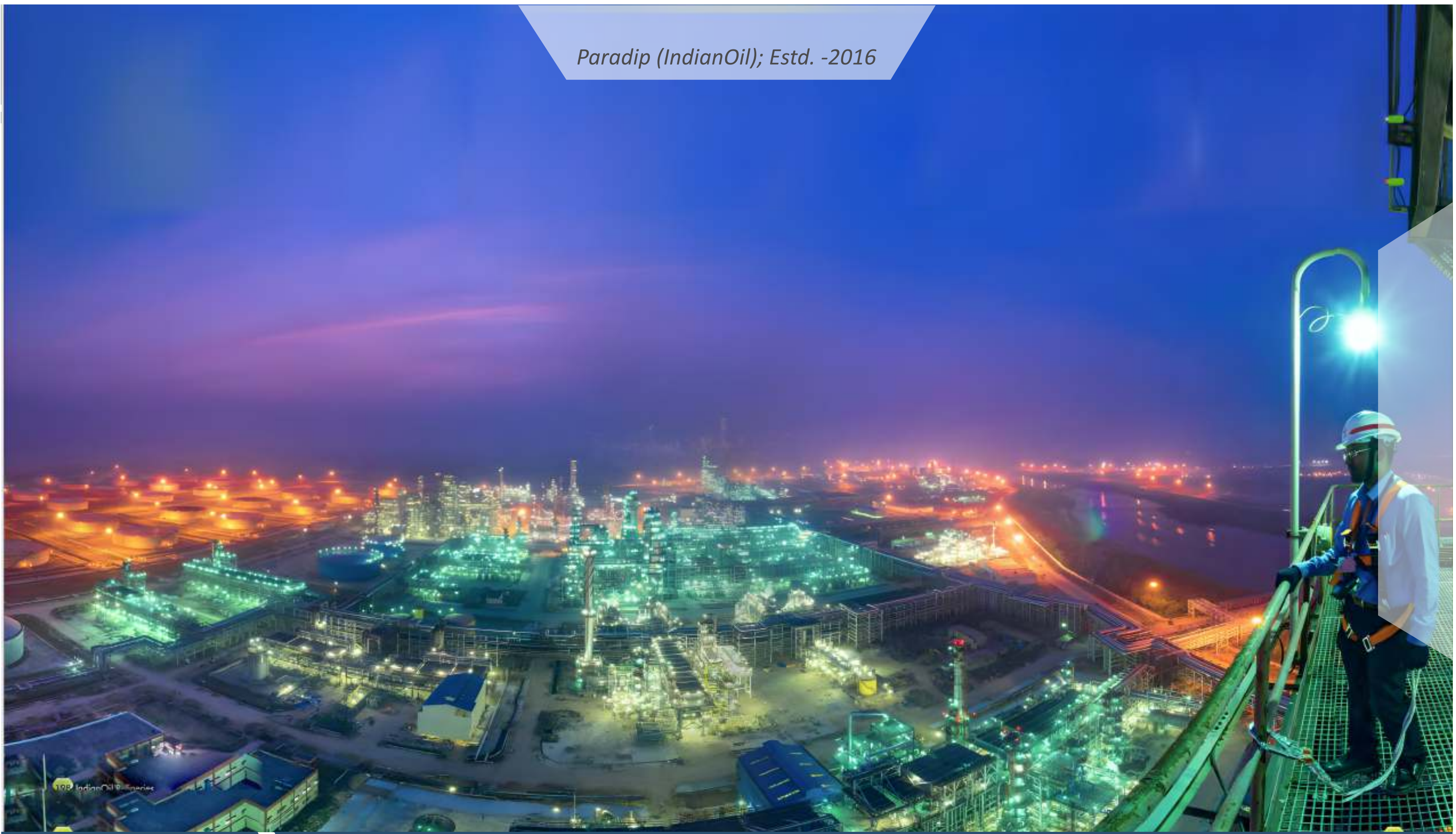
With global fuel demand plateauing and petrochemical consumption surging, TC2C™ enables refiners to pivot toward chemicals, capturing higher margins and future-proofing their operations. By reducing emissions and improving energy efficiency, TC2C™ helps refiners align with sustainability targets, regulatory requirements, and investor expectations.

The ability to process diverse feedstocks and produce multiple high-value outputs makes TC2C™ a strategic hedge against market volatility, feedstock price fluctuations, and geopolitical risks.

Despite its innovative nature, TC2C™ is built on commercially proven components, minimizing the risk associated with new technology adoption. This ensures high on-stream factors and operational reliability. The first license for TC2C™ was granted to S-OIL for their SHAHEEN project in early 2020, which is being constructed in Ulsan, Republic of Korea, marking a significant milestone in the technology's commercialization journey. The S-OIL SHAHEEN project is scheduled to begin operations in the second half of 2026. Since then, several grassroots and brownfield opportunities have emerged, demonstrating the technology's adaptability and market appeal.

Conclusions

TC2C™ technology represents a paradigm shift in refining, offering a smarter, cleaner, and more profitable way to convert crude oil into chemicals. With its high yield, integration flexibility, and sustainability credentials, TC2C™ is poised to become a cornerstone of next-generation refineries. As the industry in India and elsewhere navigates the twin challenges of energy transition and economic uncertainty, TC2C™ provides a robust, future-ready solution that maximizes value from every barrel of crude. Optimal consumption of crude will help reduce the ForEx outgo in importing crude for the domestic demands making this a technology of choice for a cleaner, sustainable and self-reliant energy future.


Paradip (IndianOil); Estd. -2016

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Turning the problem into a solution: Transforming polluting Carbon dioxide into fuel

Dr Pankaj Sharma, Addl Director;
Shri Vijay Kansal, Addl Director;
Shri V V Varaprasad Beera, Addl Director;
& Shri Surya Bhan Mall, Asst Director
Petroleum Planning and Analysis Cell, MoPNG

Ten years ago, the Paris Agreement, set a goal to limit global warming to well below 2°C above pre-industrial levels, with efforts to limit it to 1.5°C. Yet 2024 has been the hottest year on record with the global mean near-surface temperature estimated to be 1.55 ± 0.13 °C above the 1850-1900 average. With growing energy demand world over, the fossil fuels continue to rule the energy basket. Total energy driven CO2 emissions increased by 0.8% in 2024, hitting an all-time high of 37.8 Gt CO2 .

The carbon emissions have been posing major challenges before the world since the days of industrial revolution, and the world seems to be struggling to keep check on the same. The solution lies in transition to a no or low-carbon energies. But can we turn the problem into a solution. Transforming carbon dioxide (CO_2) from a climate problem into a power solution—and positioning carbon monoxide (CO) as a game changer for energy transition—has become a stimulating field at the intersection of energy, chemistry, and climate tech. The question before the Energy transition policy makers is, **"Can CO2 Power the world"**.

Energy transition, simply explained, is to bring about a change in how we produce and use energy. It means transitioning from sourcing energy that produces carbon dioxide to generating clean energy.

The emissions pollute the environment and cause climate change and we intend to shift towards cleaner sources like the sun, wind, and water that don't harm the environment. For populous countries like India, reducing waste is very important today because it helps protect the environment by conserving natural resources, reducing pollution, and lowering greenhouse gas emissions that contribute to climate change. When less waste is generated or the generated waste is utilized, there is a decreased need for landfills and incineration, which cause air, water, and soil pollution.

The energy transition focused on reducing carbon dioxide (CO2) emissions increasingly relies on carbon capture technologies as a vital tool alongside renewable energy and energy efficiency. Carbon capture and storage (CCS) involves capturing CO2 emissions from large sources—such as power plants and industrial processes like cement and steel manufacturing—before they reach the atmosphere, then transporting and securely storing this CO2 underground in geological formations. The technologies are however in the nascent stage. Instead, the alternative pathway for residue or waste utilization represents a win-win situation for all by turning waste into valuable resources rather than discarding it. This approach reduces environmental pollution and greenhouse gas emissions, supports a circular economy by maximizing resource efficiency, and conserves natural resources. For businesses, it offers cost savings, new revenue streams, and enhanced sustainability credentials. Communities benefit from job creation and economic development, while governments see reduced waste management burdens and improved public health outcomes. Overall, this pathway aligns environmental, economic, and social goals to create lasting value across the entire system.

The global energy transition increasingly emphasizes sustainable approaches like **waste-to-energy (WtE)**, where waste streams are transformed into valuable energy, fuels, or chemicals. Among advanced WtE strategies, processes that convert **carbon monoxide (CO)**—often generated from gasification or pyrolysis of waste—into useful chemicals and fuels are particularly significant. These methods utilize synthesis gas (syngas), a mixture rich in carbon monoxide and hydrogen, to produce substances such as **methanol, hydrocarbons, and other industrial feedstocks.** This not only recycles waste into marketable products but also provides a crucial environmental benefit: since CO can be further processed instead of releasing it or allowing it to oxidize into **carbon dioxide (CO_2),** these technologies **directly prevent additional CO_2 emissions.** Such integrated approaches underpin a circular economy by both supplying renewable energy (made from waste) and materials and by displacing fossil fuel use, thus reducing the carbon footprint of energy and manufacturing sectors. Continued advancements in catalytic processes and electrochemical methods are improving the efficiency and scalability of these CO conversion pathways, supporting the global move toward net-zero emissions and a more sustainable future

Carbon dioxide (CO_2, O=C=O) and carbon monoxide (CO, C≡O) are both gases composed of carbon and oxygen atoms, yet they differ significantly in their composition, properties, and impact on life and the environment. Carbon dioxide is a naturally occurring Non-flammable gas in Earth's atmosphere, essential for plant life through photosynthesis and a byproduct of respiration in animals and humans, generally non-toxic at normal concentrations, but can be harmful or fatal in high concentrations by causing respiratory distress. It is generated through the process of Respiration, decomposition of organic matter, combustion (burning of fuels). **A greenhouse gas essential for plants (photosynthesis) but contributing to global warming at excessive levels.**

Carbon Monoxide, on the other hand, does not occur naturally, **is flammable** and is primarily man-made. Its effect on human life is highly toxic even at low concentrations, binds to haemoglobin in the blood, leading to symptoms like headaches, dizziness, and confusion, with potential for fatal poisoning. It is generated through incomplete combustion of carbon-containing fuels like gasoline, coal, and wood (e.g., from car exhaust, malfunctioning heaters, fires).

The below Section details how Carbon Monoxide can be the future fuel.

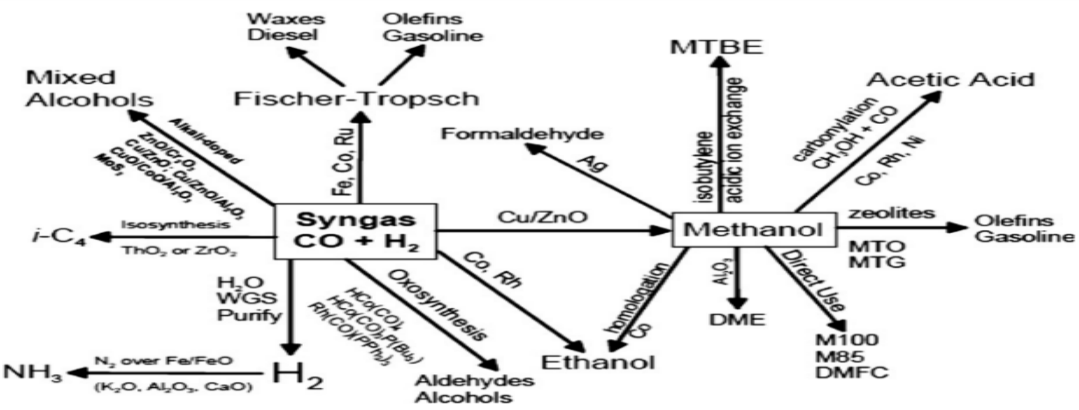
Syngas, a mixture of hydrogen (H_2) and carbon monoxide (CO) from gasifying carbonaceous feedstocks, has been in use since 1812 when the London Gas, Light, and Coke Company first commercialized it. As a key link in the circular value chain, syngas is increasingly important for process heat, power generation, and liquid fuels. Gamifying contaminated feedstocks transforms polluting fuels or waste into valuable materials, while gasified biomass supplements fossil-based energy and provides renewable chemicals and fuels. Syngas is widely used in the chemical and petrochemical industry and as a clean hydrogen-based fuel, with about half the energy intensity of natural gas.

Researchers are developing reverse water-gas shift processes to convert CO_2 to CO and H_2, with commercial-scale projects underway following pilot successes. CO_2 feed can be sourced from flue gases of industrial plants—such as coal and gas-fired power stations—using capture technologies like amine adsorption. Any carbon-based material can serve as feedstock for syngas production, though current focus is on natural gas, coal, biomass, and bio-waste. Commercial processes include steam methane reforming (SMR), auto-thermal reforming, combined and tri-reforming, partial oxidation of methane, biomass gasification, waste-to-energy gasification, and alternative methods like heat exchanger reforming, membrane reactors, and underground gasification. Gasifiers used include moving bed, fluidized bed, and entrained flow designs.

In refineries, SMR is the main hydrogen production route, producing syngas with H_2/CO ratios of 3:1 to 5:1; hydrocarbon gasification yields 1.6–1.8 ratios. Biomass gasification offers lower yields but reduces landfill waste and environmental impact. Membrane reactors separate hydrogen during reaction, while underground coal gasification burns coal seams in situ to produce syngas. Currently, CO in off-gases is often oxidized to CO_2 due to the difficulty of separating CO from N_2; when recovered, it is purified by pressure swing adsorption or cryogenic distillation. Steel and iron manufacturing emit 5–7% of global man-made CO_2, with one-third from CO oxidation—capturing CO could significantly aid carbon-neutrality.

Globally, CO-to-chemicals and fuels technologies are advancing: China leads large coal-to-chemicals and CTL projects with strong policy support; US combines mature methanol production with emerging electrochemical research backed by incentives; Europe focuses on R&D, pilot projects, and linking CCU to climate targets, with green methanol and e-fuel projects growing. Each region leverages its strengths—China's scale, Europe's innovation, and US policy support—to expand sustainable CO conversion.

<u>**Major Processes for Converting Carbon Monoxide (CO) to Chemicals and Fuels**</u>



Spath PL, Dayton DC. Golden, CO: NREL; December 2003.

1. Fischer–Tropsch Synthesis (FT)

Converts CO and hydrogen (syngas) into liquid hydrocarbons (fuels like synthetic diesel, gasoline, waxes) using metal catalysts (often iron or cobalt) at high temperature and moderate pressure.

Reaction: $(2n+1)H2+nCO \rightarrow CnH2n+2+nH2O(2n+1)H2+nCO \rightarrow CnH2n+2+nH2O$

Applications: Production of synthetic fuels from coal, natural gas, or biomass-derived syngas.

2. Methanol Synthesis

Catalytic reaction of CO (and CO_2) with hydrogen, usually over Cu-ZnO-Al_2O_3 catalysts, at high pressure and moderate temperature to produce methanol. Reaction: $CO+2H2 \rightarrow CH3OHCO+2H2 \rightarrow CH3OH$

Applications: Methanol is a key chemical feedstock and alternative fuel, underpinning the methanol-to-olefins and methanol-to-gasoline industries. It is vital for producing acetic acid, formaldehyde, methyl methacrylate, and methyl tertiary-butyl ether (MTBE). Globally, 55–65% of methanol is produced from natural gas, 30–35% from coal, and the rest from coking gas and other feedstocks. Beyond chemical uses, methanol is emerging as a key enabler in the hydrogen economy, as it can be reformed to release H_2, serving as a practical liquid hydrogen carrier with simpler storage and handling than compressed or liquefied hydrogen.

3. Carbonylation Processes

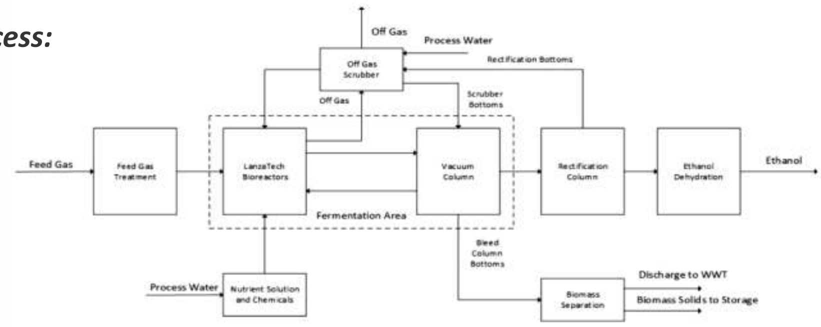
Incorporation of CO into organic molecules to produce chemicals such as acetic acid, acrylic acid, formic acid, and pharmaceuticals via transition metal-catalyzed carbonylation (hydroformylation, alkoxycarbonylation, aminocarbonylation). Applications: Industrial synthesis of acids, aldehydes, alcohols, amides. Reaction:

$RCH=CH2+CO+H2 \rightarrow RCH2CH2CHORCH=CH2+CO+H2 \rightarrow RCH2CH2CHO$ (hydroformylation)

4. Conversion to Ethanol - Gas fermentation technology

Gas fermentation technologies convert waste gases—such as steel mill off-gas, gasified unsorted municipal solid waste, and refinery off-gas—containing CO and CO_2 into ethanol and other useful chemicals. In this process, carbon-rich gas is compressed, purified, and fed into a fermentation system, where a proprietary biocatalyst converts these gases to produces ethanol. The gas is sourced directly from industrial carbon emission points. M/s LanzaTech has pioneered and commercialized a complete, integrated platform for continuous conversion of CO, H_2, and CO_2 gas mixtures into ethanol.

Schematic of process:



a) Steel mill off gases: Blast Furnace (BF) gas from steel making is one of the most abundant of the industrial off gases and is available in large quantities (single site availability of up to 1.5 million Nm3/h), BOF gas contains only 0-25 moI% CO, 0-5 moI% H2 wlth high concentrations of inert gases (20-25 moI% CO2, and 50 moI% N2). ArcelorMittal is currently operating a commercial LanzaTech gas fermentation plant in Ghent, Belgium producing ethanol from BF gas. Shougang Steel is operating a commercial gas fermentation facility to produce ethanol from BOF gas since 2018.

b) Refinery Hydrogen unit off Gases (3G Ethanol plant) : Refinery processes produce a number of gas streams that are not utilized in further catalytic processing but instead used for heat generation, flared or otherwise considered as "waste" gas streams that have the potential for higher use as feedstocks for fuel, due to rebalancing and introduction of alternate energy sources. The tail gas from Pressure Swing Adsorption (PSA) units used for purifying hydrogen, specifically from mixtures like those produced by steam methane reforming (SMR), is one example. It is relatively rich in H2 (24-26%) and low in CO (0-2%) and contains high concentrations of CO2 (50-55%) as well as methane. LanzaTech gas fermentation technology is currently being used to produce ethanol from PSA tail gas on a commercial scale.

c) Solid Waste

Municipal Solid Waste (MSW)and biomass residue can be converted to syngas via gasification for use in gas fermentation, which can process syngas from any gasifier, making all solid wastes viable feed stocks. Gasifying MSW into fuels and chemicals achieves around 40% carbon capture in products, with non-gasifiable portions removed through shredding, screening, and separation. Gasification also applies to various biomass streams, including woody biomass, with the resulting syngas converted into ethanol through LanzaTech's gas fermentation process.

Challenges and Future Outlook for gas fermentation:

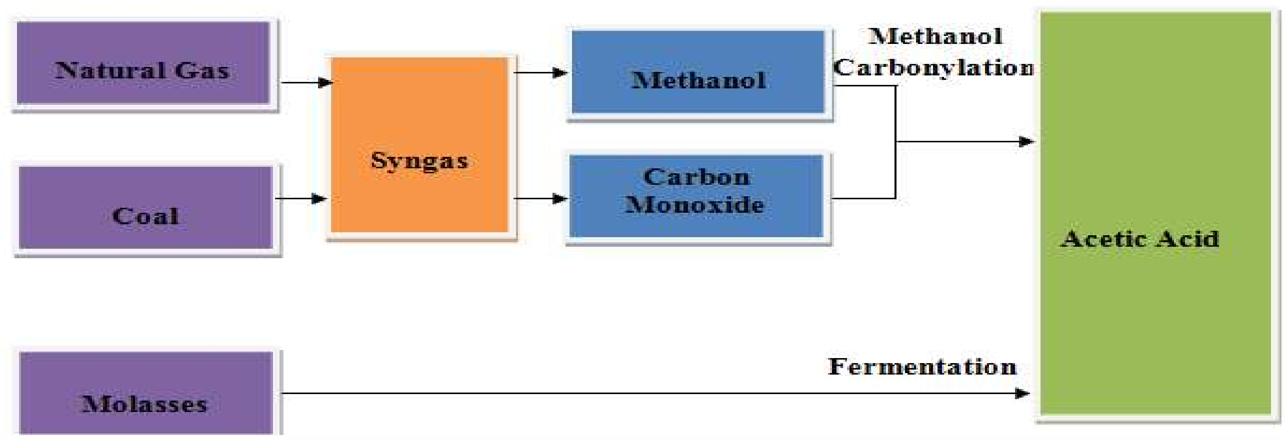
While Gas fermentation technology offer significant advantages, several challenges remain. These challenges include the development of efficient and robust microorganisms for fermentation, and successfully scaling up the entire process to commercial levels. Additionally, investment in research and development is necessary to enhance the technological advancements and reduce production costs. Looking ahead, the future of Syngas fermentation appears promising. These advancements have the potential to play a vital role in achieving sustainable energy goals, reducing carbon emissions, and diversifying the global energy mix.

5. Acetic Acid

Acetic Acid, also named ethanoic acid, is a colourless liquid organic compound with the chemical formula CH3COOH. Vinegar is no less than 4% Acetic Acid by volume, making Acetic Acid the main component of vinegar apart from water. It is used primarily in the production of ester solvents, purified terephthalic acid (PTA), acetic anhydride, diketene derivatives, drugs & pharmaceuticals, dyes & intermediates, textiles.

Manufacturing Process: The current manufacturing processes are as follows:

- **Methanol Carbon Monoxide Method (Monsanto Process):** In this process, CO is reacted with methanol under the influence of a rhodium complex catalyst at 180oC and at 30 to 40 atmospheric pressures. This results in the formation of crude acetic acid. This is purified and dehydrated into acetic acid. Methanol carbonylation is now the dominant Acetic Acid production.



- **Oxidation Process (From Molasses):** In this process, acetaldehyde derived from fermented alcohol is oxidized to produce Acetic Acid and acetic anhydride.

Feedstock Specifications: Methanol and carbon monoxide are key feedstocks for acetic acid production, with Gujarat Narmada Valley Fertilizers & Chemicals Ltd using methanol-based production in India. Global acetic acid capacity is about 18,852 KTPA, with China holding 53%, followed by North America (16%), North East Asia (13%), and Europe (7%). Bushehr Petrochemical (Middle East) and Reliance Industries (India) plan to expand to 300 and 1000 KTPA, respectively.

China's dominance stems from its large coal-derived methanol production. Vinyl acetate monomer (VAM) is the largest end use, for adhesives and coatings, followed by purified terephthalic acid (PTA), ethyl acetate, and acetic anhydride. PTA is used in PET resins, fibers, and films; acetic anhydride in cellulose flake production; and acetate esters mainly as solvents. Other uses include monochloroacetic acid, butyl acetates, and ethanol. In the Indian subcontinent, consumption growth will be led by PTA, closely followed by ethyl acetate.

6. Fertilizer Industry

In the fertilizer industry, such as at Talcher Fertilizers Limited in India, CO is derived from coal gasification and then used in a sequence of chemical reactions. First, it is converted into hydrogen and carbon dioxide through the water-gas shift reaction, and then the CO_2 is combined with ammonia to produce urea, a widely used nitrogen fertilizer.

Coal gasification to fertilizer is an advanced and integrated chemical process that converts coal (especially high-ash Indian coal) into urea fertilizer, via intermediate steps involving syngas, ammonia, and carbon dioxide (CO_2) reuse. This is the core technology being implemented at **Talcher Fertilizers Limited (TFL)** and is a significant innovation for India's energy and agricultural security.

Feedstock: Indian high-ash coal contains typically 30%–40% ash is often blended with petcoke (approx. 25%) to increase the calorific value of the feed. India imported approximately 13.1 MMT of petcoke in FY 2024-25 (as per PPAC website).

Gasifier: This mixture of petcoke and high-ash coal is crushed and subsequently dried and milled to be fed in the gasifier converting solid carbon materials like coal into a **syngas.** Processes involved include **Coal** Gasification to produce Syn Gas, Syngas Cleaning & Conditioning. The Water-Gas Shift (WGS) reaction converts carbon monoxide (CO) and water (H_2O) into carbon dioxide (CO_2) and hydrogen (H_2).

The Haber-Bosch process synthesizes ammonia (NH3) from N2 and H2, using a catalyst under high pressure and temperature.

Urea Synthesis: Urea synthesis involving the reaction of ammonia (NH3) and carbon dioxide (CO2) to produce urea (NH2CONH2) and water (H2O) through the conventional route.

7. Other Routes

- **Water–Gas Shift Reaction:** Converts CO and water to CO_2 and H_2, used to balance syngas in downstream processes or for hydrogen production.
- **Photo- and Electrochemical Conversion:** Emerging methods convert CO (and sometimes CO_2 to CO first) into fuels and chemicals using advanced catalysts, powered by renewable electricity.Emerging non-traditional CO sources

As the chemical industry shifts toward sustainability and CO_2 utilization as an alternative carbon source, new carbon-chemical processes will emerge, powered by renewable electricity or direct solar capture to achieve a carbon-neutral cycle. Like traditional fossil-based sources, CO will likely occur in complex product streams, making purification or recovery essential for its utilization.

8. Conclusion:

Converting carbon monoxide (CO), which can be synthesized from carbon dioxide (CO_2) using renewable energy, into useful fuels offers a pathway to recycle emissions while providing a sustainable energy source. Through processes like Fischer-Tropsch synthesis, CO and hydrogen are transformed into liquid hydrocarbons, methanol, or even jet fuel, creating energy-dense, storable products that can replace fossil-derived fuels. Advances in catalyst efficiency now allow these conversions at lower cost and higher speed, making it feasible to utilize industrial CO_2/CO emissions as feedstocks instead of pollutants. If powered by renewable electricity, this approach can help close the carbon loop—fuel is created, used, and its emissions captured for reuse—drastically cutting net emissions while meeting energy needs for the future.

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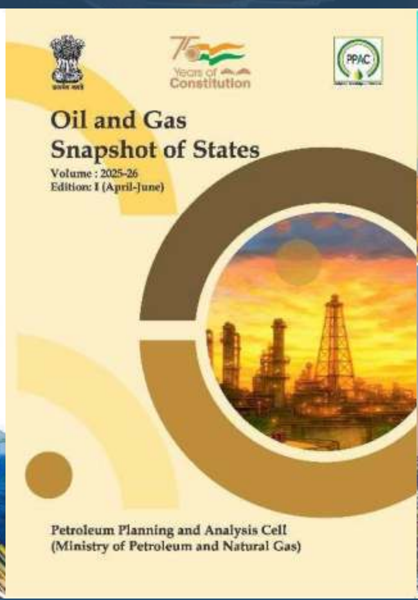

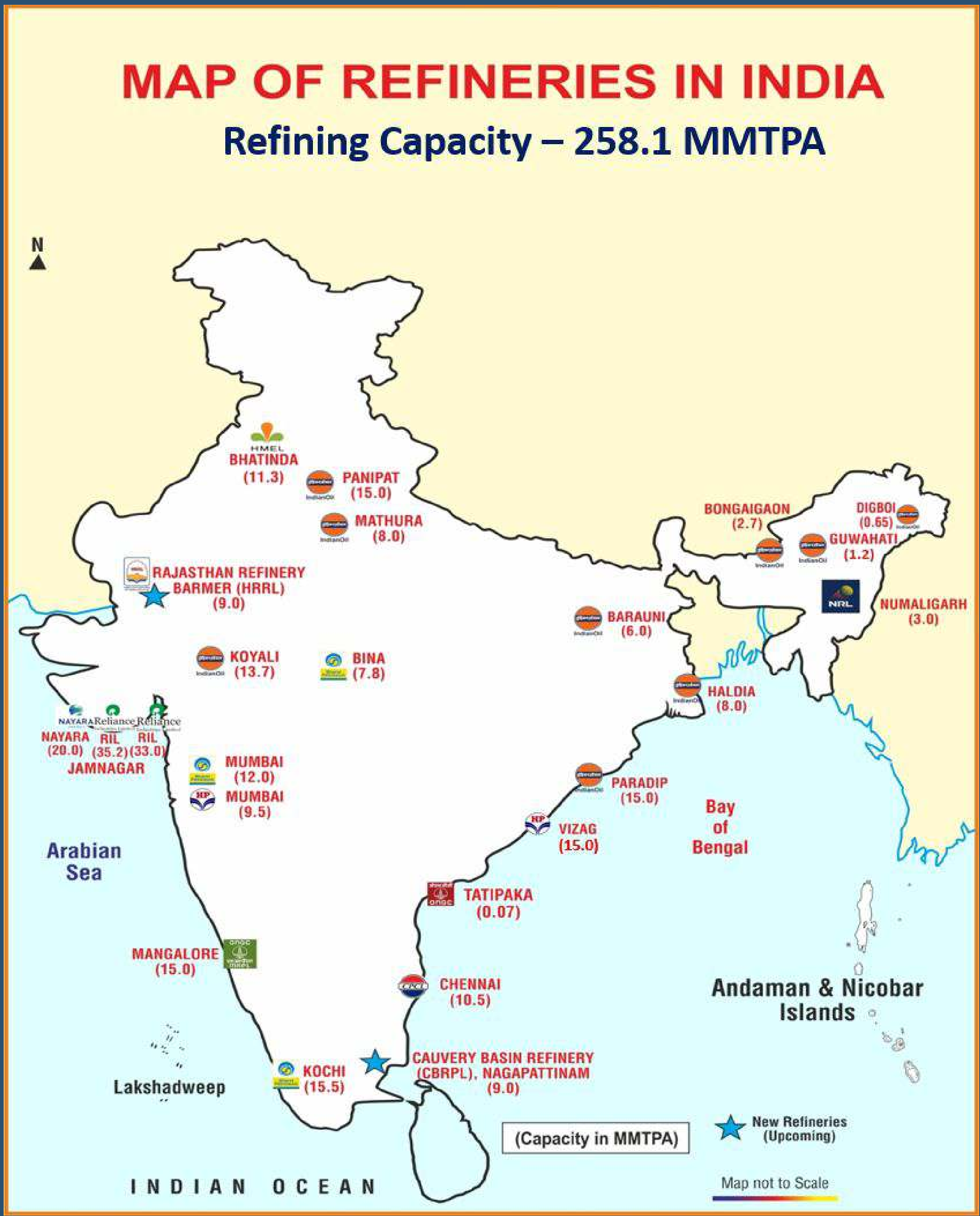

For any Information, please contact.

Petroleum Planning & Analysis Cell (PPAC)

(Ministry of Petroleum & Natural Gas, Govt. of India)

SCOPE Complex, 2nd Floor, Core 8,

Lodhi Road, New Delhi-110003

Tel.: 011-24306191/92, 011-24361314, www.ppac.gov.in