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Ministry of Petroleum and Natural Gas
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Government of India

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Foreword

First and foremost, I extend my heartfelt congratulations to all those associated with the successful completion of the 28th Energy Technology Meet (ETM). I particularly commend the speakers whose expertise enriched the discussions and the delegates whose active participation contributed significantly to the success of the event.

It gives me immense pleasure to present the 4th Edition of the CHT Oil & Gas Technical Journal. This edition stands as a testament to the collective efforts, technical excellence, and dedication of our esteemed authors, who have shared their knowledge and insights on recent advancements in refining technologies, green and alternative fuels, and catalyst development.

As we stand at a pivotal juncture in the global energy transition, India's journey toward green fuels and sustainable energy is not merely a strategic pathway but a clear reflection of our commitment to innovation, adaptability, and environmental stewardship.

The increasing emphasis on renewable energy sources has gained significant momentum, marking a decisive shift away from traditional dependence on fossil fuels. The integration of solar, wind, biofuels, and other renewable sources into the national energy matrix has not only diversified India's energy portfolio but has also strengthened the country's position as an emerging global leader in clean energy adoption.

In this era of rapid technological transformation and evolving challenges, platforms such as the CHT Oil & Gas Technical Journal and the Energy Technology Meet play a crucial role in knowledge dissemination, technical collaboration, and in driving the oil and gas industry forward in a responsible and sustainable manner.

I express my sincere appreciation to the authors, contributors, reviewers, and organizers whose unwavering commitment has made this publication possible. I am confident that this edition will serve as a valuable source of knowledge and inspiration, fostering continued innovation and sustainable progress within the oil and gas sector.


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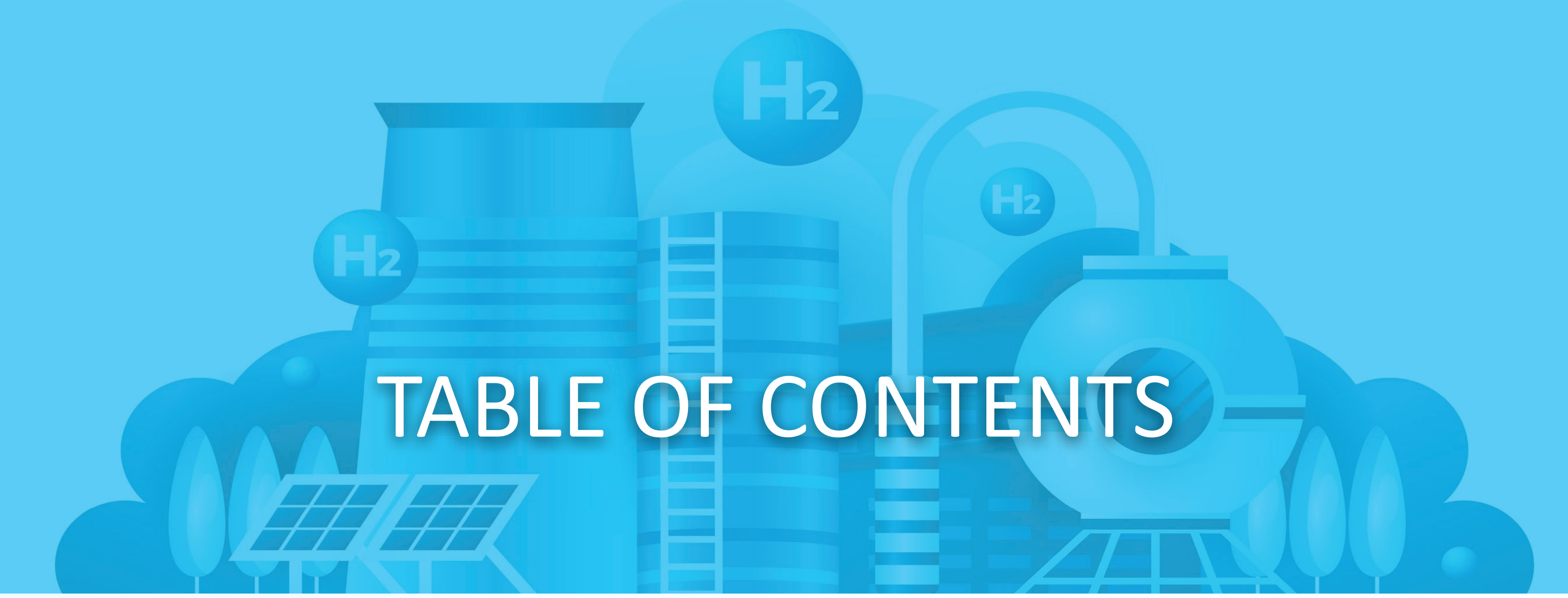

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1. Indian Refineries: Journey of Improvement, Expansion, and Future Outlook

Mr. Manish Agarwal presently working as Joint Director at the Centre for High Technology (CHT), a technical wing of Ministry of Petroleum and Natural Gas, India. Acquiring 16 years of extensive experience in downstream hydrocarbon sector, predominantly in the refining sector, he joined CHT as Joint Director in 2022. In his current role he is engaged in PSU Refineries performance Improvement programs, member of technical committee for Perform Achieve Trade (PAT) scheme for refinery division etc. He is also involved in monitoring and assessment of future refining capacity and Net Zero targets of PSU refineries.

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Mr. Kishore Kumar Bhimwal serves as an Additional Director at the Centre for High Technology (Ministry of Petroleum & Natural Gas). He possesses 22 years of extensive experience in process and heat transfer design, having specialized as a thermal design expert during his tenure at Engineers India Limited. In his current role, he oversees the SIGHT-2B scheme, focusing on Green Hydrogen procurement for Oil Marketing Companies (OMCs). Additionally, Mr. Bhimwal actively contributes to projects related to Carbon Capture Utilization and Storage (CCUS), CCTS Scheme, and e-Fuels. He earned his B. Tech degree in Chemical Engineering from MNIT, Jaipur.

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 become 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 as on
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

***Under Reconfigration**

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.

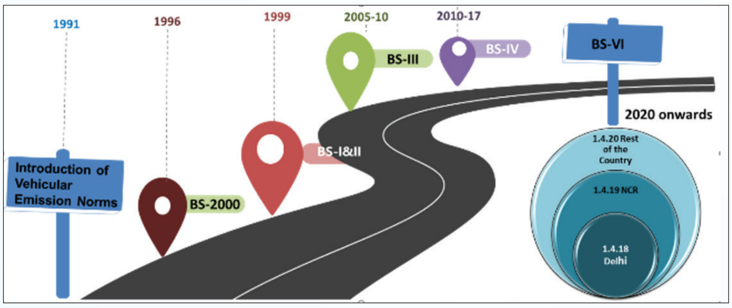
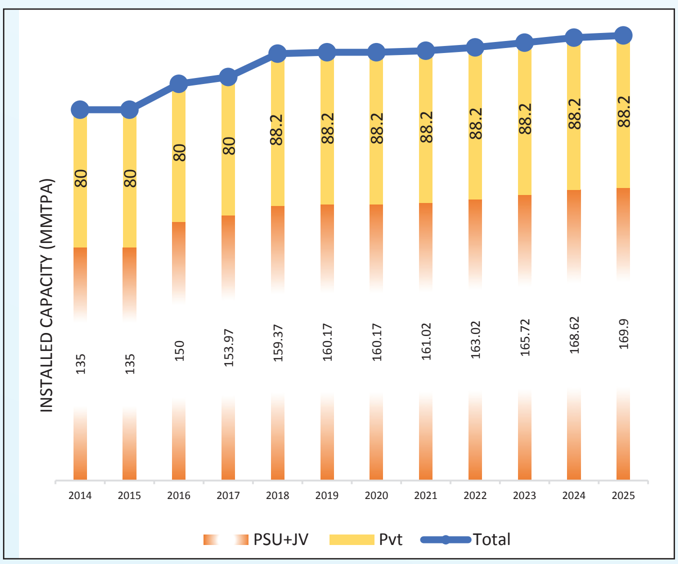


Fig. -1 Indian Fuel Quality Improvement Journey

3. Current Capacity and Operational Excellence

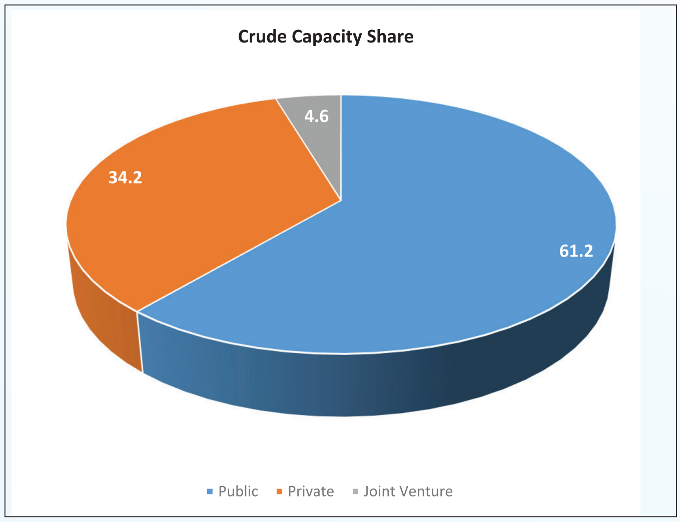
3.1 Refining Capacity & Refinery Crude Throughput

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

reflecting capacity utilization at 103.5% against the design capacity. (Ref. graph - 4)



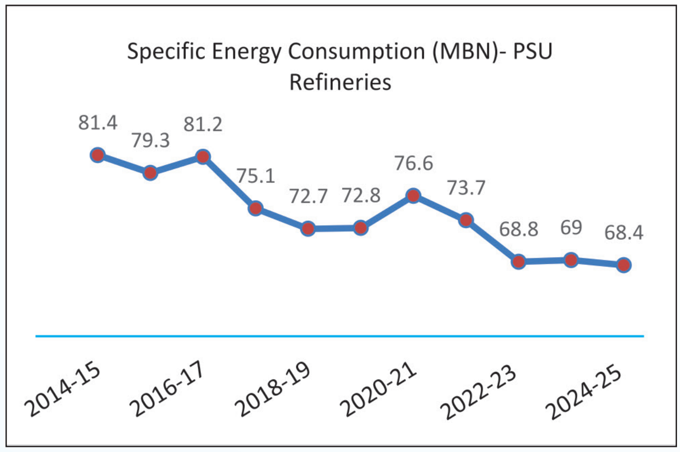
Graph:2 % sharing of Refining capacity

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.

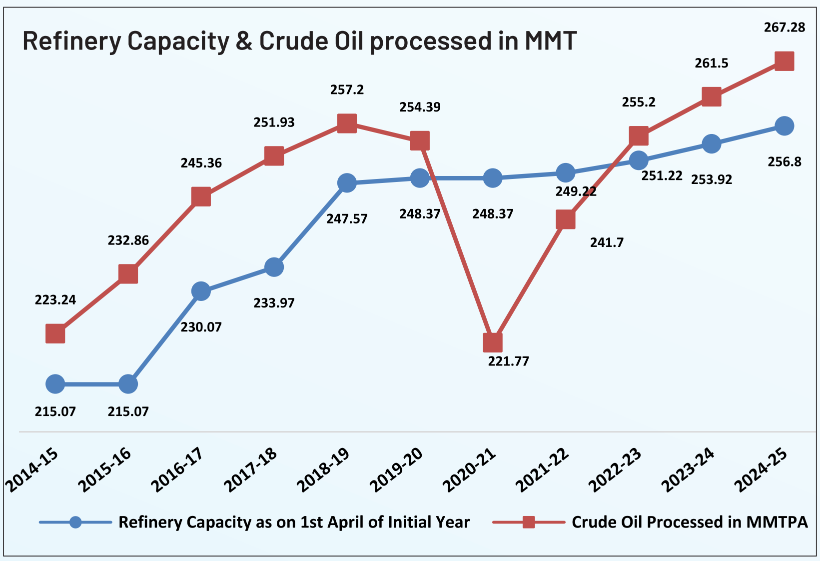
PSU refineries have been benchmarked by CHT regularly through M/s Solomon Associates (SA), USA since 2010. PSU refineries have improved their EII in last 10 years, EII has reduced by 19% during the period 2010 to 2022 and have been reducing EII at 3 times the rate of global average, however, significant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

As of April 2025, India operates 22 refineries (18 public, 4 private/joint ventures) with a cumulative capacity of 258.1 MMTPA. In FY 2024-25, crude oil processed reached 267.28 MMT,



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.

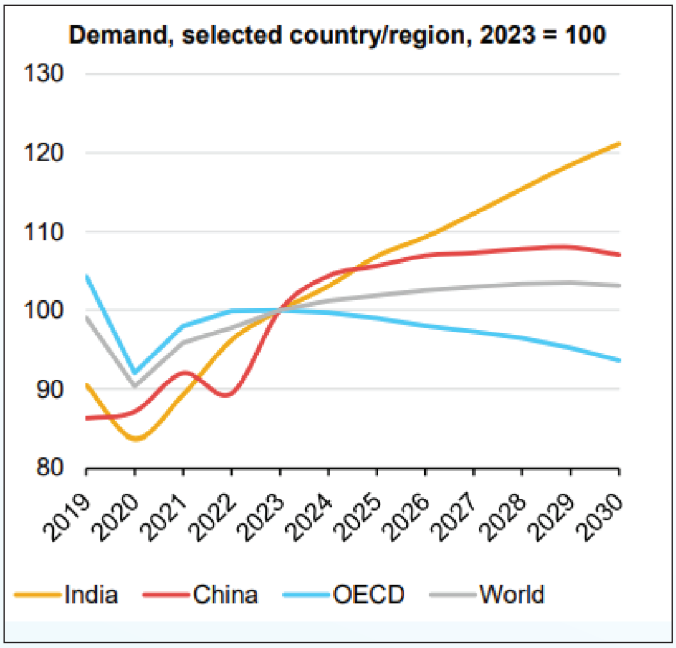
4. Expansion and Future Outlook

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



List of Green Field Refinery 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

***CBRPL Project under Reconfiguration phase.**

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 Refinery:

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.

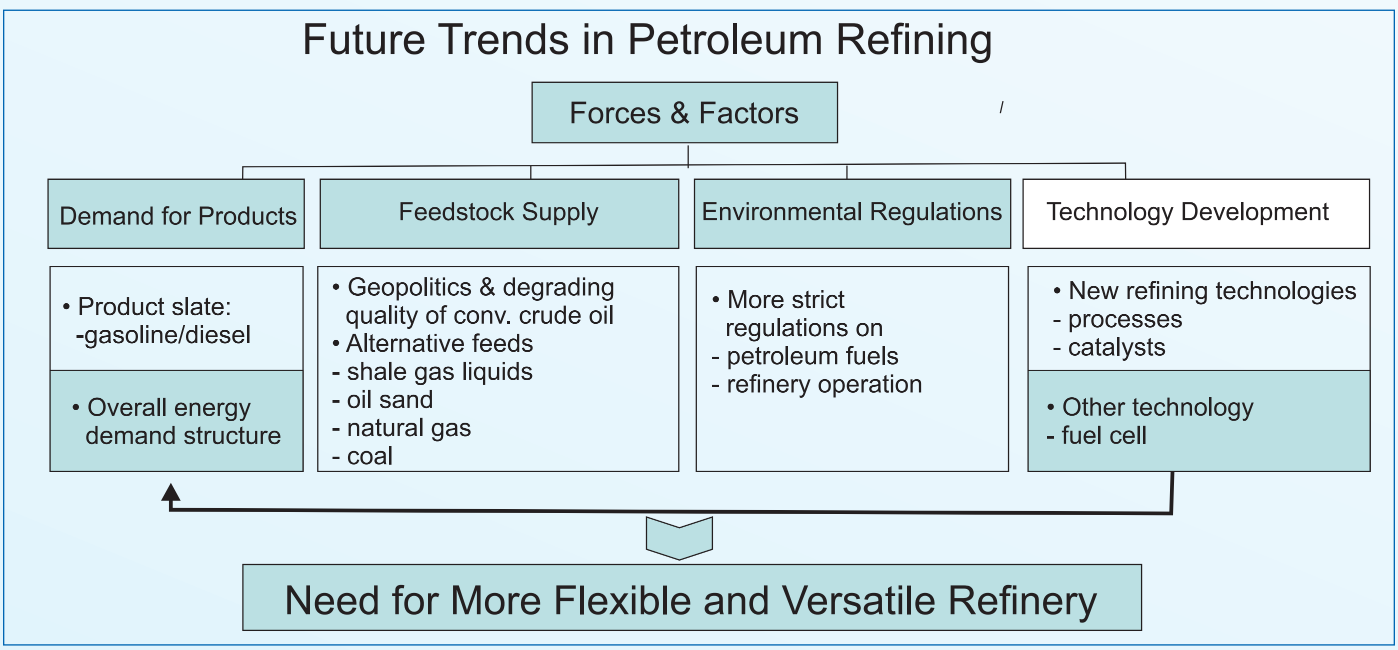


Fig. 1 - Future Trends in Petroleum Refining

6.0 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.

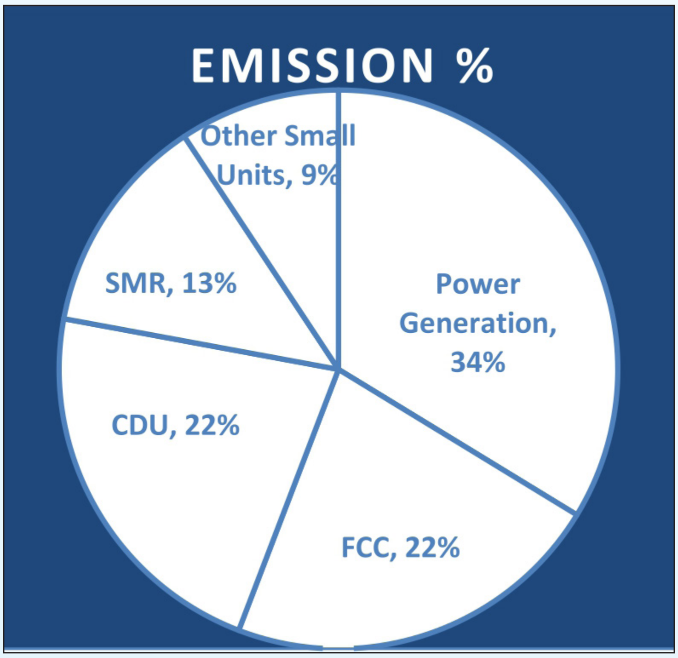
The devastating floods in regions like **Chennai (2015) and Kerala (2018)** serve as stark reminders of the critical need for robust climate resilience measures. Refineries that had not adequately prepared for such events faced prolonged shutdowns, incurring significant costs for repairing damaged electrical 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 CO_2 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 CO_2 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 CO_2 concentration (around 8%vol).

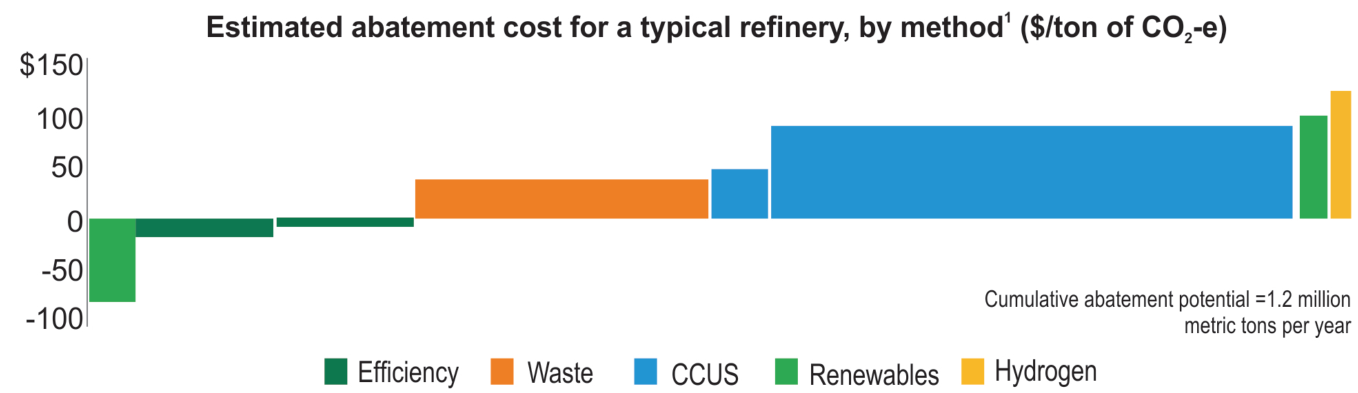


Graph 7: Typical Emission sources from a refinery

Many Indian refineries have announced ambitious goals for reducing their carbon emissions, but achieving those goals would not be easy being a hard to abate sector. As Figure 3 shows refinery's Scope 1 and 2 emissions will require actions across various levers. Efforts to reduce emissions will rely on various technologies that have not yet become practical for commercial-scale use. Even though to meet country's Net Zero targets, 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. Cost also vary by asset and location.

Fig. -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 (CO_2-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 CO_2 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, BPCL 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 CO_2 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 CO_2 (20-70 vol%), followed by CDU/ VDU (10-12 vol.%), FCC (8-16 vol.%) and PP / CGP (4-8 vol%). The majority of CO_2 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 CO_2 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 CO_2 being captured.

Ultimately, the economic benefit of carbon capture hinges on our ability to store and re-use the captured CO_2. The captured CO_2 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 potential 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.

6.3.3 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.

6.3.4 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

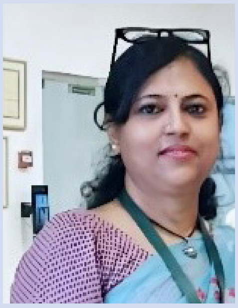
India's refining sector is a testament to resilience, innovation, and strategic foresight. By balancing operational excellence, petrochemical integration, and decarbonization, Indian refineries are not only meeting today's energy needs but also shaping a sustainable future. Key priorities include:

- 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.



2. Net Zero in Shipping-Possibility of On-Board Carbon Capture, Storage, Utilization and Opportunities for India



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Introduction

IMO's Marine Environment Protection Committee (MEPC 83)[1] meeting held in April 2025 has established binding measures to reduce the well-to-wake (WTW) greenhouse gas fuel intensity (GFI) of Ocean going vessels (OGVs)/ International ships over 5,000 gross tonnage. The new rules include a two-tiered compliance system, which not only imposes penalties on CO2eq emissions, but also provide rewards based on emission compliance of the ship. The attained GFI, expressed in terms of gCO_2eq/MJ, will be calculated based on Well-to-Wake (WtW) GHG emissions for each marine fuel/fuel-mix/blend-fuel options as per the following Equation-1,

Equation -1 $$GFI_{attained} = \frac{\sum_{j=1}^{j} EI_J \times Energy_J}{Energy_{total}}$$

Where, Elj represents GHG Emission Intensity of each fuel/energy source used by the ship, Energyj represents Energy Value/Lower Heating Value of each fuel/energy source used and Energytotal is the Total Energy consumed by the ship. A lower GFI value indicates more environmentally friendly energy usage, contributing to reduced overall GHG emissions.

GFI targets for emissions from ships are set to be progressively stricter over the years. For instance, the Base Targets and Direct Targets for the years between 2028 to 2035 are given in Table

1 below. The Well-to-Wake (WtW) fuel GFI Target for the period until 2034, is set as 19.0 gCO_2e/MJ, and from 2035 onward, 14.0 gCO_2e/MJ.

Table 1: IMO's Proposed Emission Reduction Targets from OGVs> 5000GT

Year	Base Targets (GHG emission reduction % with 2008 as Reference)	Direct Targets (GHG emission reduction % with 2008 as Reference)
2028	4.0	17.0
2029	6.0	19.0
2030	8.0	21.0
2031	12.4	25.4
2032	16.8	29.8
2033	21.2	34.2
2034	25.6	38.6
2035	30.0	43.0

Onboard carbon capture and storage (OCCS) is considered as a technology that will play a role in decarbonizing shipping, in combination with energy efficiency and alternative fuels. OCC can be applied to all carbon-containing fossil, electro, and biofuels/biocrude and, as a result, could play a mid- to long-term role in maritime decarbonization.

As per the Marine Environmental Management Report 2023, in 2022, 236 Indian OGVs>5000 GT have total fossil fuel consumption 1.240099 MT. This comprises of Diesel Oil 0.122377 MT, Heavy Fuel Oil (HFO) 0.646436 MT, Light Fuel Oil (LFO) 0.471286 MT. This implies Well-to Wake (WtW) GHG emission of 4.65MT CO_2 equivalent which includes ~3.88 MT of CO_2 emission itself.

Alternative Fuel Transition in Marine Vessels

In maritime decarbonization, global focus is rapidly shifting on low GFI based Zero and Near Zero (ZNZ) fuels produced through Bio and e-pathways. India's National Centre of Excellence on Green Port and Shipping (NCoEGPS), hosted at TERI, set-up by Ministry of Port Shipping and Waterways (MoPSW) has analyzed the Clarckson's global alternate fueled vessel data which shows that presently ~98% of OGVs operate on conventional fuels, and only ~2% are on alternative fuels/propulsion systems. This 2% in turn comprises of the number of propulsions using different alternative fuels. Table 2 provides snapshot of alternative fuel adoption in OGVs w.r. to fuel types.

Table 2: Overall Alternative Fuel Vessels Statistics: Comparative Assessment (w.r.to Fuel Types)

	In-service Vessel Data	Orderbook Vessel Data
	Alternative Fuel based Marine Vessels	Alternative Fuel based Marine Vessels
Fuels	Total Number of Vessels among all Alternative Fuels (%)	Total Number of Vessels among Alternative Fuels (%)
LNG	1105 (76 %)	991 (67 %)
LPG	125 (9 %)	251 (17%)
Biofuel	123 (8%)	114 (8%)
Methanol	37 (3%)	45 (3%)
Ethane	24 (2%)	24 (2%)
Hydrogen	20 (1%)	23(2%)
Nuclear	10 (<1%)	22(1%)
Ammonia	3 (<1%)	7(<1%)

Globally, the Marine sector is thus moving towards LNG (near and medium term though fossil-based but later can be shifted to CBG), Methanol (immediate), and Hydrogen & Ammonia (long term) as dual fuel & retrofitting options for marine engines. From medium term perspective in the timeline between 2028 to 2035, among the various bio/green fuel options, bio/e-methanol, bio-DME, bio/e-LNG, and upgraded bio-oil/bio crude appears well suited for the marine sector owing to their potential for scale-up, global advanced production status, and low costs. These options are close to each other in their overall fitness. Nevertheless, on board Carbon Capture Storage and Utilisation (OCCUS) as priority for deep decarbonization option in synergy with broader green energy sector will accrue long term benefit. Each of these fuels have intrinsic strengths and limitations that could favour that fuel under specific circumstances. In a recent study, as shown in Table 3, a critical assessment is also made on the possibility of integrating deployment of these low carbon bio/green fuels in combination with CCS for ambitious emission reduction in marine sector[2]. This awareness, though at present, is lacking among industrial stakeholders but is likely to be enhanced in future.

Table 3: Scores for the fuels [2]

Present technology status	0.08	3.5	3.8	1.8	3	3.2	1.5	4	3.7	1.8	3.5	3.3	1.6
Potential availability (EJ/y)	0.2	3	3.3	4.0	3	2.9	3.5	3	3.3	4.0	3.5	3.4	4.1
GHG mitigation potential (%)	0.2	4	3.9	4.7	4	3.7	4.4	3	3.4	4.1	3.5	3.7	4.4
Cost (€/GJ)	0.31	3.5	3.5	6.5	3.5	3	5.6	2	2.7	5.0	3	3.3	6.1
Infrastructure compatibility	0.16	3	3.4	3.3	3.5	3.6	3.5	3.5	3.3	3.2	3	3.7	3.6
CCS compatibility	0.05	3	3.2	1.0	3	2.9	0.9	4	2.7	0.8	2	2.7	0.8
Sum		**20.0**		**21.2**	**20.0**		**19.4**	**19.5**		**18.8**	**18.5**		**20.6**

* **A:** Score allotted to fuel for criterion based on literature study; **B:** Score allotted to fuel criterion by stakeholders; **C:** Weighted score of fuel for criterion **(C=Weight*B*6, as 6 criteria used; rounded to one decimal place)**

In a comparison between Hydrothermal Liquefaction (HTL) derived bio crude (Technology mostly deployed for wet feedstock like algal biomass, organic food wastes etc.) and pyrolysis oil derived biocrude (dry biomass including forestry, wood and agro-residues), it is argued that though the former is favorably considered as drop-in fuel for heavy marine engines owing to its lower moisture content, higher calorific value and higher H: C ratio, the later, being a near-commercial technology, with a higher TRL level deserves closer attention as well. Nevertheless, the simplicity, maturity, applicability for dry wastes and low cost of pyrolysis bio-oil production could be balanced against the present cost of its downstream upgrading.

Another critical study is conducted on OCC as part of the Green Fuels Optionality Project (GFOP) at the Mærsk McKinney Møller Centre for Zero Carbon Shipping (MMMCZCS). To gain a better understanding of the role of OCC in maritime decarbonization and assess OCC's business case for different vessel types and sizes, the applicability of OCC to the largest shipping segments (container, bulk, and tanker), main carbon-based fuels and full and partial application as part of a retrofit or newbuild is analyzed. Based on the case studies completed, it is inferred that among OCC technologies the one with chemical absorption is technically feasible and expected to reach commercial availability by 2030. Potential application of OCC shows the most promise for newbuilds as retrofits are costly and can require major modifications. A detailed techno-economical study [3] reveals that retrofitted CO_2 capture plant on-board scenario is technically feasible and economically competitive. This study also reveals that the transport of liquid CO_2 is a major safety concern due to its instability at the triple phase point. However, at ambient pressure, gaseous CO_2 requires large space available on-board, which would make this option infeasible even for a week trip.

As it is unrealistic to achieve a complete replacement of fossil fuels in the maritime sector due to lack of both fuel supply chain and alternate engines there is a need to increasingly implement CO_2 capture on-board and switch over to bio/synthetic e-Fuels from HFO with the advancement of alternate fuel engines. This could even lead to achieving negative emissions in the next generation of container fleets. However, there is an urgent need of larger number of Pilot demonstration of CCUS projects through valorization of adsorbed CO_2 especially for the countries like India with lack of geological CO_2 storage sites along with innovation in sustainable CO_2 adsorption material production.

Onboard Carbon Capture Technology Pathways

The IMO has initiated discussions towards creating a regulatory framework for Onboard Carbon Capture and Storage (OCCS), with the Marine Environment Protection Committee (MEPC) planning to review progress this year in 2025. Meanwhile, the European Union (EU) has woven shipping emissions into its climate policy, which includes the EU Emissions Trading System (EU ETS) and the FuelEU Maritime Regulation, though OCCS isn't yet included in these regulations. The Intergovernmental Panel on Climate Change (IPCC), in its special report on carbon capture and storage (CCS), identifies three primary methods for capturing CO_2 emissions from fossil fuel sources, as illustrated in **Figure 1.** Regarding OCC technology, CO_2 can be separated or captured both pre- and post-combustion.

A detailed techno-economical study[3] reveals that retrofitted CO_2 capture plant on-board scenario is technically feasible and economically competitive. This study also reveals that the transport of liquid CO_2 is a major safety concern due to its instability at the triple phase point as shown in Figure 6. However, at ambient pressure, gaseous CO_2 requires large space available on-board, which would make this option infeasible even for a week trip.

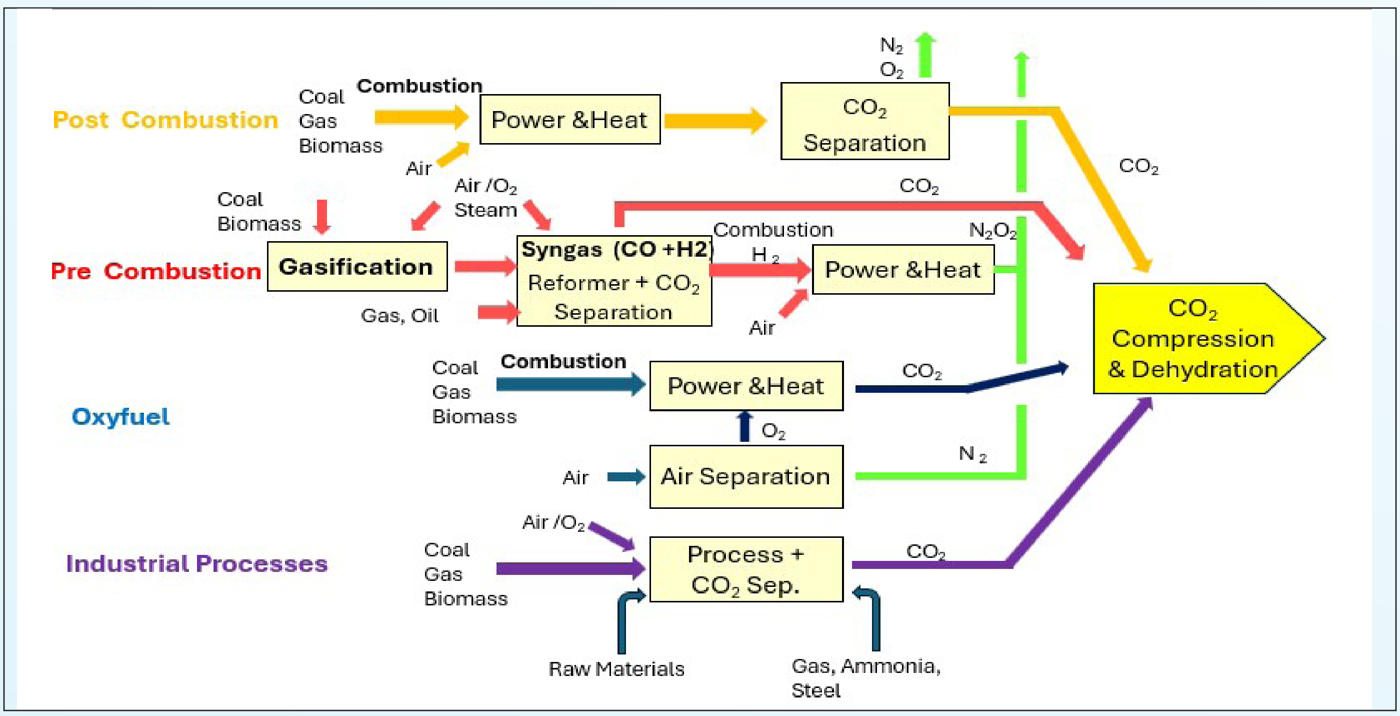

Fig. -1: Different Pathways of OCCS [inspired by **4**]

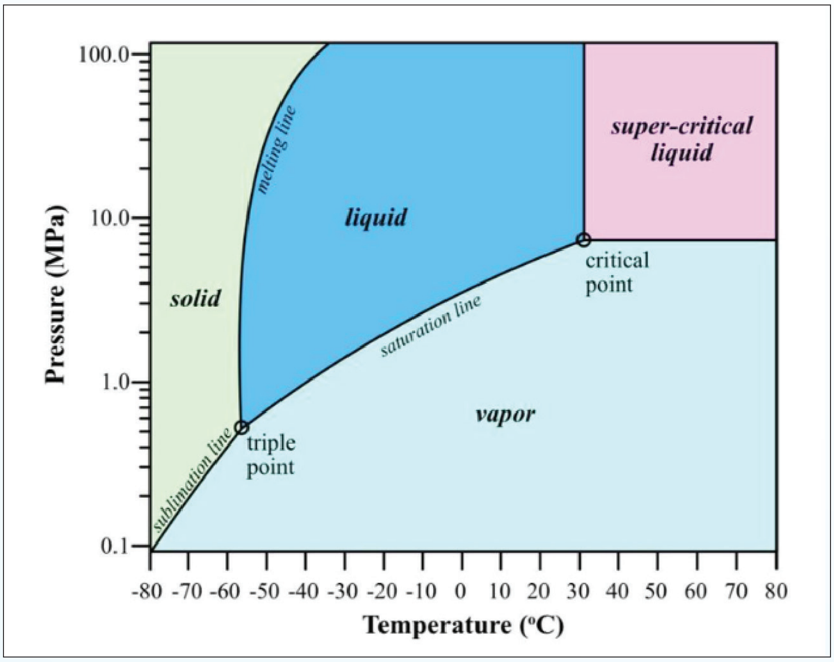

Fig. -2: Phase Diagram of CO2 **[5]**

Viable Options for Onboard CO_2 Storage

The viable options for storing CO_2 onboard include a gaseous state, supercritical state, solid state, or liquid state. Large number of studies [6] have shown the gas phase storage of CO_2 impractical owing to the significant volume it would occupy, despite its pressurization and cooling requirement been much lower in comparison to other phases. In addition, gaseous CO_2 has lowest density among other forms. **In gaseous state CO_2 has a density of 172 kg/m3 at 30 °C and 60 bar <density of supercritical CO2 757 kg/m3 at 35 °C and 125 bar < the density of liquid CO_2 1011 kg/m3 at–15 °C and 30 bar < and the density of solid CO2 1562 kg/ m3 at–80 °C and 1 bar [7].** It is therefore not used for the transport of large quantities of CO_2 in gaseous form.

The supercritical phase is attained by compressing CO_2 above 73 bar (critical pressure) and beyond 31.1 °C (critical temperature), as illustrated in **Figure 2.** Supercritical fluid phase is the favored state for pipeline transportation due to its higher density compared to compressed gas where the typical operating pressure is >96 bars and it is cost-effective. Pressures < 96 bars are preferably avoided due to the possibility of two-phase flows as shown in **Figure 2.**

There are two methods in which CO_2 can be solidified. In one method, it is cooled to −78 °C at atmospheric pressure, requiring an enthalpy of sublimation of 573 kJ/kg. This means, beyond cooling, an additional 573 kJ/kg must be extracted for CO_2 solidification, demanding significant amount of energy. Another method of CO_2 solidification involves chemically binding it to another substance. Although solid stage is promising shipboard storage [8], it remains in the lab stage and has not yet been mature enough for widespread commercial application. Additionally, this also requires onboard materials for binding process, therefore increasing ship weight. Both refrigeration and chemical sequestration demand a robust system to manage solid CO_2 effectively on ships. For refrigerated CO_2, a closed system is crucial to prevent sublimation, which could pose asphyxiation risks due to the air escaping out from the engine room, making implementation a complex maritime challenge.

Storing CO_2 in liquid form is advantageous because it is easy to handle with pumps. In addition, the volume required to store CO_2 is significantly lower due to the density of the liquid form. There

are several strategies for this, each differing in the temperature and pressure at which storage takes place. The triple point of CO_2, which is 5.18 bar and–56.6 °C, indicates that CO_2 only exists as a gas or solid at atmospheric pressure. To keep it in liquid form, a pressure of at least 5.18 bar is required. However, storing CO_2 near its triple point carries the risk of solid CO_2 formation, which could clog pipelines and be difficult to remove from storage tanks. It is therefore recommended to store CO_2 well above its triple point. Another critical study reviews optimal temperature and pressure for onboard liquid CO_2 storage by analyzing ship-based CCS chains at pressures from 5.18 to 73.8 bar, assessing life cycle cost (LCC) across five modules (liquefaction system, storage tanks, CO_2 carrier, intermediate storage tanks and pumping system [5]. Results show 15 bar as optimal, balancing liquefaction, storage, and transport costs.

To effectively manage captured carbon on ships, as on today, liquefaction stands out as the best storage option. The liquefied CO_2 must be kept under cryogenic conditions in pressurized and insulated tanks to stop it from turning back into gas. These tanks are usually built following the guidelines set by the International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC Code)[9]. In particular, Type C liquefied gas tanks are the go-to choose for storing pressurized CO_2, due to their proven safety, durability, and ability to handle liquefied gases even in tough maritime environments [10].

Captured CO_2 needs to be periodically offloaded at ports, either at the end of a journey or transferred to vessels designed for carrying CO_2. After that, it gets transported to reception facilities using ships, pipelines, trucks, or trains for either storage or utilization. As on 2024, there are 35 carbon storage projects in operation with a capacity of 37 Mtpa. Looking ahead, projections suggest that by 2050, there could be up to 8,400 MTCO2 stored annually, which would be a significant boost for CO_2 management in shipping[9].

OCCS Demonstration Projects

Onboard Carbon Capture and Storage (OCCS) demonstration projects play a vital role in assessing how practical, effective, and economically feasible OCCS technologies really are. These initiatives put various systems and components to the test, including CO_2 capture, onboard liquefaction, storage, and offloading, all in real maritime environments. By tackling important operational hurdles and ensuring they meet regulatory standards, these projects are designed to promote the adoption of OCCS and help achieve maritime decarbonization goals. **Table 4** provides a list of significant OCCS demonstration projects, highlighting their objectives, the country, stakeholders involved, and their status.

Table 4: Some significant OCCS demonstration projects, detailing their objectives, the country, stakeholders involved, and their current status

S. No.	Project	Objective	Vessel Type	Technology Used/ Technology Provider	CO2 Capture Target/Scale of Capture	Key Features and Progress	Country	Ref.
1.	**CC-Ocean Project (2020)**	Validate onboard CO2 capture systems	88,000-tonne bulk carrier	Post-combustion chemical absorption / Mitsubishi Heavy Industries (MHI)	Achieved CO2 purity > 99.9% / 200 CO2-ton/day	6 months of operation met targets for CO2 quantity, ratio, and purity. Supported by Japan's Ministry of Land, Infrastructure, Transport, and Tourism.	Japan	[11,12]

S. No.	Project	Objective	Vessel Type	Technology Used/ Technology Provider	CO2 Capture Target/Scale of Capture	Key Features and Progress	Country	Ref.
2.	**EverLoNG Project**	Advance Ship-Based Carbon Capture (SBCC) technology	LNG-powered carrier	CO2 capture prototype/-	Capture 10 tonnes CO2 over 3000 hours / 250 kg of CO2 per day	Aiming for 70% reduction in CO2 emissions. Further testing planned on other vessels.	16 partners from 5 countries: Germany, Netherlands, Norway, the UK, and the USA	[13,14]
3.	**Decarbon ICE Project (2019)**	Develop cryogenic CCS system (CO2 stored as dry ice)	Not specified	Cryogenic CO2 capture and dry ice storage / DecarbonICE	Not specified	Targeting carbon-negative shipping by storing CO2 in seafloor sediments.	Copenhagen N	[15]
4.	**Green Marine Project**	Retrofit ships with emission control technologies	Passenger ferry (MV Coruisk)	Emission control retrofits, including CCS	Ca/Mg-alkali solvent capture process is capable of removing 75% of CO2 from flue gases	Develop protocols for retrofitting engines and integrating CCS systems. Supported by Horizon Europe.	European Union	[16]
5.	**Bulk Carrier Carbon Capture Project**	Develop CCS for bulk carriers	Bulk carriers (Tianjin Venture, CSSC Wan Mei)	Organic amine solution for CO2 absorption	Over 85% CO2 capture rate	Approved by Bureau Veritas (BV). CO2 capture system uses chemical absorption.	-	[17]
6.	**REMARCCABLE Project**	Evaluate CCS performance during sea trials	Medium-range tanker (Stena Bulk)	CO2 capture via chemical absorption	Continuous CO2 capture during deep-sea voyages	Approved by American Bureau of Shipping (ABS). Planned two-year sea trials with potential for long-term CCS integration.	23 Study Partners and 2 Observers. This includes Shell, Woodside Energy, Alfa Laval, Panasia, Maritime and Port Authority of Singapore, Port of Rotterdam Authority	[18,19]
7.	**HyMethShip**	Develop OCCS with simultaneous elimination of CO2, SOx, and PM emissions	Not specified	Pre-combustion capture	Closed CO2 cycle	EU-funded under Horizon 2020; explores pre-combustion capture and closed fuel cycle		[20]
8.	**Deltamarin**	Analyze OCCS system feasibility for RoPax ferries	RoPax ferries	Pre-combustion capture	Closed methane cycle	Found OCCS more suitable for LNG than HFO; integrates CO2 capture with methane fuel production	Finland	[21]
9.	**Value Maritime (2022)**	Store CO2 in a rechargeable onboard "battery"	13,000-GT container ship Nordica	Exhaust gas CO2 capture	Not specified	World's first OCCS installed on operating vessel; approved by ABS in 2023	Dutch	[22]
10.	**CO2ASTS (2020)**	Analyze OCCS effects on LNG-powered ships	LNG-fueled ships	MEA solvent-based capture	75%, 54%, and 69% capture rates	Demonstrated cost efficiency by integrating heat from exhaust gas and cold from LNG vaporization	Germany, the Netherlands and the EU	[23]
11.	**Daewoo Shipbuilding (2022)**	Verify OCCS performance on large LNG vessel	LNG vessel	Not specified	Low-energy consumption system	Achieved relatively low CO2 emissions from equipment operation	South Korean (Daewoo Shipbuilding , Marine Engineering (DSME) and GasLog)	[24]

S. No.	Project	Objective	Vessel Type	Technology Used/ Technology Provider	CO2 Capture Target/Scale of Capture	Key Features and Progress	Country	Ref.
12.	**SMDERI (2022)**	Real-vessel OCCS application tests	Bulk carriers	Post-combustion capture	86.3% capture rate	Issued AIP certificate by China Classification Society; conducted real-vessel tests with Bureau Veritas	China Classification Society	[25]
13.	**Headway Technology (2022)**	Develop OCCS system and obtain certification	Ferries	Not specified	Not specified	Obtained AIP certificates from DNV and RINA; scheduled for ferry-based testing	China	[26]

Conclusions

Present Technological status of Onboard Carbon Capture and Storage (OCCS) are poised to cut CO_2 emissions from ships by as much as 20% each year, while keeping the fuel consumption penalty below 10%. Projects like EverLoNG and various pilot studies have established the feasibility of OCCS, although rolling it out on larger scale comes with its intrinsic set of economic, technical, and regulatory hurdles. For instance, retrofitting a vessel like the Stena Impero is expected to cost around $13.6 million, with an abatement cost of $769 for every ton of CO_2 captured [19]. Ongoing research and development are focused on driving these costs down and boosting efficiency, which would make OCCS a more attractive option for decarbonization. Among all carbon capture technologies, chemical absorption stands out as the most developed and commercially viable choice today, owing to its impressive capture efficiency and the wealth of research backing it. Nevertheless, alternatives like membrane separation and cryogenic capture are being considered for ships that have limited space and energy resources. The feasible method for storing captured CO_2 onboard is liquid storage at 15 bar and −27°C, which helps optimize handling and lifecycle costs. While storing CO_2 in gaseous form lacks practical viability due to space limitations, solid-state storage too in early development stage although hold future potential. The global capacity for CCS is expected to grow from the current 37 million tonnes per year (Mtpa) to between 4,000 and 8,400 Mtpa by 2050, with a substantial portion of that potentially dedicated to maritime uses. Most importantly, for larger adoption, OCCS needs carbon pricing strategies, government incentives, and the development of CCS clusters to support CO_2 storage and utilization. While OCCS boasts a high technology readiness level (TRL) for capturing and storing carbon, its integration readiness level (IRL) and commercial readiness level (CRL) are still lagging, indicating a need for clearer regulations and operational and pilot level experience.

As it is unrealistic to achieve a complete replacement of fossil fuels in the maritime sector due to lack of both fuel supply chain and alternate engines there is a need to increasingly implement CO_2 capture on-board and switch over to bio/ synthetic e-fuels from HFO with the advancement of alternate fuel engines. This could even lead to achieving negative emissions in the next generation of container fleets. However, there is an urgent need of larger number of Pilot demonstration of CCUS projects through valorization of adsorbed CO_2 especially for the countries like India with lack of geological CO_2 storage sites along with innovation in sustainable CO_2 adsorption material production.

Recommendation for India

i. Sustainable production of amine-based compound (similar to mono ethanol amine) from specific renewable feedstock, especially marine algae and other biomass-based resources for CO_2 Adsorption (short to medium term)

ii. In addition to Amine based CCS, India should focus (through timebound innovative R&D) for cryogenic & solid-state storage technology upscaling and adoption in shipping (short to medium term projects to undertake)

iii. In order to minimize CO_2 transport and enable larger adoption of OCC, policy support is needed in developing CCU units in ports along India's coastal belt for frequent offloading of captured CO_2 (short to medium term)

iv. Among CCU options, onboard captured CO_2 utilization for e-Methanol synthesis could be given priority for leveraging twin benefit of CO_2 capture and e-Methanol supply sustainability to maritime application (short to medium term)

v. Developing Collaborative (National/Cross National) Pilot scale project for Indian Marine Coastal Vessel's CCUS project with LCA analysis over the whole value chain (short-medium term)

vi. Other promising CCU options such as captured CO_2 utilization especially via direct epoxide/CO_2 copolymerization for CO_2-based copolymers, like poly (propylene carbonate) (PPC) should be encouraged for supporting local economy. PPC occupies a unique place among plastics by virtue of its biodegradability and unparallel CO_2 utilization. (medium to long term)

vii. Commercially viable biorefinery plants through onboard captured CO_2 utilization for largescale marine algae cultivations in coastal/port area should be undertaken for long term sustainability (Medium to long term)

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3. Unlocking Fired Heater Potential: Strategies for Boosting Performance and Lifespan

Ms. Sadhna Singh is serving as Chief General Manager (HOD) of Heat Transfer Department in Engineers India Limited. She has over 32 years of work experience in thermal design, engineering and optimization studies of fired and unfired equipment for Hydrocarbon Industry. Efficiency improvement studies including retrofitting of Heat Recovery Equipment, NOx abatement studies. Development of new products/ upgradation of existing products through in-house R&D testing facilities. Published multiple technical papers in reputed Oil& Gas Journals and prominent speaker in various conferences.

Mr. Navneet Agarwal is presently working as General Manager with Engineers India Limited. Holds a B.Tech degree in chemical engineering and has over 27 years of work experience in the field of Fired heater design and Hydraulic design of Mass Transfer internals, revamp & troubleshooting for hydrocarbon industry. Presently in charge of the Mass Transfer Department and also manages a team of engineers working on fired heaters and combustion systems. Published technical papers in reputed journals including Hydrocarbon Processing.

Ms. Ishita Bhattacharya works as Senior Manager with Engineers India Limited. She holds a Bachelor's degree in Chemical Engineering. She has over 13 years of work experience in design, engineering and troubleshooting of fired heater and combustion systems for large scale domestic as well as various international projects. She has rich experience in revamp/ retrofitting, efficiency improvement studies and site experience including Performance Guarantee Test Run for fired heaters. She is also Prominent speaker in webinars & technical conferences on Fired heater and published technical papers in reputed journals.

Mr. Avijit Barman is Senior Manager in Engineers India Limited. He has over 13 years of experience in the thermal and hydraulic design, engineering, revamp and troubleshooting of fired Heaters. He holds a Bachelor's degree in Chemical Engineering from Jadavpur University, Kolkata, India.

Fired heater plays pivotal role in Oil & Gas Industries, providing the high temperatures needed for thermal processes that convert heavy hydrocarbons into lighter, high-value products like gasoline, diesel, and olefins. A typical refinery, processing around 10 MMTPA, typically operate 10 to 12 fired heaters, with a combined fuel-fired duty reaching approximately 400 Gcal/h. Maintaining the proper temperature is critical in refinery processes to ensure refinery efficiency, product yield, and safety.

Fired heaters operate in harsh environments such as extremely high temperatures, often ranging between **500°C to 800°C (932°F to 1472°F)**, and in some cases, even higher. Any malfunction be it tube failure, flame instability, or fouling can lead to reduced efficiency, unplanned shutdowns, and significant safety risks. Ensuring continuous and reliable heater performance, therefore, requires robust design, careful material selection, proactive operation and maintenance strategies. **Few major design, operation and maintenance aspects may be highlighted in this regard** which will lay the path forward for improving performance and extend lifespan of fired heater and making life easier for the refiners or industry owners.

1. Essential Elements of Design:

Conceptualizing optimum performance of the heater starts from the nascent stages of Design. Finetuning air-fuel ratio, uniform firing, heat recovery system & implementing modern burner technology are essential concepts for improving the performance of industrial furnaces.

Uniform firing distribution:

This is crucial because uneven firing can lead to several issues, including **local hot spots, and excessive wear** on furnace components. Burner Design and Placement directly impacts the distribution of combustion gases inside the firebox. Burners should be strategically placed to provide uniform heat distribution across the entire furnace load. Using multiple burners or burner zones within the furnace helps distribute

Figure 1: Stable flame vs. Impinging Flame

heat more evenly, especially in larger furnaces. In case required, burners at the side wall of the furnaces are considered to achieve uniform firing rates.

Advanced Burner Technology:

Burner design significantly influences combustion quality and heater reliability. Effective mixing of fuel and air is essential for stable flame formation. Poor mixing can lead to unstable flames, flame impingement, and damage to tubes and refractory linings, ultimately shortening the heater's service life.

Modern burner technologies address these challenges through designs based **on air swirler or restriction mechanisms, precision tip drilling** for ensuring optimized fuel discharge velocities. These features ensure controlled flame direction and improved combustion stability. Additionally, the refractory burner block design plays a key role in flame stabilization, contributing to safer and more efficient heater operation.

Air-fuel Ratio: To ensure complete combustion, operators should provide more combustion air than theoretically required for the combustion process (stoichiometric air to fuel ratio). This is indicated by the excess oxygen measured by **zirconia** or **Tunable Diode Laser Spectrometers** (TDLS) based analyser installed in the radiant section (Figure 2.0) which provides near-real-time O_2 measurements that are not skewed by tramp air.

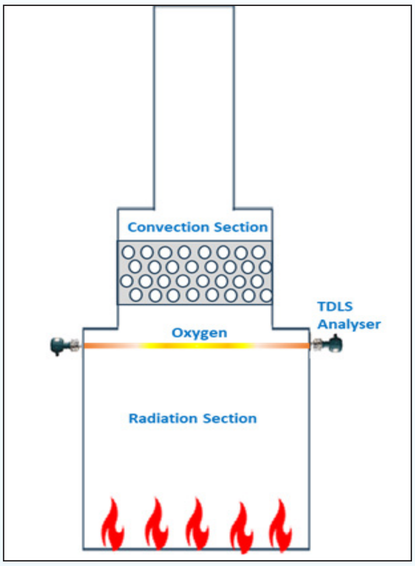

Fig. - 2: 02 Measurement by TDLS Analyser

Maintaining the correct air-to-fuel ratio is essential to ensure that combustion is complete and furnace performance is satisfactory. If the air-fuel ratio is too fuel-rich, combustion may be incomplete, resulting in unburned fuel, excess CO formation and safety hazard. It also risks the performance & lifespan of the furnaces by causing wear & tear of the components. On the contrary, if the mixture has too much excess air, furnace temperature will be lower leading to inefficient heat transfer. Figure 3 illustrates the relationship between excess air, stack temperature and fuel efficiency.

Optimum level of excess air depends on the type of fuel fired, burner & draft type of the fired heater. As per International API-560 standard, minimum 10-20% of excess air (approx. 2-3% excess oxygen) should be always maintained for ensuring safe and efficient combustion.

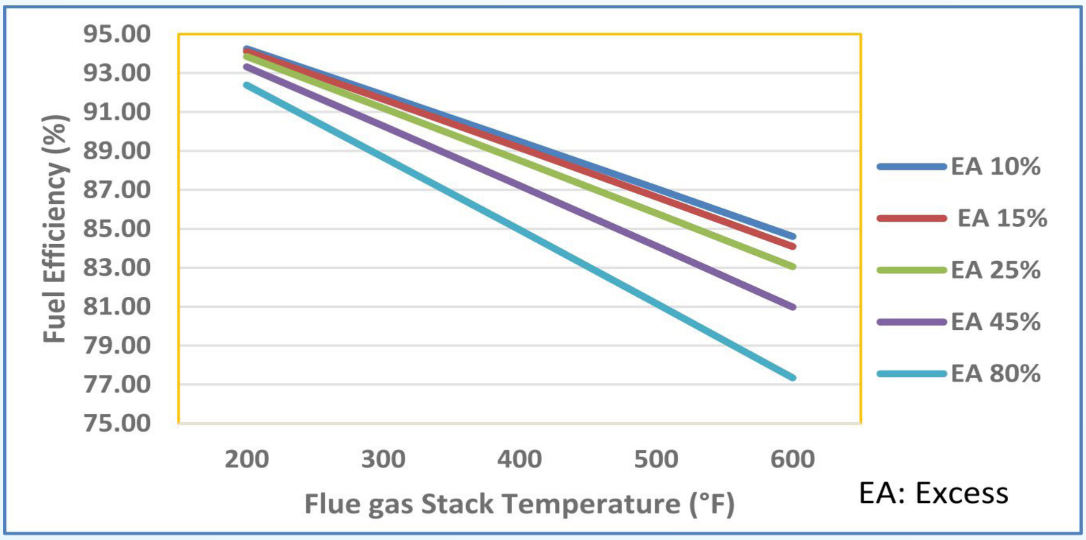

Fig. -3: Fired Heater Efficiency vs.% Excess Air for Various Stack Temperatures

Heat Recovery Systems:

Heat Recovery equipment are fundamental part of heater performance. Heat recovery systems capture excess heat from flue gases that would otherwise be lost during the furnace operation and reuse it to preheat air. This reduces the amount of fuel needed to maintain the furnace's operating temperature, leading to significant energy savings and efficient furnace operation.

While installing heat recovery systems may involve upfront costs, the savings in fuel and maintenance costs over time can make them a highly cost-effective investment, hence long run of the fired heater are preferred with the addition of a heat recovery equipment. Figure 4 illustrates the typical types of heat recovery equipment associated with fired heater system and their characteristics such as:

- Cast Air Preheater
- Glass Air Preheater
- Top Mounted Air Preheater
- Steam Superheating or Generation in Heater Convection Section

Upgraded Materials:

Fired heaters typically operate within a temperature range of 500°C to 900°C, with corresponding tube metal temperatures falling typically between 300°C and 700°C. At elevated metal temperatures, even in the absence of corrosion or oxidation, tubes can fail due to **creep rupture**—a time-dependent deformation that occurs under sustained stress levels. For the steel operating at the lower temperature, the effects of creep are nonexistent or negligible. Hence, it is important to select upgraded tube materials such as **chromium-molybdenum steel** of suitable grade for enhanced resistance to creep and thermal degradation. **Creep-rupture based design** should be considered at higher temperatures, in which allowable stresses are based on the long-term rupture strength and are directly related to service life expectations.

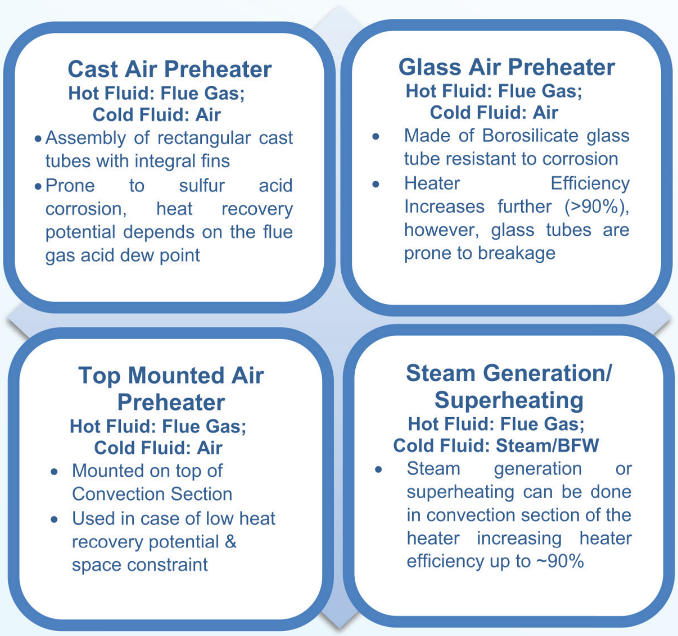

Figure 4: Types of Heat Recovery Equipment

Corrosion presents another major threat to the integrity and performance of fired heater tubes. It can degrade the tubes from both the interior and exterior surfaces, thinning the walls and significantly increasing the risk of rupture or failure. In addition to material loss, corrosion can lead to the formation of rust, scale, or other deposits that form insulating layers on tube surfaces. This buildup acts as an insulating layer, hinder heat transfer efficiency, requiring more energy to maintain process temperatures and placing additional thermal stress on the equipment. Over time, this not only reduces heating efficiency but also compromises the structural integrity of the tubes, ultimately shortening the operational life of the heater.

Case Study-1:

Change in Tube MOC of Existing Heater & Tube thickness Determination

Change of materials and tube design performed for a heater with stainless steel coils. During planned Turnaround of the unit, failures were observed in the heater tube of MOC SS321. After detailed analysis it was found that the tubes were failing because of chloride stress corrosion cracking, which arises from chloride penetration in protective oxide layers on stainless steel, initiating corrosion.

To avoid such cracking it was proposed to change to P9 (9Cr-1Mo) alloy metallurgy which are resistant to such phenomena and considering Feed design & specifications.

Performance Parameters	Value
Max. Tube Metal Temperature, °C	560
Max. operating Pressure, kg/cm2g	27.3
Corrosion Allowance, mm	2 (min.)
Design Life, Hrs	100000

Table 1: Performance Parameters Case Study 1

For determination of tube thickness to be selected for P9 metallurgy, performance parameters as per Table 1 were taken into consideration. It was found that rupture design is governing for the estimated tube metal temperature.

As per the rupture stress for P9 MOC, tube thickness of Sch 40 (6.02 mm) of tube OD 114.3 mm has been worked out.

Figure 5 illustrates a curve showing the heater tube design life w.r.t corrosion thickness at different tube metal temperatures. It can be seen that for a particular tube thickness if the corrosion

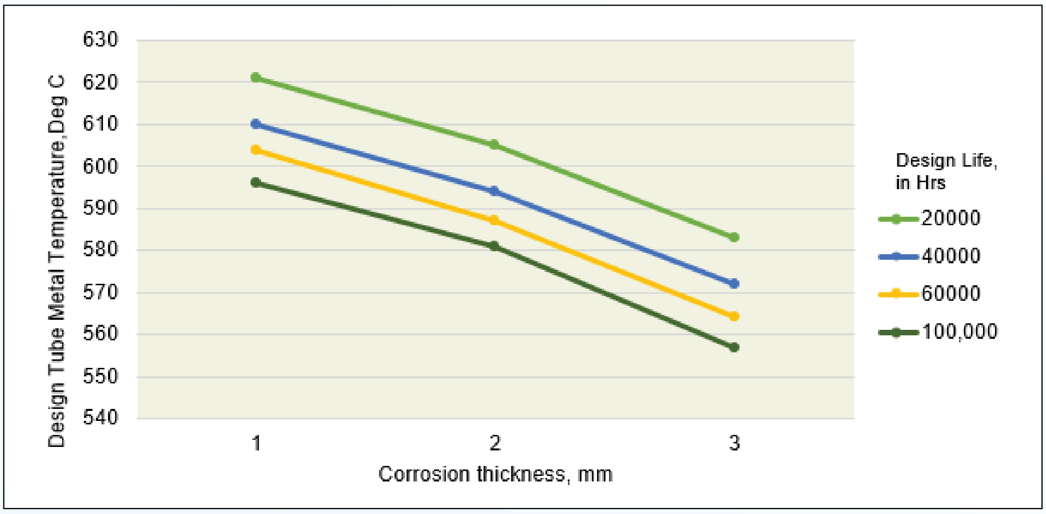

Fig. -5:Tube Metal Temperatures & Design Life for different Corrosion Allowance

increases, the tube metal temperature which can be sustained by the tube over a period of time, decreases. Also, if the tube metal temperature decreases the design life of the tube increases for the same tube thickness. Hence, it is imperative to consider suitable corrosion allowance during heater design for the specified tube material & service.

Improved Refractory & Insulation:

In process plants, heaters are typically not equipped with standby units, and operations often continue uninterrupted for periods of 3 to 5 years between scheduled maintenance turnarounds. As a result, ensuring optimal performance depends heavily on reliable design, construction, and maintenance practices.

Fig. -6: Firebrick, Ceramic Fibre & Castable Refractory (left to Right)

Proprietary heater designs can differ greatly and are usually composed of several zones and components—such as the radiant chamber, convection section, breeching, air preheater, flue gas duct, and stack. Each of these zones requires specific refractory materials selected based on the fuel blend, operating temperatures, and service conditions. Figure 6 illustrates the various types of refractory materials installed within a fired heater.

The **American Petroleum Institute (API) 560 – Fired Heaters for General Refinery Service** standard is widely used as a reference for refractory design, material selection, and installation practices. Temperatures inside the heater can vary significantly across different zones, typically ranging from **200°C to 900°C**. To manage this heat, the refractory lining is designed to keep the **external casing temperature between 60°C and 90°C (140°F to 194°F)** under defined ambient conditions.

As a result, **two to three layers of different refractory materials** are often required—particularly in the **radiant and convection sections**—to ensure adequate thermal insulation and performance (see Table 2).

Zone	Operating Temperature Range (°C)	Refractory/ Insulation Types
Radiant Floor	500-800	Firebrick+ Insulating castable
Radiant Walls & Arch	500-900	Ceramic fibre Module+ blanket or Insulating Castable
Convection	200-800	Ceramic Fibre Board+ Insulating castable
Fuel gas Ducts	200-400	Insulating Castable
Combustion Air Ducts	200-300	Mineral Wool insulation
Stack	100-300	Insulating Castable

Table 2: Fired Heater Refractory Guide

Concrete or castable refractory drying is compulsory and must take place before heater start-up. Dry-out is to eliminate excess of water of castable refractory by vaporization.

2. IIoT Based Real Time Optimization to Drive Operational Improvement and Predictive Maintenance in Fired Heater Operations

Traditionally Fired heaters are operated based on manual monitoring and scheduled maintenance, which often results in inefficiencies, unexpected failures, and high operating costs. As the fired Heater are often designed for worst case scenario and operates at a very different condition it becomes important to analyze and optimize the performance of the heater real time to maximize the efficiency and hardware utilization. The adoption of **Industrial Internet of Things (IIoT)** technologies offers a transformative approach by enabling real-time data acquisition, advanced analytics and intelligent decision-making.

IIoT Infrastructure for Fired Heater Operations

The **Industrial Internet of Things (IIoT)** enhances fired heater operations by enabling data-driven decision-making and automation of physical processes. It provides remote monitoring and operational support by collecting real-time data from Fired Heater and associated systems.

Key benefits of IIoT implementation include improved fuel efficiency, reduced downtime, optimal utilization of heater hardware, enhanced safety, and lower maintenance costs. These gains are enabled by smart sensors, internet connectivity and powerful computing platforms hosted in the remote computers serially interfaced with DCS. At the core lies the **digital twin**, a real-time simulation model of the fired heater, it optimizes operations using models based on thermal and hydraulic calculations.

Real time data from the plant, flows securely into the system, where it is cleaned, validated, and reconciled in **Data Validator**. before being fed into the simulation and optimization module. The **digital twin**, combined with a knowledge base, enables accurate analysis and performance optimization. The twin compares actual behavior to ideal conditions, helping detect deviations and simulate future failure scenarios without impacting live operations. The system then provides

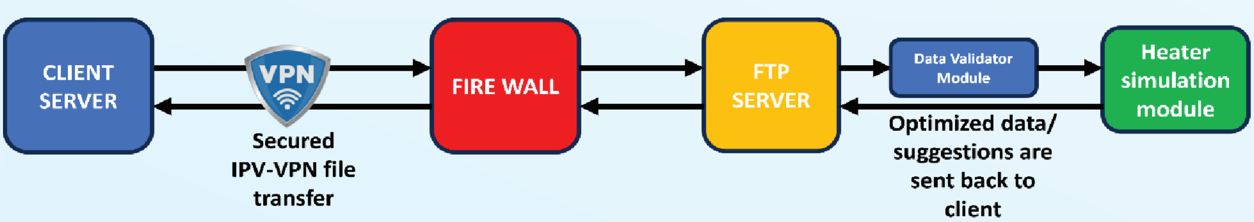

Fig. -7: Data Flow Diagram of IIOT Module

actionable insights as specified in subsequent section, which are sent back to the plant to guide better decision-making. Overall, IIoT shifts Fired heater operations from reactive to predictive, improving flexibility, safety and long-term performance.

Operational Improvements Enabled by IIoT

IIoT enables a shift from reactive operations to **smart, optimized control** through the following mechanisms:

It enables operators' insights on stack temperature, metal temperature profiles, burner performance, flue gas O_2 & CO levels, pressure trends etc. continuously. This real-time awareness helps in early identification of performance drifts such as efficiency loss, flame impingement on tubes, excessive air or incomplete combustion.

For example, if the draft and O_2 level in flue gas is too high at arch in a natural draft heater, it can be a result of too much air entry into the firebox either through Burner or leakage through sight doors causing loss of efficiency of Heater. Closing the damper to an appropriate level can improve both of these issues and improve the efficiency of the heater.

IIoT shall provide real-time dashboards for operators with Key Performance Indicators (KPIs) like stack exit temperature, duty, tube metal temperatures, pressure dops, bridge wall temperature etc, that will help operator track performance of the heater with respect to design condition. Also optimized KPIs shall be suggested in the dashboard based on simulation results which shall help operator for quick decision making.

Predictive Maintenance through IIoT

IIoT based realtime optimization platforms empower maintenance teams to shift from fixed-interval schedules to **condition-based and predictive maintenance strategies**, reducing costs and preventing failures. It can detect an early fault or underperformance of a heater component based on simulation and logics that is built in based on past experience.

For example, it can detect **drop in the coils** by analyzing the pressure dop and tube metal temperature and suggest the maintenance team an appropriate time to consider decoking of the tubes. Likewise, it can detect **Burner performance** by evaluating excess air, draft at arch etc and provide inputs to the maintenance team for any maintenance foreseen.

The performance of auxiliaries is also key for overall performance of the heater. The module can predict underperformance of any auxiliary like **Air preheater, FD/ID fans, Stack Damper** etc and suggest for any maintenance requirements.

Predictive insights allow maintenance teams to plan interventions during minor shutdowns or scheduled turnarounds rather than during costly emergency stoppages. This increases availability and extends asset life.

The adoption of IIoT in fired heater operations brings measurable improvements. Figure 8 shows key improvements in Oil & Gas Fired heaters by implementing IIoT.

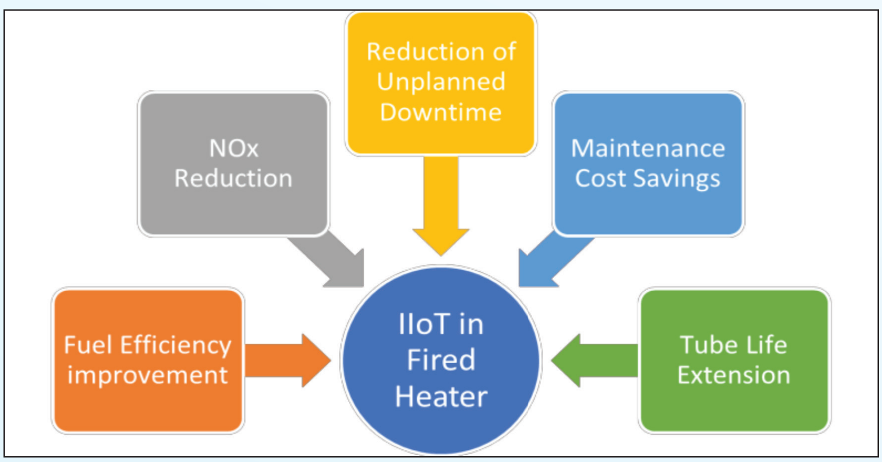

Fig. -8: Key Improvements through IIoT

3. Strategic Maintenance Tips to boost Performance & Extending Lifespan:

Preventive maintenance of heaters is crucial to avoid unplanned shutdowns, dangerous conditions, and efficiency loss. Regular inspections, operational monitoring, and timely corrective actions are necessary to maintain safety and performance.

Maintenance Cycle:

Maintenance procedure as per Figure 9.0 should be followed during shutdown of a heater.

Frequent Inspection for Early issue Detection:

During operation, the furnace should be subject to regular inspections whose purpose is to visually determine the extent of general damage and deterioration and heater performance appraisal. Visual inspection of the furnace should be performed on a frequent schedule, and particular emphasis must be placed on the burners, dampers, internal lining, coil tubes and their supports. API-573 provides a recommended instruction regarding inspection methodology of heater and associated components. Table 3 provides a thorough idea of inspection requirement related to each component of fired heater.

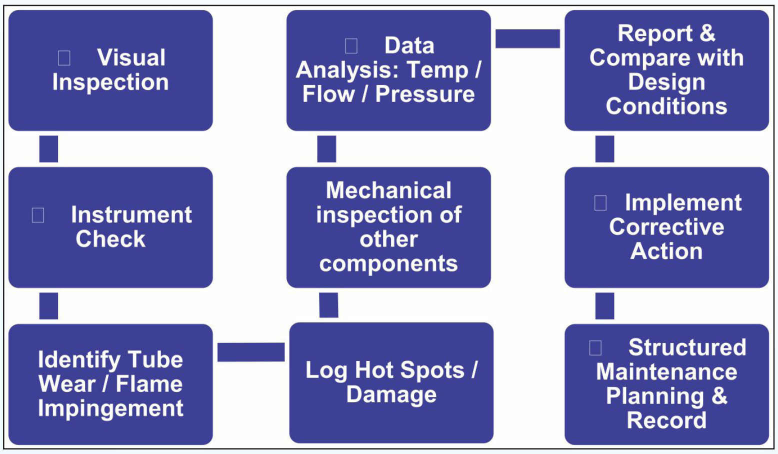

Fig. -9: Recommended Maintenance Cycle for a Heater

Inspection Requirements by Component

Component	Inspection Details
Burners	➢ Flame shape/stability, ➢ Erosion, plugging of gas or oil ports ➢ nozzle damage ➢ tile cracks
Process Coils	➢ Check tube thickness (ultrasonic and radiation type instruments) ➢ local hot spots ➢ coking inside tubes ➢ External scaling ➢ internal corrosion
External Casing, Ducting	➢ Visual corrosion/leak checks ➢ thermographic casing temp detection
Structural Members	Check for deflection, corrosion, weld quality
Explosion Doors & Ports	Ensure sealing fit, hinge integrity, leak checks
Tube Supports	Check for cracks, oxidation, corrosion, proper seating, no open gaps
Refractory	➢ Look for large open cracks, breakage of insulating castable ➢ sagging, spalling or damage of ceramic fibre
Cast Air Preheater	Check corrosion in cold-end section
Fans	Vibration monitoring, motor & impeller condition

Table 3 Inspection Requirements by Components

Regular Maintenance Procedures:

Regular maintenance during shutdowns and turnarounds is essential to ensure the optimal performance, safety, and longevity of fired heater. The parts or systems that could lead to unexpected failure during heater operation as inspected in Table 3.0, needs to be repaired or replaced through various procedures by repairing, and replacing parts or systems. Description & criticality of some of the basic regular procedures (Figure 10) have been included.

Coil Servicing:

MP steam is required to purge & cool the heater coils in case of feed failure or fuel cut-off etc. The entire coils shall be purged to ensure complete removal of hydrocarbon from system as per acceptable plant limit. Periodic check with hydrocarbon detector at discharge point may be done to ensure the same. Purging for minimum 15-30 minutes should be sufficient.

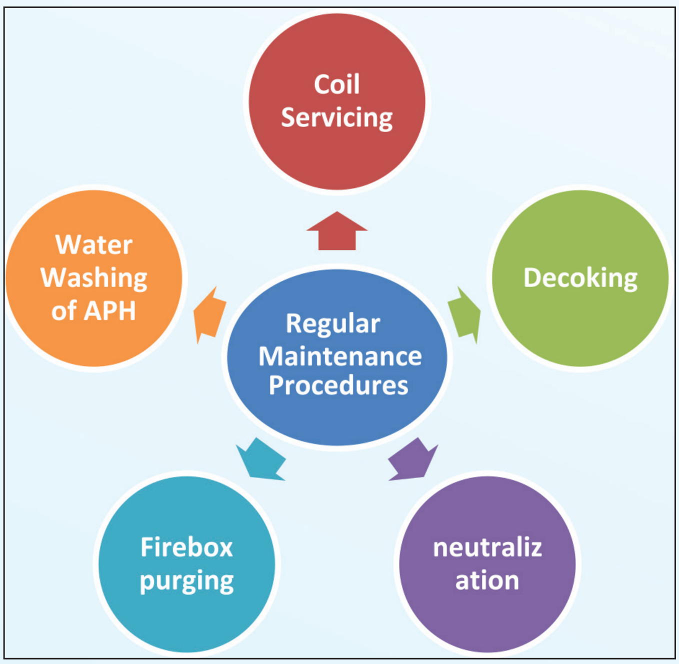

Fig. -10: Regular Maintenance Procedures

Decoking: HC gas/oil when processed at high temperatures form coke particles. Same should be removed from the heater coils on time-to-time basis during scheduled shutdowns for better operation and higher output.

Mechanical decoking is done by flushing out coke from equipment using a pig–a mechanical device with radial appendages like a wire brush. Pressurized water traverses the pig through the equipment, and as it moves, its appendages scrape out the coke on the internal surfaces.

In case of steam-air decoking, coke is spalled with a high steam rate at elevated temperatures and air is introduced to burn the residual coke.

Steam-air decoking is the generally preferred method used to ensure complete coke removal.

Mechanical decoking/ Pigging method ensures removal of stubborn coke deposition. Pigging operation shall be carried out by authorized skilled persons specifically trained in its safe use.

Fig. -11: Coking inside Tubes

Neutralization: When heater is shut down and opened for inspection or maintenance, moist air enters the equipment. Prior to opening to atmosphere, stainless steel tubes will require neutralization to protect against polythionic acid attack. Neutralization is normally carried out with a weak (2%) solution of soda ash inhibited with sodium nitrate to protect against chloride stress corrosion cracking.

Firebox purging: For the safety of operation at the time of startup and during emergency, permanent low-pressure steam connections are provided in the radiant section firebox for snuffing out combustibles. snuffing steam to the firebox and purge the heater for 15 minutes (minimum) or until white plumes are seen to emerge from the stack.

Water washing of APH: Due to the tubular construction of the cast finned air preheater, there are neither extensive flat surfaces, nor small ducts or no flow zones. The whole working surface is swept by the flow of flue gases thus preventing soot deposit.

However, for the safe operation, it is recommended to carry out washing of cast tubes, immediately after shut down in order to eliminate the acid forming. Slightly Alkaline filtered water with temperature above 15°C is used for water washing. Caustic Soda or Soda Ash may be used for Alkalinity. pH of the outlet wash water should be checked to determine the point when washing may be stopped.

Preventive Maintenance & Troubleshooting:

Preventive maintenance of the furnace, including the regular inspection of the equipment and the correction of the observed weaknesses, is a task of prime importance for the team in charge of operating the furnace. It will ensure a safe operation of the furnace, and most likely increase its lifetime.

Following indications of faulty operation as in Table 4 may be checked when the heater is operating as per design capacity:

S. No	Indications	Potential Cause	Corrective Action
1	Positive pressure at firebox top	Closed stack damper, high firing rate, fouled convection section, ID fan issues	Open stack damper, reduce firing rate, clean tubes, check ID fan
2	High/Uneven tube skin temp	Flame impingement, low flow, coking	Adjust burners, decoke coils, check thermocouples
3	Excessive firebox temp	Overfiring, excess air, after-burning	Check fuel input, reduce firing, inspect burners
4	Different Excess Oxygen reading at different location	Tramp Air Ingress	Open stack damper, clean convection tubes surfaces, check ID fan
5	High flue gas temp after convection	Tube fouling (inside/outside)	Use soot blowers, add fuel additives, decoke heater
6	High tube pressure drop	Coke buildup, high flow rate	Decoke, reduce flow

Table 4: Fired Heater Troubleshooting Guide

Case Study II

Troubleshooting of Crude Heater Performance

This case study is for a Crude Heater that was experiencing recurring issues, including flame impingement, hot spots in radiation section tubes of heater, higher convection section exit temperature, positive draft etc.

Site Observations	Probable Reasons as Derived	Recommendations
Heater Operating at higher crude capacity	❖ Overfiring with lower excess air ❖ Tramp Air Ingress ❖ Fouled Convection ❖ Non-uniform air distribution through each burner	check/clean burner tips & air register settings
Higher flame length touching tubes		Modifications in burner tips & air restriction plate
Opening of burner air registers are non-uniform and not fully open		
Bridge wall temperatures are lower than those in the original design conditions of the furnace.		Repair of damaged refractory packing of openings through Ceramic Fibre, tape gasket, ceramic fibre rope etc.
Variation in Excess O_2 Readings		
Higher casing Temperatures ranging from 90-170°C at various locations of heater based on thermography report		Modification in convection section & replacing existing stack damper with new low DP damper
Flue gas convection Exit Temperatures are higher		

Table 5: Recommendations for Troubleshooting & Improving Performance

After implementing the recommendations, following improvements are found:

- Crude flowrate in heater increased by 5%
- Heater Operating Duty increased by ~11%

4. Key Takeaways:

It is evident that the performance and longevity of a fired heater are closely linked to a combination of optimized design, effective maintenance, and efficient operation through advanced control. A well-engineered heater should integrate key design elements such as modern burners, high-quality materials, and air-fuel ratio control systems—are essential for maintaining combustion efficiency, minimizing heat loss, and ensuring long-term durability.

Equally important is a proactive inspection and maintenance program, including regular checks of burners, refractory, tubes, and convection sections. Timely troubleshooting of issues like temperature irregularities or draft fluctuations, along with routine tasks such as burner calibration and tube thickness monitoring, helps prevent failures and maintain safe operation.

By integrating these practices, operators can significantly improve thermal efficiency, reliability, and equipment lifespan, while reducing emissions and operational costs.

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4. Refinery-Specific Feasibility for Scaling Sustainable Aviation Fuel (SAF) in India

Mr. Sachin, Energy Lead at ARUP India, spearheads the hydrogen and energy agenda for the global consultancy. Previously at IndianOil R&D, he led initiatives advancing alternative fuels, pioneered hydrogen-blended CNG, established fuel cell/electrolyser labs, and launched Delhi's first fuel cell bus trials. Academically strong (DCE M.Tech., IISc Cert.), he has contributed 12 patents and over 20 research papers in the hydrogen domain.

Background

The global energy landscape stands at the cusp of a transformative shift, where the pursuit of sustainability is no longer a choice but a compelling imperative. Conventional fossil fuels, long the bedrock of industrial progress, now carry the heavy burden of carbon-intensive legacies that stretch far beyond the smokestack. Their environmental toll is not confined to direct combustion alone—it permeates every stage of the value chain, from extraction and refining to final use, manifesting most prominently in the elusive yet critical Scope 3 emissions. In stark contrast, sustainable fuels—born of biogenic origin or conjured from the purity of green hydrogen—emerge as harbingers of a cleaner, more responsible future. These fuels, rooted in agricultural waste, organic residues, or harnessed from renewable electricity, embody a dramatic departure from carbon-heavy paradigms. Their adoption not only slashes emissions across the lifecycle but also offers industries a powerful lever to redefine their climate narrative, elevate ESG performance, and align with the sweeping momentum of global net-zero ambitions.

Findings Summary

Technology Assessment Summary

Technology \ Criteria	Assessed/Indicative TRL for system integration	Least cost to integrate	Technical feasibility of Defence integration	Presence of global industry	Presence of domestic industry	Demonstrated Defence application	Demonstrated application in other asset heavy industry	Ease of user requirements and training	Performance	Carbon reduction	Overall Rating
Biogenic SAF & RD	🟢	🟢	🟢	🟢	🟠	🟢	🟢	🟠	🟢	🟠	Short Term
Microgrids	🟢	🟠	🟢	🟢	🟢	🔴	🟠	🔴	🟠	🟢	Short term
Electrification / Hybrid Systems	🟠	🔴	🟠	🟠	🟠	🟠	🟢	🟠	🟠	🟢	Medium Term
E-Diesel	🟢	🟢	🟢	🟠	🔴	🟠	🔴	🟠	🟢	🟢	Medium term
E-SAF	🟠	🟢	🟢	🔴	🔴	🔴	🔴	🟠	🟢	🟢	Medium term
E-Ammonia	🟠	🔴	🔴	🟠	🟠	🔴	🔴	🔴	🟠	🟢	Long term
Bio & E-Methanol	🟠	🟠	🟠	🟠	🔴	🔴	🟠	🟠	🟠	🟢	Long term
E-Natural Gas	🟠	🔴	🔴	🔴	🔴	🔴	🔴	🟠	🟠	🟢	Long term
Green Hydrogen (as a direct combustion fuel)	🟠	🔴	🔴	🟠	🟠	🔴	🟠	🔴	🟢	🟢	Long term
Green Hydrogen (as fuel cell technology)	🟠	🔴	🔴	🟠	🟠	🔴	🟠	🔴	🟠	🟢	Long term

🟢 High, representing a strong score in the criteria relative to the rest of the technologies.

🟠 Medium, representing an average score in the criteria relative to the rest of the technologies.

🔴 Low, representing a low score in the criteria relative to the rest of the technologies.

Table 1: Technology Assessment Summary (Source: Based on Authors Analysis)

Table 1 presents a comprehensive comparative assessment of emerging and sustainable energy technologies across a spectrum of criteria relevant to integration, performance, industry maturity, and carbon mitigation potential. Conducted by Arup, this study draws on its deep global experience in the sustainable energy domain, offering critical insights into the relative readiness and applicability of various technologies—ranging from biogenic sustainable aviation fuel (SAF) and microgrids to advanced solutions like green hydrogen and electro-fuels. Notably, biogenic SAF and microgrids stand out as near-term solutions with high technical readiness and low integration costs, making them attractive for immediate deployment. In contrast, technologies like green hydrogen (both as a combustion fuel and via fuel cell systems), e-ammonia, and e-methanol are recognized for their transformative long-term potential, particularly in decarbonizing hard-to-abate sectors, despite current limitations in ease of integration and user readiness. Arup's multi-criteria evaluation approach underscores the nuanced balance between innovation maturity and strategic impact, helping stakeholders prioritize investments that align with decarbonization goals and operational feasibility.

SAF: Background on Need & Current Path

The global momentum around Sustainable Aviation Fuel (SAF) is no longer a distant aspiration—it is fast becoming a regulatory inevitability, sweeping across continents with bold mandates and transformative implications. From the European Union's ReFuelEU Aviation Regulation, which stipulates a mandatory SAF blend starting at 2% in 2025 and rising to 70% by 2050, to the United States' SAF Grand Challenge, aiming for 3 billion gallons annually by 2030, governments are sending an unequivocal signal: the age of fossil-derived jet fuel is nearing its twilight. India's government has set a goal of 1% SAF in jet fuel for international flights by 2027, with this percentage doubling to 2% by 2028. To achieve these targets, the country will require approximately 140 million liters of SAF annually. Airlines, under pressure from carbon markets, customer expectations, and ESG commitments, are looking to SAF as the silver bullet to decarbonize flight without compromising fleet performance.

This tectonic shift calls for a disruptive innovation in the refining industry. For decades, traditional refineries have thrived on the production of aviation turbine fuel as a high-value, high-volume product. Now, they face a dual-edged challenge: adapt rapidly to accommodate biogenic feedstocks and novel process technologies, or risk business in the jet fuel value chain. The refining sector must reimagine its role—not just as fuel producers but as bio-refiners and hydrogen-integrated SAF hubs, capable of synthesizing fuels from waste lipids, alcohols, and CO_2 using green hydrogen. This transformation demands capital reinvestment, process innovation, and regulatory alignment—but it also opens the door to premium markets, carbon credits, and future-proofed operations. In essence, SAF mandates are not merely policy signals—they are clarion calls for a bold reinvention of the refining industry on the altar of sustainability.

The Indian Aviation Sector

India, standing proudly as the world's fifth-largest economy, is a vibrant mosaic of diverse landscapes, cultures, and untapped economic potential. Its rapid growth is fuelled by an ever-expanding infrastructure, and air transport plays a critical role in this upward trajectory. Aviation is not merely a mode of transport—it is a lifeline that binds the country together, strengthens the fabric of society, and drives economic dynamism. It bridges the vast distances between families, connects remote regions, and opens up a world of experiences, enabling the exchange of ideas, cultures, and innovations.

Rank	Country	% Share of Global O-D Traffic (2024)	Estimated O-D Passengers (millions)	Remarks
1	United States	18.1%	796	Mature domestic aviation market
2	China PR	16.7%	735	Strong state-backed aviation growth
3	**India**	**4.2%**	**185**	Fastest-growing aviation market
4	Japan	3.8%	167	Robust regional connectivity
5	Spain	3.4%	150	Major tourism-driven traffic
6	United Kingdom	3.3%	145	Strong international O-D movement
7	Italy	2.6%	114	High intra-Europe connectivity
8	Indonesia	2.2%	97	Archipelagic demand drives growth
9	Brazil	2.2%	97	Large domestic aviation footprint
10	Turkey	2.0%	88	Strategic Eurasian air hub

Table 2: Global growth snapshot of Aviation Industry. Source: IATA

Moreover, air travel is the backbone of India's business ecosystem, facilitating crucial investments, fostering trade, and unlocking new markets while nurturing a climate of global competitiveness. The aviation industry is far more than a sector in itself—it is a formidable engine of employment, international trade, and investment, providing millions of livelihoods and catalysing exponential economic activity. In 2023 alone, the industry made a monumental contribution of USD 53.6 billion to India's economy, directly sustaining over 7.7 million jobs. In essence, aviation is not just part of India's growth story; it is the very wings that carry the country towards a more interconnected, prosperous future.

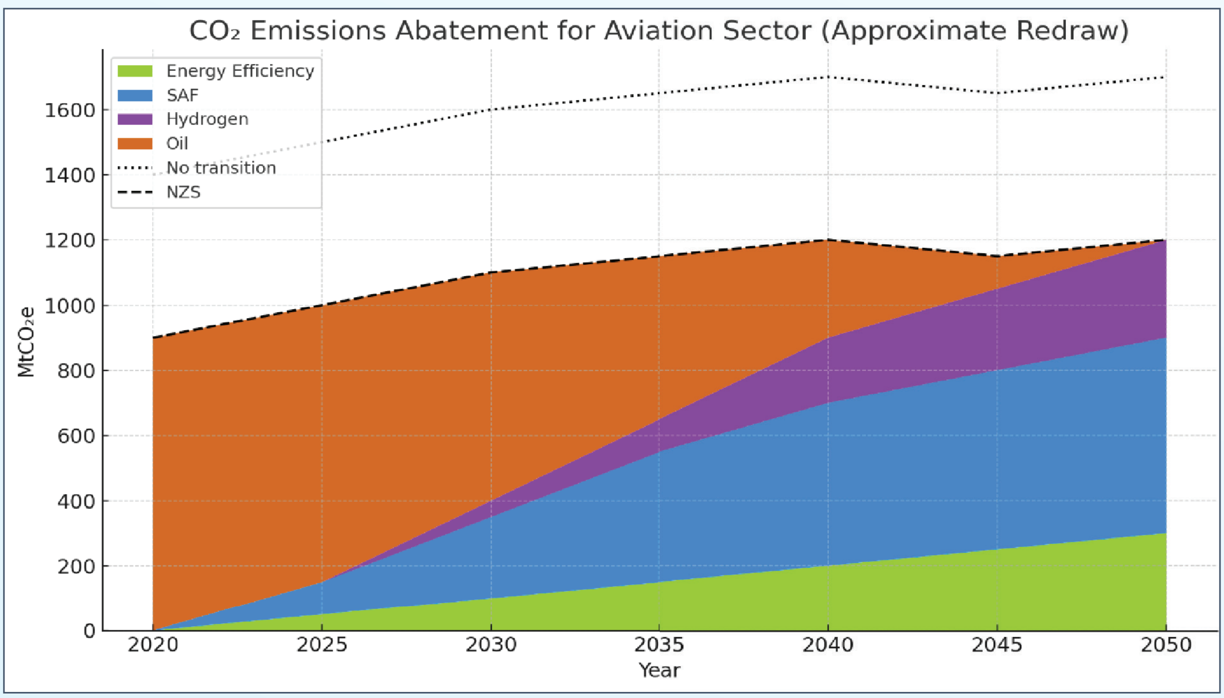

Fig. -1 Mitigating CO2 from Aviation sector. Source: Multiple and Arup Analysis

Finding Jet fuel for the Climate Age

The global and Indian aviation sector stands as one of the most formidable frontiers in the global quest for net-zero emissions by 2050—an enigma in motion, contributing an estimated 2–3% of global CO_2 emissions yet proving notoriously difficult to decarbonize. Unlike road transport, where electrification has found a solid footing, aviation demands extraordinary energy densities and presently lacks a commercially viable, zero-emission propulsion alternative that can meet its uncompromising performance needs.

While futuristic solutions such as hydrogen-powered flight, battery-electric aircraft, and next-gen operational efficiencies shimmer on the technological horizon, they remain—at best—decadal aspirations. The consensus is loud and clear: for the next critical window of climate action, these solutions alone cannot carry aviation toward net-zero.

Enter Sustainable Aviation Fuel (SAF)—the most potent, immediate, and scalable decarbonization lever at the sector's disposal. With its ability to seamlessly integrate into existing infrastructure, SAF offers not just a transition, but a transformation. It brings with it not only dramatic reductions in CO_2 but also substantially curbs harmful pollutants like sulphur dioxide (SO_2), nitrogen dioxide (NO_2), and particulates, offering a breath of fresher air—both literally and figuratively.

If nurtured through the right mix of policy ambition, capital infusion, and technological innovation, SAF, as depicted in Figure 2, holds the golden ticket to aviation's green future, capable of rewriting the rules of flight for a cleaner, more connected world.

SAF and the broader context of e-Fuels

The concept of e-fuels, or synthetic fuels, involves creating liquid hydrocarbons from renewable electricity, captured CO_2, and hydrogen. These fuels are designed to function much like fossil fuels but offer a significantly lower lifecycle carbon intensity, often usable as direct "drop-in" replacements.

The closely related term of biofuels refers to biogenically produced chemicals that, similar to e-fuels, also are generally drop-in compatible, while offering significant emission reductions.

A major advantage of SAF is that it is "drop-in" ready, meaning it blends seamlessly with conventional jet fuel and can utilize existing aircraft and infrastructure; it is already certified for current fleets and is being used commercially on flights today. Crucially, SAF offers the same performance as traditional jet fuel but with drastically lower emissions, making it a vital and necessary component for the decarbonization of air travel.

Thus, the question becomes: How do we produce SAF sustainably at scale, at reasonable costs?

Comparison of SAF Production Pathways

Unlike conventional ATF, SAF can be produced from different pathways depending upon the raw materials / feedstocks being used. Few of these routes are discussed below:

HEFA (Hydro-processed Esters and Fatty Acids)

HEFA is currently the most technically and infrastructure-wise mature and readily deployable technology and is the most common pathway for making SAF today. It primarily uses lipid-based feedstocks like Used Cooking Oil (UCO) and non-edible oils (vegetable oil or waste fat) into jet fuel.

Hydroprocessing uses 0.04-0.12 tons of H_2 per ton of SAF in hydrotreating, hydrocracking and isomerization (a process specific to jet fuel), with an average of 0.08 tons of H_2. This is still much higher H_2 use than conventional oil refining, which requires around 0.02-0.04 tons of hydrogen per ton of oil refined, depending upon the complexity factor of the refinery.

While globally operational and having the lowest CAPEX and OPEX costs, its scalability in India in the short term is constrained by the limited availability of these specific feedstocks. HEFA benefits from potentially being adapted into existing refinery hydroprocessing units, though dedicated pre-treatment facilities are needed. It offers a moderate GHG reduction potential (50-80%).

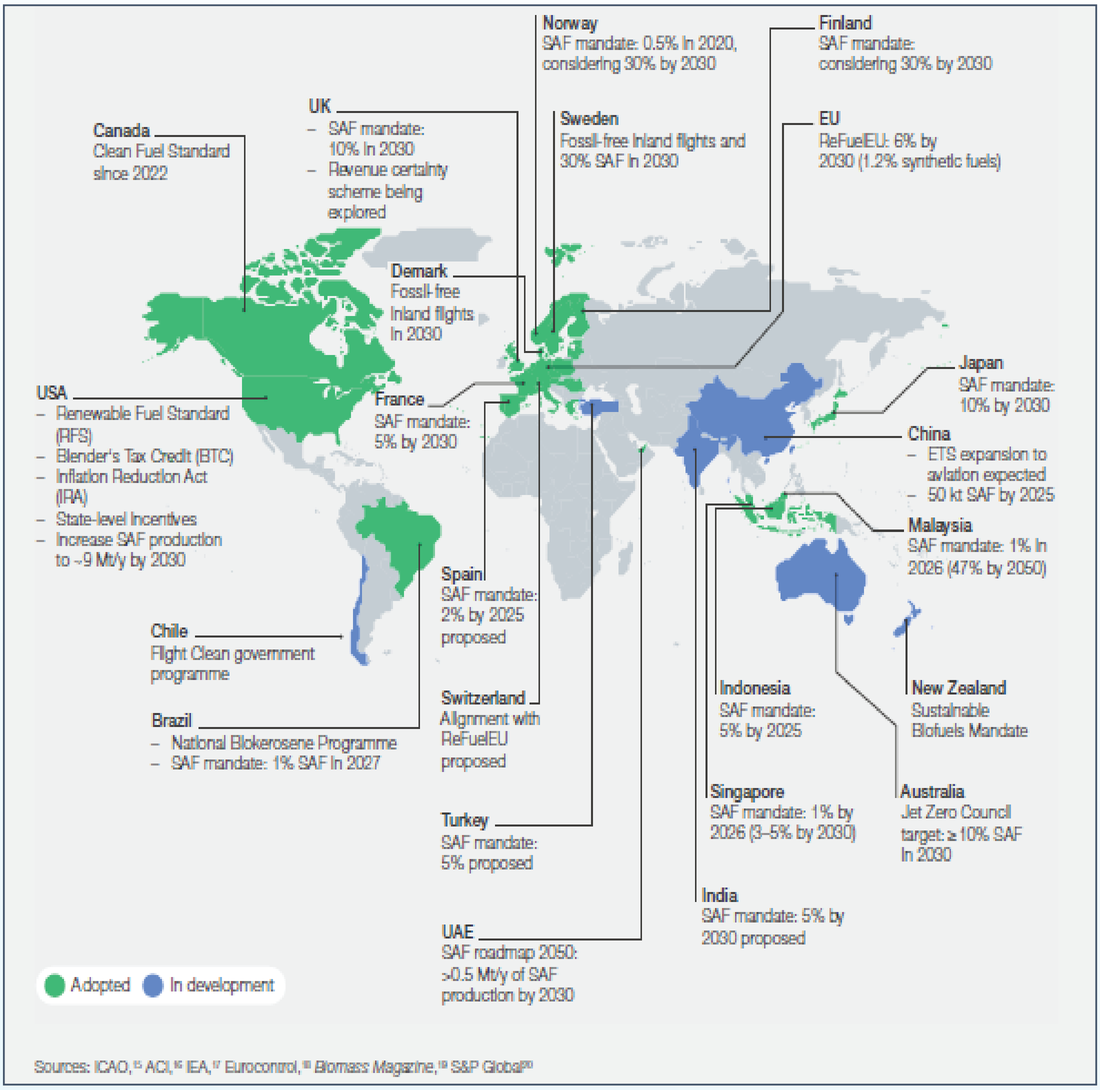

Fig. -2 Global Status of SAF Blending mandates. Source: WEF Report March 2024

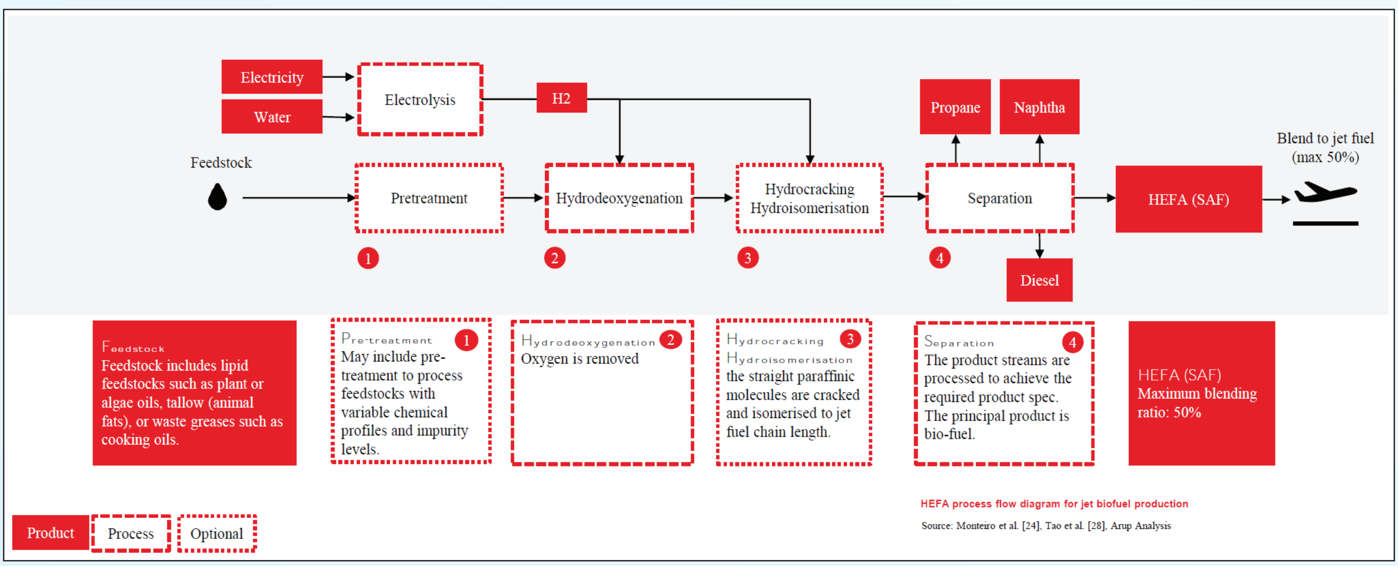

Fig. -3 Hydro-processed Esters and Fatty Acids (HEFA) Process Diagram

Gas-FT (Gasification/Fischer-Tropsch)

The Gas-FT pathway utilizes carbon-rich feedstocks such as agricultural residues and Municipal Solid Waste (MSW). This pathway turns syngas (a mix of carbon monoxide, hydrogen and other gases), typically obtained from biomass gasification, to jet fuel via the Fischer-Tropsch process.

It technically does not need any external hydrogen supply, but injecting hydrogen can significantly improve the utilization of biogenic carbon and reduce biomass consumption.

It is an emerging technology, mostly at the pilot stage globally, but shows significant potential for mid-term scale-up in India due to the abundant availability of these biomass and waste resources. Gas-FT requires new, large-scale gasification and FT synthesis plants, resulting in high CAPEX and logistics costs for biomass handling. It offers a high GHG reduction potential (80-90%). Due to the promise of its scalability, it could benefit significantly from carbon pricing.

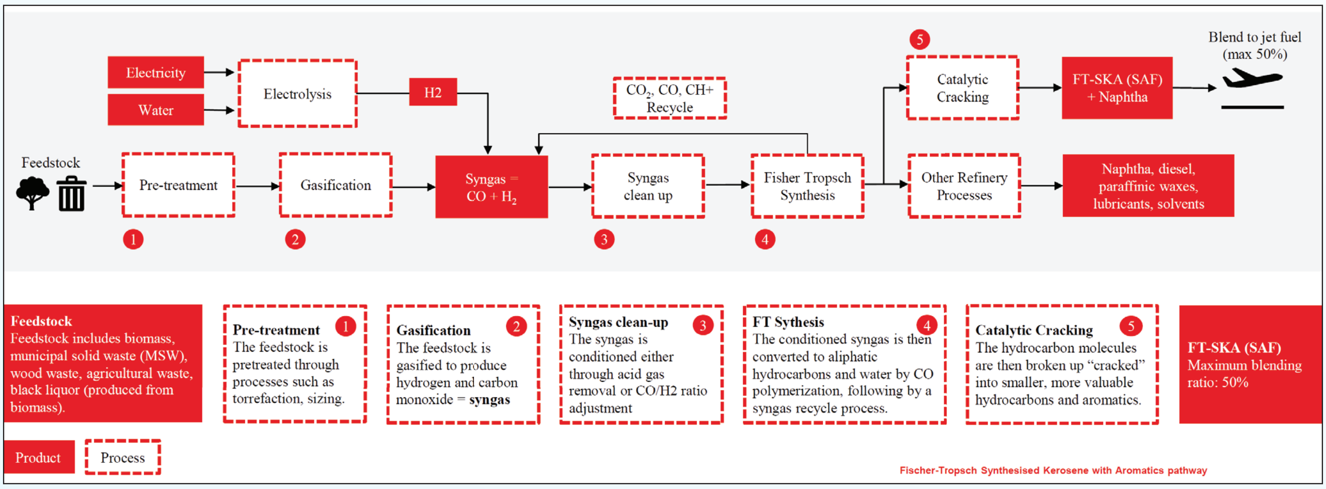

Fig. -4 FT-SPK (Fischer-Tropsch Synthetic Kerosene) From Bio Sources Process Diagram

AtJ (Alcohol-to-Jet)

AtJ technology converts alcohols – primarily ethanol from sugarcane, corn, or agricultural residue – into jet fuel. Similar to Gas-FT, it is also in the emerging phase with few commercial plants globally but can scale in India given the significant existing ethanol production along with the production push for road transport. AtJ may require new ethanol processing units and benefits from existing refining infrastructure for downstream steps. While promising and leveraging India's ethanol base, the outcome of feedstock competition with both food as well as road fuel remains to be seen. Its GHG reduction potential is moderate (50-70%).

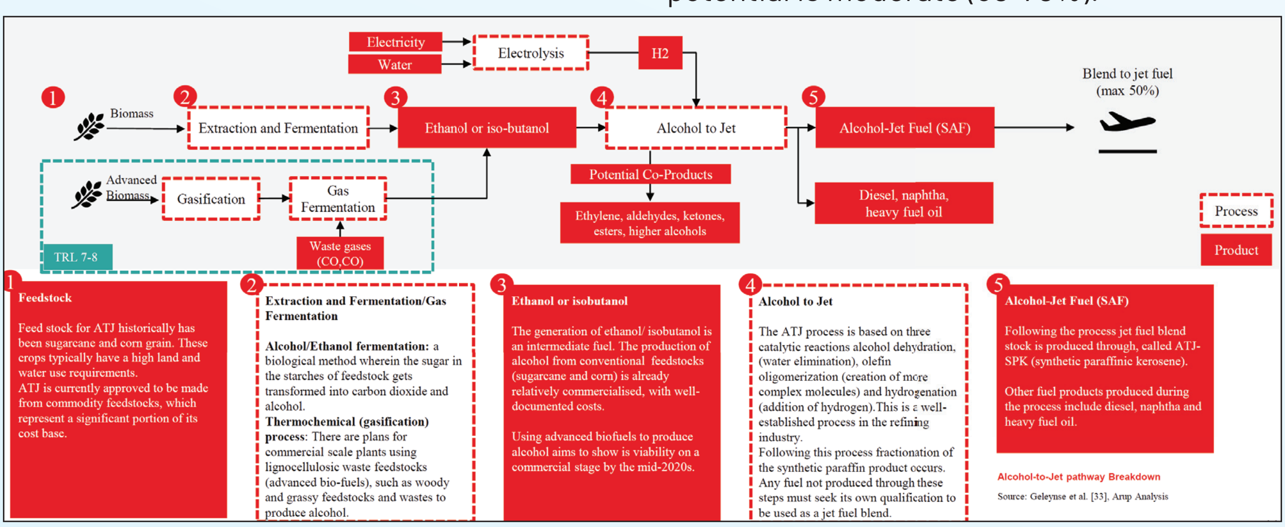

Fig. -5 Alcohol to Jet (AtJ) Process Diagram

PtL (Power-to-Liquid)

Considered the long-term, crucial pathway for net-zero aviation, PtL synthesizes fuel from green hydrogen (produced via electrolysis using renewable electricity) and captured CO_2 through the Fischer-Tropsch process, with the output often referred to as e-fuels.

This technology is currently experimental and in the R&D phase, making it the most expensive and capital-intensive option today. Its viability is entirely dependent on the future scalability and cost reduction of green hydrogen and CO_2 capture technologies. PtL requires extensive new infrastructure but offers the highest GHG reduction potential (90-100%) and minimal land/water footprint compared to bio-based pathways. It benefits most from high carbon pricing policies.

As CO_2 needs to react with hydrogen (the reverse-water-gas-shift reaction) to produce carbon monoxide (CO) for the Fischer-Tropsch process, this pathway is more hydrogen-intensive than gas-to-liquids. Power-to-liquids uses 0.58 tons of hydrogen per ton of jet fuel produced.

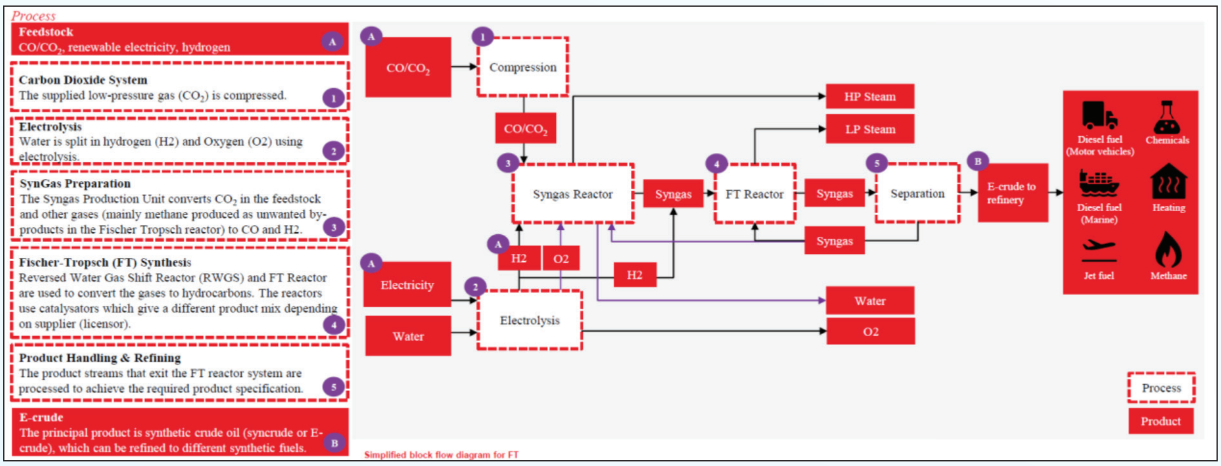

Fig. -6 PtL Process Diagram

Methanol-to-jet

This pathway turns low-carbon methanol (CH_3OH) directly into jet fuel. Its proponents highlight its higher yield of jet fuel versus other pathways. If the methanol is produced through the power-to-liquids process (e-methanol produced through synthesizing green hydrogen and carbon dioxide), the hydrogen use would be around 0.56 tons of hydrogen per ton of jet fuel.

Unlike the previous 4 processes, this process does not have SAF certification yet.

Chemical Comparison of Fuel Composition

The chemical composition of Sustainable Aviation Fuels (SAFs) is a determining factor in their performance and emissions profile, varying significantly and contrasting with conventional Jet A/A-1. Understanding these differences is crucial for assessing their integration into the aviation sector.

Conventional Jet A/A-1 aviation fuel is a complex mixture of hydrocarbons, primarily consisting of:

- Paraffins (Alkanes): ~30-60% (normal, iso, and cyclo-paraffins/naphthenes). These provide energy and good combustion.
- Aromatics: Typically 8-25% (up to 25%). Including compounds like benzene, toluene, xylenes, they contribute to density and are important for seal swell in older aircraft systems, but are also major precursors to particulate matter.
- Olefins (Alkenes): Restricted to very low levels (e.g., <1%) due to poor gum stability.
- Sulfur Compounds: Present in trace amounts (up to 3000 ppm, typically lower), leading to SOx emissions.

In contrast to this varied blend, SAFs generally have a cleaner, more uniform composition depending on the specific pathway used to create them. The table below outlines the chemical profiles of major SAF types:


Pathway	Paraffins	Aromatics	Olefins	Sulfur	Key Composition Comparison vs. Jet A/A-1
Conventional Jet A/A-1	~30-60% (n-, iso-, cyclo-)	8-25%	<1-5%	Trace (>0)	Baseline complex hydrocarbon mixture.
HEFA	Predominantly iso-, some n-paraffins	Virtually none	Virtually none	Virtually none	Significantly "cleaner" (no aromatics, sulfur). Higher H/C ratio.
ATJ	Primarily branched iso-, some cycloparaffins	Very low (can be engineered)	Very low/ None	Virtually none	Similar paraffinic nature & no sulfur to HEFA. Can include cyclics/controlled aromatics.
Gas-FT	Highly paraffinic, rich in iso-paraffins	Essentially zero	Essentially zero	Essentially zero	Very similar to HEFA – highly pure paraffinic fuel.
PtL-FT	Highly paraffinic	Negligible	Very low/ None	Virtually none	Aligns with HEFA and Gas-FT (highly paraffinic).
PtL-MTJ	Present, higher purity than FT due to oligomerization and hydrogenation steps	Present (broader range)	Very low/ None	Virtually none	Offers flexibility to produce aromatics, potentially closer to conventional in this respect, but sulfur-free.

Table 3: Chemical Composition Profiles of Key SAF Pathways vs. Conventional Jet Fuel

The distinct differences in chemical composition, particularly the significant reduction or absence of aromatics and sulfur in most SAF types compared to conventional jet fuel, have notable impacts on how the fuel performs and the emissions produced during combustion.

Impacts on Engine Performance and Emissions

The compositional variations between SAFs and conventional jet fuel directly influence several key aspects of engine operation and environmental output, mentioned below.

Impact Area	Conventional Jet A/A-1	SAFs
Particulate Matter (PM/Soot)	Main precursor is aromatics, leads to significant soot.	Low-aromatic SAFs (HEFA, Gas-FT, PtL-FT) show 50-90% reduction. Engineered-aromatic types (Some ATJ, PtL-MTJ) may have PM closer to conventional but often lower.
NOx (Nitrogen Oxides)	NOx formation linked to combustion temperature/ time.	Modest reductions potentially due to slightly lower combustion temperatures (typically 0-10%). Highly dependent on engine design.
SOx (Sulfur Oxides)	Present due to sulfur content.	Near-complete elimination due to virtually sulfur-free composition.
Energy Density	Lower gravimetric, higher volumetric (due to aromatics).	Higher gravimetric (energy per mass) due to higher hydrogen content, but lower volumetric (energy per volume). Could slightly impact range if used neat.
Seal Swell	Aromatics cause seals to swell, ensuring tight fits.	Purely paraffinic types lack this property. Managed via blending with conventional fuel, engineered aromatics in some SAFs, or newer seals.
Lubricity	Sulfur/aromatics contribute to lubricity for fuel pumps.	Highly refined paraffinic types have lower lubricity. Addressed by blending or approved additives.
Cold Weather Performance (Freeze Point)	Varies based on composition.	Iso-paraffin rich types (HEFA, ATJ, Gas-FT) generally have excellent low-temperature properties (lower freeze points), which is an advantage.

Table 4: Comparative Impact on Engine Performance and Emissions

In summary, while HEFA appears to offer an immediate, low-cost entry point limited by feedstock, FT-SPK and AtJ present promising mid-term options leveraging India's abundant biomass/waste and growing ethanol production, respectively, albeit with higher initial investment and infrastructure needs. PtL, though currently the most expensive and least mature, holds the key to deep decarbonization in the long run, contingent on the build-out of green hydrogen and CO_2 infrastructure and falling costs.

India's strategy needs to consider the unique strengths and challenges of each pathway in alignment with regional resources and fleet requirements.

Yield and Cost Analysis

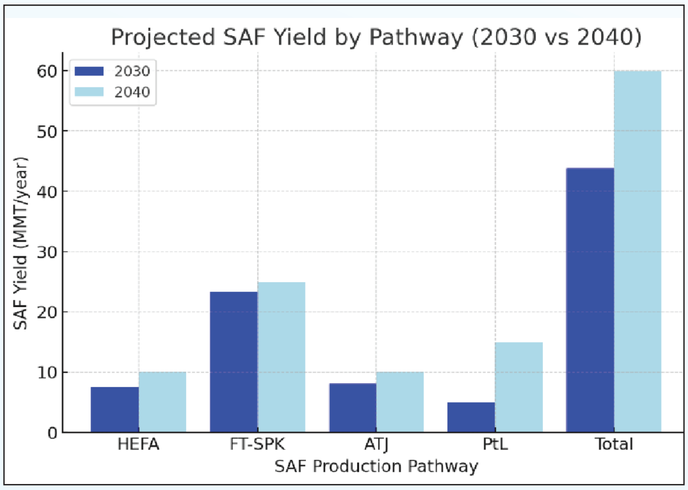

Fig. -7 Cost Analysis (by Authors - based on assumptions)

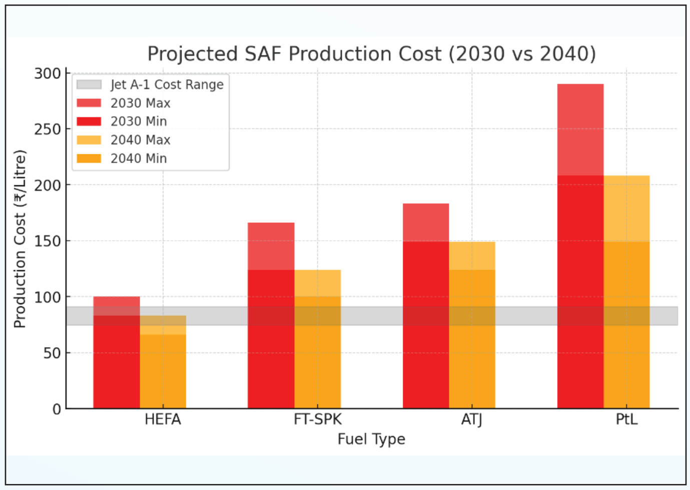

Fig. -8 SAF Production Pathways in India

The chart illustrates the projected production costs of various Sustainable Aviation Fuel (SAF) pathways for the years 2030 and 2040, benchmarked against the conventional Jet A-1 cost range (highlighted in grey). Among the fuel types, HEFA (Hydro-processed Esters and Fatty Acids) shows the lowest cost range, potentially nearing parity with Jet A-1 by 2040 however, its scalability is constrained by limited feedstock. FT-SPK (Fischer-Tropsch Synthetic Paraffinic Kerosene) and ATJ (Alcohol-to-Jet) demonstrate moderate cost reductions over time but remain significantly above Jet A-1. PtL (Power-to-Liquid), although a promising long-term solution for deep decarbonization, remains the most expensive pathway due to high renewable electricity and conversion costs.

Between 2030 and 2040, SAF production is expected to scale significantly, with total yield increasing from approximately 43 MMT/year to 60 MMT/year. All pathways — HEFA, FT-SPK, ATJ, and PtL — show growth, but FT-SPK leads in yield contribution, followed by ATJ and HEFA. PtL, although contributing the least by 2030, shows rapid yield growth by 2040, aligning with anticipated advances in renewable electricity and CO_2 capture infrastructure.

This juxtaposition reveals a fundamental tension in the SAF transition — while technical scalability is improving, particularly for FT-SPK and PtL, economic viability continues to be a barrier, especially for synthetic fuels like PtL. Thus, a balanced SAF strategy should prioritize early deployment of lower-cost pathways like HEFA, while investing in R&D, policy support, and infrastructure for higher-yield but currently costlier technologies like PtL to achieve long-term decarbonization goals in aviation.

This reinforces the need for policy support, innovation, and refinery-specific assessments to strategically scale viable SAF technologies in alignment with net-zero aviation ambitions.

Arup's preliminary assessment highlights the importance of aligning feedstock and technology choices with each refinery's geographic and

operational context. A targeted approach – grounded in refinery-specific data, feedstock mapping, and logistical analysis—will be essential for scaling SAF in India. Tailoring strategies to local conditions can help maximize both technical feasibility and economic returns as India charts its path toward SAF deployment through 2040.

While the unit cost of Sustainable Aviation Fuel (SAF) is often considered a primary metric in technology selection, it should not be viewed as the sole determinant—particularly for oil companies navigating the complex transition to low-carbon operations. Arup, drawing on its deep global expertise in sustainable fuels and refining systems, conducted a detailed and refinery-specific analysis to guide this critical decision-making. The assessment went far beyond cost, incorporating a wide array of crucial parameters such as refinery configuration and complexity (Nelson Index), proximity and availability of viable feedstocks, hydrogen production and integration readiness, water and land availability, conversion efficiency, and overall energy intensity.

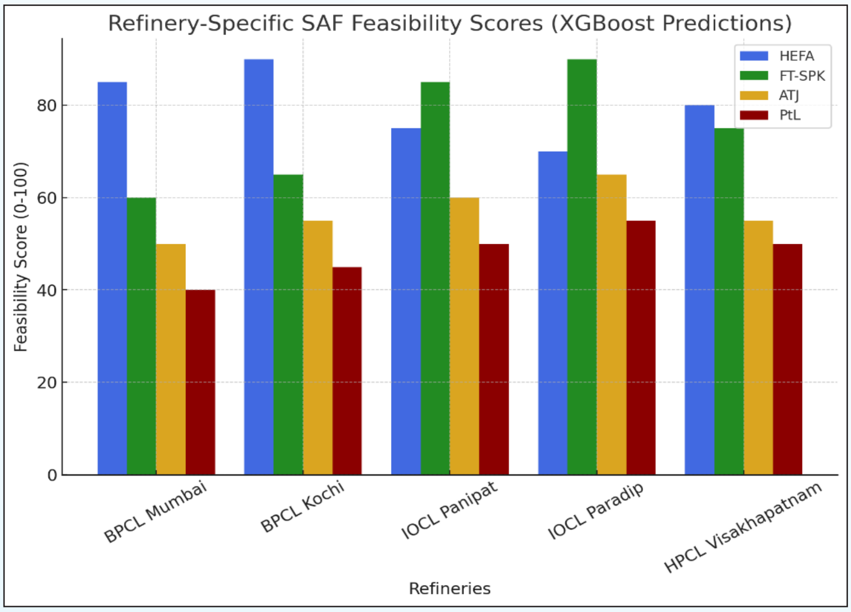

Fig. -9 Feasibility Score of Refineries for different SAF production technologies

Source: Authors analysis - based on assumptions)

Based on the in-house developed algorithms, Arup has conducted a robust, multi-criteria feasibility assessment across key Indian refineries using advanced predictive modelling and a rich dataset of geographical, infrastructural, and techno-economic parameters. The analysis clearly shows that the optimal SAF technology varies by location—while HEFA scores high in coastal refineries like Mumbai and Visakhapatnam, FT-SPK and ATJ emerge stronger for sites like Paradip and Panipat. This data-driven approach can empower refiners to select technologies not just based on cost, but on long-term feasibility and site-readiness. For oil companies seeking to make informed SAF investments and navigate this complexity, **Arup offers the strategic lens, engineering depth, and location-specific insights to drive sustainable, bankable decisions.**

Conclusion:

Sustainable Aviation Fuel (SAF) and e-fuels are emerging as vital enablers in the decarbonization of the aviation industry. The chemical properties of SAF significantly influence jet engine performance, emissions, and operational behavior. Although the cost of SAF is expected to remain higher than conventional fuels until at least 2040, technology selection must go beyond simple cost comparisons. Arup's refinery-specific, multi-criteria assessment—leveraging predictive analytics, infrastructure readiness, and regional resource availability—offers tailored pathways for Indian refiners to make informed, strategic technology decisions. This data-driven approach will be critical in achieving national SAF targets while supporting global net-zero ambitions.

Summary:

- SAF and e-fuels are set to become sustainable levers for the Aviation Industry
- Chemical composition of the SAF produced through different pathways impact the jet engine performance
- Cost of SAF is expected to stay higher upto 2040
- Choice of technology for SAF production is a function of multiple parameters besides cost
- Arup can help innovate and tailor strategies that empower Indian refineries to make optimal technology choices aligned with their operational realities and decarbonization goals.

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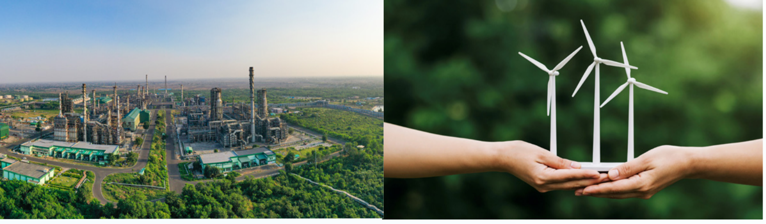
5.0 Safe and Compact Metal Hydride Based Solid State Hydrogen Storage, Compression, Refuelling Solutions and Their Promising Applications in The Industry

Ms. Suvechya Chattopadhyay is an Electrical Engineer with over 8 years of industry experience, currently serving at Hind Rectifiers Ltd. For the past two years, she has been actively involved in cutting-edge work on solid-state hydrogen storage, contributing to the promotion of this innovative technology.

Mr. Shailesh Mehta is a mechanical engineer from VJTI. His 40+ years of experience, in NELCO, CG Power and Hirect, includes working on ToT projects ranging from Mitsubishi TVs, ABB and CAF Converters and Koncar Traction Systems. He has gained rich experience during manufacturing and indigenizing the technology and items with local vendors. Mr. Mehta is from the design field and currently is working as GM-Marketing in Hind Rectifiers Ltd. (Hirect).

Mr. Lalit Tejwani is an electrical engineering graduate, and has a Diploma in Business Management. He is an established professional with almost 35 years of experience in electrical & electronics engineered solutions in various sectors like railways, power, metals-mining, and industrial automation. He had been associated with companies like Siemens, ABB, Alstom, Titagarh Rail for business in SE Asia & Africa and currently working as the Chief Strategy Officer for Hind Rectifiers Ltd.

Dr. Noris Gallandat has completed his PhD in mechanical engineering from Georgia Institute of technology and has co-founded GRZ Technologies SA in 2017 as the Chief Executive Officer of the company. Working at the intersection of science, technology and business, he aims to have a positive impact on the energy transition by contributing to the growth of a triple-bottom line cleantech company: creating earnings with renewable energy, help reduce the human impact on environment and allow every team member grow at GRZ Technologies.



Introduction

Green Hydrogen has become a promising zero-emission fuel alternative for decarbonizing various sectors like transportation, industry and power generation, by offering a sustainable and clean energy source. But the flammability, handling and storage issues of hydrogen are big challenges and any lapse on the systems results into many life taking accidents.

Based on the properties of Hydrogen, several processes are designed for storage of Hydrogen in Gaseous, Pressurized Gas, Liquid or Solid form. Among these, the MH based Solid state Hydrogen storage technology is gaining importance because of its high safety features.

Hind Rectifiers Limited (www.hirect.com), founded in 1958, is a listed company on the NSE and has been one of the leading manufacturers with thousands of installations of Power Supplies used for various industrial applications. HIRECT pioneer in Design and Manufacturing of DC Power Supplies for Hydrogen Generation since last 20 years. Around 80% of the Hydrogen generation plants in India are powered by HIRECT make Power Supplies.

In 2024, HIRECT tied up with GRZ Technologies (GRZ), Switzerland to explore revolutionary solutions on Metal Hydride based Solid Hydrogen Technology to enhance India's transition from fossil fuel to Green energy with "Dense and Safe Hydrogen" (DASH) Solutions.

The MH based solutions with very high volumetric density and excellent safety characteristics can operate at the lowest possible pressure and work mainly on thermal technology which involves no mechanical/moving parts for compression of the gas. This ensures highest possible safety amongst all methods of Hydrogen storage at current times.

Concept and Utility of Metal Hydride (MH) Hydrogen Storage

The most convenient way of storing Hydrogen in solid form is to store it in inorganic carrier Metal alloys which absorb Hydrogen under the right conditions, just by physical reaction. During the absorption process, the Hydrogen molecules (H_2) are dissociated to form Hydrogen atoms (H) which are absorbed or dissolved into specific metal alloys and crystals. Thus, the absorption of Hydrogen molecule in metal alloys is an exothermic process. This process is shown in Figure 1. **In the same way, the process to release/extract Hydrogen from Metal Hydride (MH) storage requires heat so that the gas gets excited and comes out of the metal lattice to form molecular hydrogen again and hence is an endothermic process.**

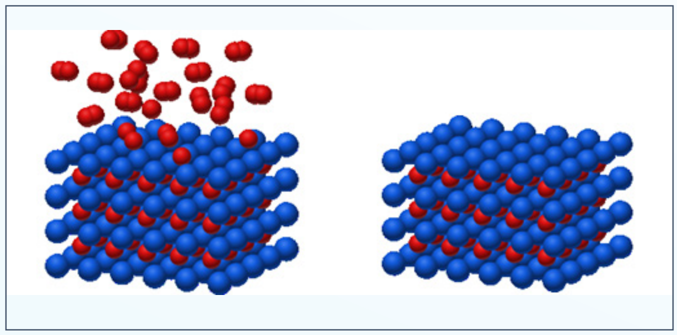


Fig. -1 : Absorption of hydrogen in Metal alloys

In this absorbed state, the hydrogen atoms occupy the interstitial sites of the metallic lattice, forming a Metal Hydride (MH). In such a storage, the distances between the individual atomic nuclei become significantly smaller than they would be in the gas phase. As a result, the volumetric density of the metal hydride-based hydrogen storage is very high and so is the energy density of the system. As elaborated in Figure 2, in MH storage of hydrogen, the reduction in gap by a factor 16.6 (i.e. 35 Å/2.1 Å) increases the volumetric density by a factor of 2300.

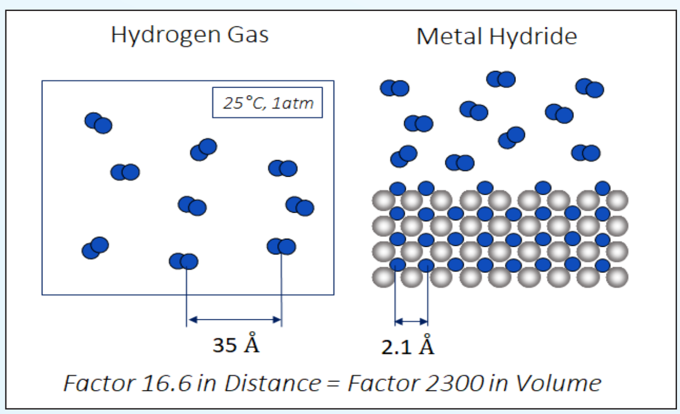


Fig. -2: Volumetric density increases for storage of Hydrogen using Metal Hydride (MH) Technology

Materials for MH Technology

There are a variety of possible alloys that can be selected as the optimum hydrogen carrier material. An example of an alloy is Lanthanum Penta-nickel (LaNi5). When hydrogen is absorbed by such an alloy, the following reaction takes place:

$$LaNi_5 + 3H_2 \longrightarrow LaNi_5H_6$$

In the same way, Nanostructured Titanium Iron (TiFe) alloys can react highly, exothermically and reversibly, with hydrogen at ambient temperature to form hydrides of the approximate compositions: TiFeH and $TiFeH_2$. Depending on the doping variety of the alloy, the reaction may vary as:

$$TiFe + ½\,H2 \longrightarrow TiFeH$$

$$TiFe + H2 \longrightarrow TiFeH_2$$

It is important to state that these are few examples from a whole class of materials. At present there are more than 300 such alloys developed and evaluated by the GRZ engineers, which are chosen as hydrogen carrier material.

The selection of a particular alloy can be done as per suitability, availability, requirements for specific application, and thereby optimizing the properties of the overall storage solution.

Family type	Metal hydrides	$-\Delta H^\theta$ (kJ mol^{-1} H_2)	$-\Delta S^\theta$ (J K^{-1} mol^{-1})
AB	TiFe	28.1	106
	$TiFe_{0.85}Mn_{0.15}$	29.5	107
	$TiFe_{0.8}Ni_{0.2}$	41.2	119
AB_2	$TiMn_{1.5}$	28.7	114
	$ZrFe_{1.5}Cr_{0.5}$	25.6	97
	$Ti_{0.98}Zr_{0.02}V_{0.43}Fe_{0.09}Cr_{0.05}Mn_{1.5}$	27.4	112
	$Ti_{1.1}CrMn$ (Kojima et al., 2006)	22.0	94
AB_5	$MmNi_5$	21.1	97
	$LaNi_5$	30.8	108
	$LaNi_{4.25}Al_{0.75}$	44.1	117
	$CaNi_5$	31.9	101
Solid-solution	$V_{0.855}Ti_{0.095}Fe_{0.05}$	43.2	140
	$V_{92.5}Zr_{7.5}$ (Lototsky et al., 2005)	40.3	147
	$(Ti_{0.16}Zr_{0.05}Cr_{0.22}V_{0.57})_{0.95}Fe_{0.05}$ (Kao et al., 2010)	34.8	

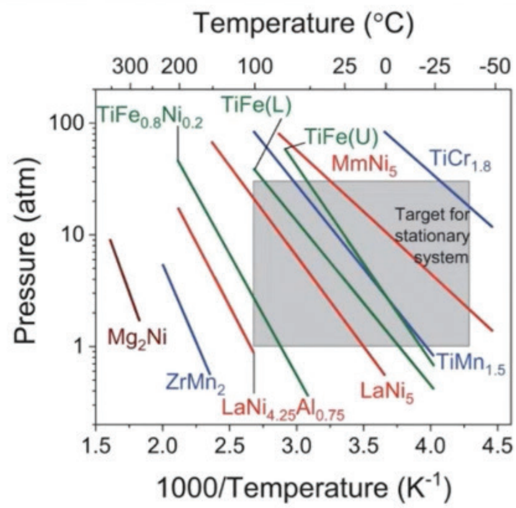


Fig. -3: Some metal alloys generally used in MH storage applications

Safety feature

Unlike the conventional methods of storing hydrogen as Pressurized Gas or Cryogenic Liquid forms, the Hydrogen stored in the DASH Solid MH Storage technology is at ambient temperature and low pressure of approx. 30-45 Bar. The desorption of hydrogen from MH Storage is an endothermic process, so heat must be supplied to the system to keep the extraction running. Hence there is minimal leakage probability in the system. Yet compared to pressurized gas vessels, the hydrogen release rates are much lower. Thus, the MH storage technology provides enormous safety characteristics to prevent leakage and explosion as the discharge in case of leakage is self-inhibiting.

In the event of a leak, only a limited fraction of the stored hydrogen can be instantly leaked. The desorption process being endothermic, the leaked hydrogen takes the required heat from the

Fig. -4: Storage module which is frozen because of fast (leak) flows.

surrounding moisture causing the system to cool down resulting to freezing of the opening itself. Hence, the leakage rate decreases and may even cease completely. Figure 4 shows a storage module from which the hydrogen was removed with a very high flow rate causing it to freeze and exemplifies the process described above.

The limitation or stop of the leakage flows means that the escaping hydrogen can be detected long before the lower hydrogen-to-air mixture explosion limit is reached. Due to the above-described phenomenon, the inherent physical properties of the system itself guarantee that enough time is available to reliably prevent the creation of an explosive mixture with appropriate measures.

Scalability of the MH storage

When it comes to application orientation of any technology, scalability is a significant question to be answered. It is worth mentioning that along with high volumetric density and good safety features, the MH technology of Hydrogen storage is highly scalable.

GRZ has successfully designed and manufactured MH based hydrogen storages for a wide range of capacity ranging from 1Kg to 675 Kgs. These storages are available in standard DASH M series (Modular) & DASH C series (Containerized Plug Play type with HVACs, all required auxiliary and safety equipment such as ventilation, H2 sensor, alarms etc.) as per requirement of the application.

These systems can be charged with hydrogen directly from an electrolyser or other source, store hydrogen as long as needed, and deliver ultra-pure hydrogen to a downstream application. Whether it is for safe and dense buffer storages, long-term storage, or other applications, this technology will enable storage of large quantities of hydrogen safely and efficiently.

Fig. -5: Scalability of MH based Hydrogen storage in parallel Tubular structures

MH storage Application for Green Power

Green Hydrogen and Hydrogen Fuel cells have emerged as a alternative source of green electricity at present times. The MH storage in line with a Fuel Cell can play a significant role in decarbonizing the power sector. This decarbonization takes place in three steps. First, green hydrogen (H_2) is produced by splitting water (H_2O) with renewable electricity, which releases Oxygen (O_2) as byproduct. This hydrogen is then stored for later usage in no solar or no green power hours. Finally, when there is power demand, the stored hydrogen is consumed by the fuel cell system and converted into electrical power. The only exhaust gas in this process is steam which is again recyclable.

GRZ's DASH Power solution is a compact & innovative approach to enhance this decarbonization from fossil fuel to green energy. DASH Powers are containerized and fully integrated plug and play systems combining GRZ's MH based solid-state hydrogen storage, automotive-grade fuel cell systems, DC/AC inverter and auxiliary components. They can be charged with hydrogen from any source and deliver on-demand backup electrical power for 14 hours. The basic functionality of the system is illustrated in Figure 6.

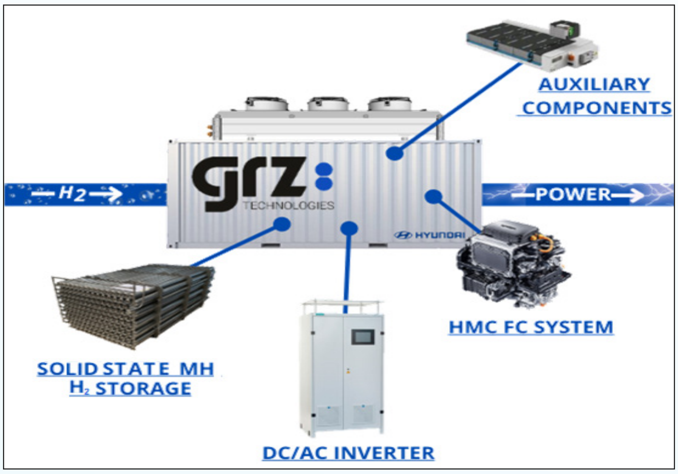


Fig. -6: Dash Power combining MH Solid Hydrogen Storage, Fuel cell, DC/AC inverter and Aux components.

This technology is extremely cycle resistant and enables a service life of 20 years or longer as the storage technology is MH based on a fully reversible process without lifetime limitations or degradation. The entire specified capacity can be used without limitations. This technology enables the decentralized storage of electrical energy in the range of megawatt hours (MWh). At present GRZ's largest Dash Power standard configuration is capable of storing 4.5 MWh hours of electrical energy on the very small footprint of only 14.8 m2.

MH based Storage cum Compression application for Transport Sector

Apart from just storing hydrogen in solid form, the MH storage can also act as a superior hydrogen compressor using the thermal compression technique. Unlike the traditional mechanical compressors, the MH based thermal compression equipment involves no moving/ rotary parts. Instead for thermal compression systems using MH, the potential compression ratio of the hydrogen initial and final pressure is solely controlled by the temperature differences during the absorption and desorption process.

At the time of absorption, hydrogen is absorbed into the metal alloy at a lower temperature, resulting in a lower equilibrium pressure and when released, heating the MH to a sufficiently higher temperature causes the gas to come out at a higher equilibrium pressure. Higher the desorption temperature greater is the amount of hydrogen released, thereby compressing the gas to the demanded pressure.

Definitely, the thermodynamic properties of the metal hydride materials have their unique impact on the compression ratio as excessive temperature differences may lead material degradation or other issues. Therefore, it is necessary to optimize the temperature difference within the material's operational limits.

This revolutionary technology can be utilized to compress hydrogen up to a pressure of 380 bar for any Industrial application as well as Hydrogen Refueling Stations (HRS). Hydrogen as a green fuel has achieved a valid space in the transport sector in the last few years. Hydrogen trucks and buses running with an onboard storage at 350 bar pressure can be refueled using this MH based thermal hydrogen compression technology.

In 2023, GRZ Technologies has built the first MH based Hydrogen Refueling Station solution called HYCO HRS at Switzerland for refueling a 1.5Kg forklift at a pressure of 370 bar. Recently they have also launched their MH based HYCO HRS solution which is capable to refuel a 28Kg standard Hydrogen bus in 15 minutes at a pressure of up to 380 bar. Thus, appreciable scalability of the MH based HYCO HRS technology is definitely noteworthy.

The Solid-State Hydrogen Compression solution HyCo offered by GRZ provides a containerized storage cum compression function in a single plug and play device, resulting in a simplified chain & a more compact setup in comparison to the traditional HRS system. For refueling applications, the HyCo HRS can accept Hydrogen (@ 35 bar) directly from any Electrolyser Source, and dispense it to refuel a vehicle tank with Hydrogen (@up to 380 bar) replacing four equipment as per the conventional method i.e. Buffer storage, HP compressor, High Pressure Hydrogen Storage, Dispenser, in a single Container between the Electrolyser and Hydrogen Vehicle as illustrated in Figure 7.

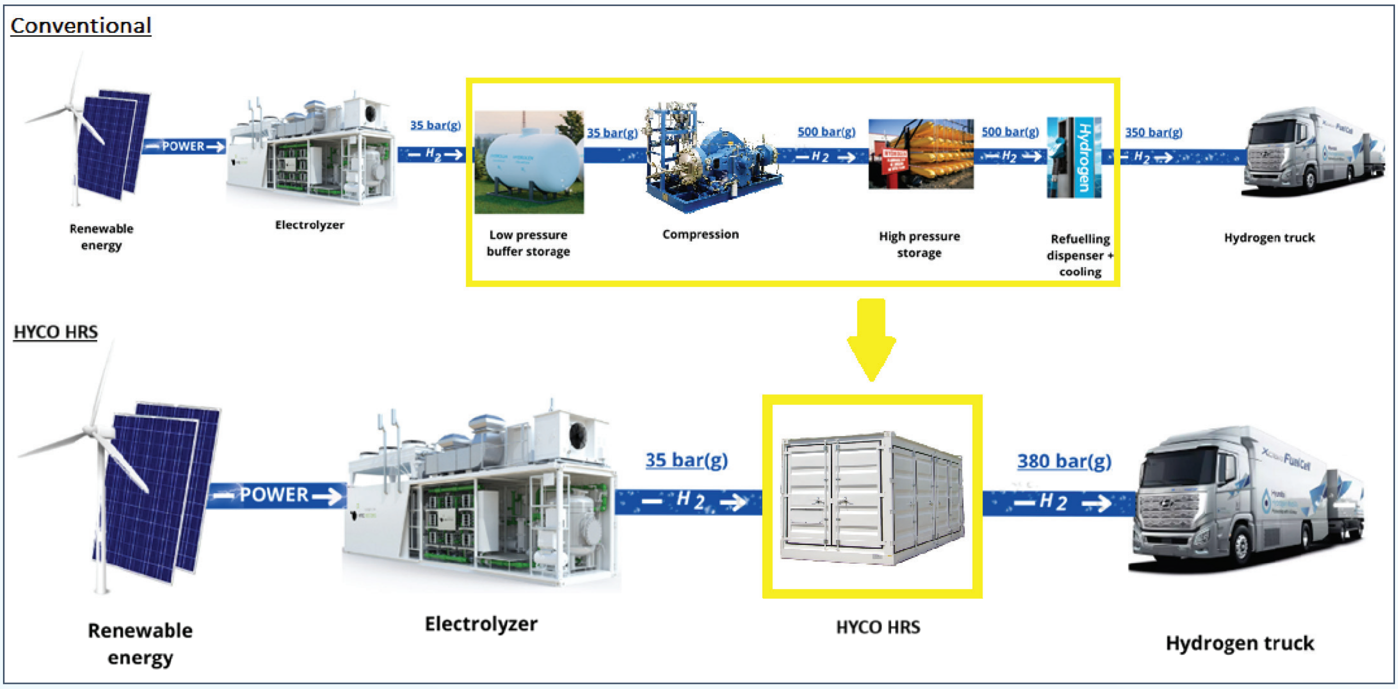


Fig. -7: HYCO HRS replacing four equipment of the conventional HRS

Thus, the HYCO HRS can superiorly save a huge area or space, civil, piping, instrumentation, and installation costs. Also, as it stores 95% of the Hydrogen in solid MH state the system is has very high safety features and does not have any chance of explosion. Further unlike conventional method, involving no moving parts results in noise free, vibration less operation and a long life of twenty years with minimal maintenance.

Conclusion

The MH technology can serve as a safe alternative and provide compact solutions for all relevant Hydrogen Applications within a very small foot print. As the most promising and highly energetic green fuel, Hydrogen will soon put its step ahead into the aerospace, marine and space sectors also. Safe Hydrogen operation techniques like the MH technology can play the most significant roles in this to enhance usage of Hydrogen and mark its way forward towards faster decarbonization for a clean and sustainable environment.

6. Operational Challenges and Troubleshooting Approach for Heat Exchangers and Air Coolers

Ms. Sadhna Singh holds a bachelor's degree in chemical engineering & is serving as Chief General Manager (HOD) of heat transfer department in Engineers India Limited. She has over 32 years of work experience in thermal design, engineering and optimization studies of fired and unfired equipment for hydrocarbon industry. Efficiency improvement studies including retrofitting of Heat Recovery Equipment, NOX abatement studies, Development of new products/up-gradation of existing products through in-house R&D testing facilities. Published multiple technical papers in reputed oil & gas journals and prominent speaker in various conferences.

Ms. Harshita Gupta holds a bachelor's degree in chemical engineering and an Executive MBA, and is presently working as Senior Manager at Engineers India Limited. She has over 12 years of professional experience in the thermal design and engineering of heat exchangers, air coolers, ejectors, and preheat networks. She has been actively involved in conducting optimization studies, revamp projects, troubleshooting and reliability improvements for critical refinery and petrochemical equipment.

Introduction

Heat exchangers and air coolers are indispensable components in refinery and petrochemical plants, directly influencing energy efficiency, process stability, and equipment reliability. Despite robust design practices, operational challenges frequently arise due to complex process conditions, variable fluid properties, and demanding start-up or shutdown sequences. Common issues such as flow-induced vibrations, expansion bellow failures, and winterization challenges often lead to performance deterioration, mechanical failures, or safety risks. Unplanned shutdowns linked to exchanger or air cooler malfunction cause production losses in addition to elevated energy consumption and potential environmental releases.

Studies indicate that more than 40% of process unit reliability issues in refining/ petrochemicals are linked to exchangers and air coolers, making troubleshooting a high-value activity for operations. While fouling remains the predominant cause of thermal underperformance—responsible for nearly 70% of capacity losses—mechanical and operational challenges are equally critical. Flow-induced vibration alone is estimated to cause 20-25% of tube failures in shell-and-tube exchangers. Troubleshooting these problems requires a holistic approach that goes beyond conventional design checks. It demands careful evaluation of operating data, mechanical constraints, process configurations, and fluid behavior, combined with advanced tools like CFD simulations, specialized thermal reviews, and site experience-based interventions.

This article presents three practical case studies highlighting typical problem areas in heat exchangers and air coolers and a systematic approach which can be adopted for troubleshooting.

Vibration Issues in Reactor Feed/Effluent Heat Exchangers

Reactor feed/effluent heat exchangers are among the most critical pieces of equipment in refinery and petrochemical operations. Designed for very high pressures (up to ~125 kg/cm^{2}g) and temperatures around 450 °C, they often handle two-phase flows on both shell and tube sides in hydrogen-rich and fouling services. Any instability in these exchangers not only reduces thermal efficiency but also compromises mechanical reliability, with significant implications for safety and operating costs.

Case Background

During operation, vibrations and flow fluctuations are frequently reported as the shell-side inlet flow was increased in such services. This results in:

- Reactor feed to be bypassed reducing exchanger duty.
- Increased fuel firing in the downstream heater to compensate for lost heat recovery.
- Instability in the high-pressure loop, affecting process control.
- Mechanical concerns such as tube leakages, tube fractures, and baffle damage.
- Potential for product contamination, energy penalties, and costly repairs in the event of tube failures.

A detailed review indicates that the primary driver of such instability is flow-induced vibration (FIV). Key contributors include:

- High local cross-flow velocities within the shell-side, particularly in two-phase regimes.
- Flow maldistribution and slug flow across shells in series, amplifying fluctuations.
- Inadequate piping configuration, with insufficient straight lengths after bypass mixing points, leading to unstable flow at the exchanger inlet.
- Unfavorable baffle configurations creating turbulence and pressure pulsations in critical regions.

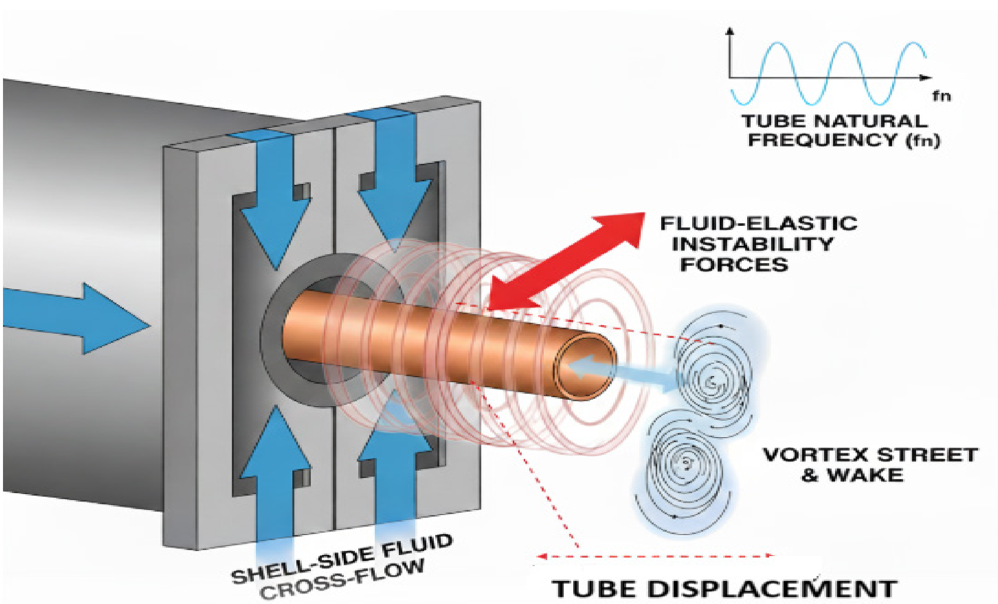


Fig. - 1

Troubleshooting Measures

- Thermal Design Review: Comparison of design and operating temperature profiles can highlight performance gaps. Local velocity profiles across the exchanger length shall be analyzed to identify high-risk vibration zones.
- Flow Regime Analysis: Flow patterns in individual shells to be assessed to pinpoint conditions prone to slugging or maldistribution.
- Piping Configuration Checks: Review against licensor standards (example- minimum 10D–20D straight lengths after bypass mixing) to ensure improved inlet stability.
- CFD Simulations: Two-phase CFD modeling can help visualize regions of slugging, aiding in corrective strategies.
- Baffle Modifications: Vertical cut baffles are recommended for such two-phase services, reducing shell-side pulsations and vibration risks compared to horizontal cut designs.
- Anti-Vibration Supports: Strengthen tube supports, removing few tube rows near baffle tip, adding de-resonating baffle are some of the remedies to be considered in new exchangers to enhance vibration resistance.

This case underscores the principle that vibration-free design is not optional but fundamental for reliability, especially in critical high-pressure and hydrogen services where tube failure can have catastrophic consequences.

Expansion Bellow Challenges in Heat Exchangers

Expansion bellows are widely employed in fixed tubesheet heat exchangers to accommodate differential thermal expansion between the shell and tube sides. Their role is critical in services where large temperature gradients exist or where transient operating conditions, such as start-up, shutdown, or steaming out, generate significant thermal stresses. If not adequately addressed, these conditions can result in mechanical overstress, leakage, and long-term reliability issues.

Industry data shows that thermal expansion joints subjected to frequent cyclic loading have a limited fatigue life. For instance, while bellows may be designed to survive ~15,000 cycles under controlled conditions, unfavorable installation, flow-induced vibration, or off-design operation can sharply increase damage rates and shorten service life.

Case Background

Operational experience across refineries and process plants has shown recurring problems in exchangers fitted with bellows, including:

- Frequent tube leakages in exchangers where bellows were provided.
- Severe thermal stresses during start-up, shutdown, or steaming-out operations.
- Mechanical infeasibility of bellows in exchangers with very short tube lengths.
- High maintenance requirements due to protection or replacement difficulties.

  The primary drivers of bellow-related reliability issues can be summarized as:

- Large temperature differentials between shell and tube sides, especially during transient operations (e.g., rapid heating or cooling of one side).
- Side allocation mismatches, where service placement complicates stress distribution or corrosion protection.
- Geometric constraints, such as very short tube lengths, which make bellow installation mechanically impractical.
- Cyclic thermal and pressure loads, which accelerate fatigue damage in the thin-wall bellow elements.

  Troubleshooting Measures

  A combination of design and operational

strategies can help mitigate these challenges:

- Side Interchange: Reallocating services (e.g., cooling water to tube side, process fluid to shell side) reduces thermal gradients and simplifies corrosion protection, eliminating the need for bellows in some cases.
- Condition Modification: Replacing severe transients (e.g., steaming out) with milder alternatives (e.g., controlled water flushing) minimizes thermal shock and reduces bellow fatigue.
- Change of TEMA Type: For exchangers exposed to high differential expansions, conversion to U-tube or floating head designs provides inherent flexibility without requiring bellows.
- Material Upgradation: Selecting compatible materials for shell and tube sides ensures uniform corrosion resistance and reduces dependence on cathodic protection systems.
- Operational Controls: Monitoring ramp rates during start-up and shutdown, and reducing vibration through proper flow distribution, extend bellow service life.

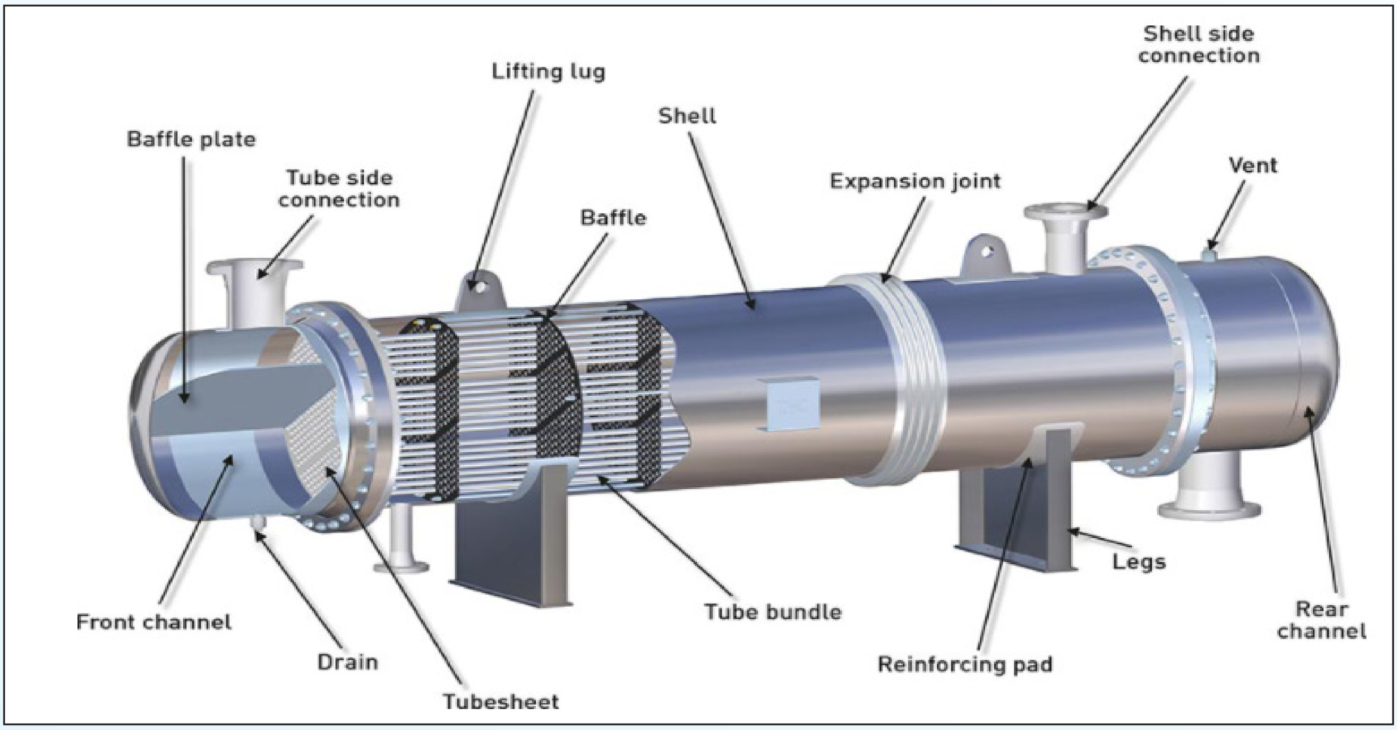


Fig. - 2

Winterization Challenges in Air Coolers Handling Congealing Services

Air coolers are critical equipment in refinery operations, particularly in hydrocarbon processing units where process streams must be cooled under controlled conditions. However, during winters and at night-time, low ambient temperatures pose significant operational risks for air coolers handling streams with high pour points. If the process fluid temperature drops below its pour point, waxes or heavy hydrocarbons may solidify inside the tubes, leading to severe fouling, increased pressure drop, and in extreme cases, complete equipment failure.

To safeguard against such conditions, steam coils are often employed to preheat the cooling air before it enters the tube bundles. This ensures that the process fluid remains above its pour point throughout its passage. While effective, this strategy can result in excessive steam consumption, thereby increasing operating costs, and if not designed properly, may reduce system reliability.

Case Background

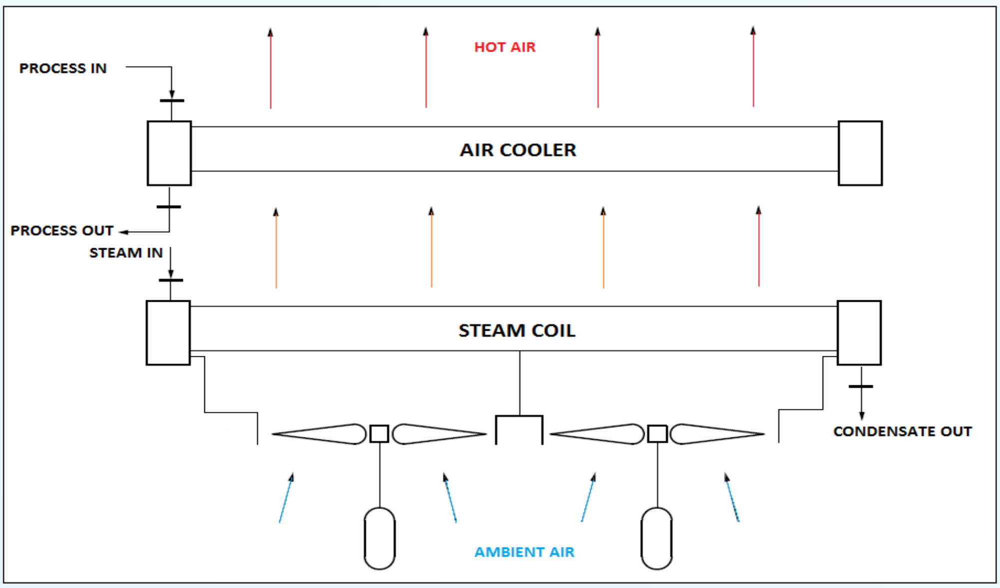
In one refinery revamp case, the air coolers were required to handle a hydrocarbon stream with a high pour point of 50-60 °C. To ensure safe operation, steam coil air preheating was incorporated in the design. However, during design review, it was observed that the steam consumption for coils was exceptionally high. This was attributed to the requirement of raising the inlet air temperature significantly to avoid congealing.

An alternative method of external air recirculation—whereby part of the hot air leaving the air cooler is recirculated back to the inlet—was evaluated. While technically feasible, this option was found to be cost-intensive and plot-space prohibitive, as additional ducts and fans would be required. Hence, alternate troubleshooting measures were pursued.

Troubleshooting Measures

1. Flow and Tube Pass Arrangement

- Traditionally, air coolers are designed for counter-current flow, where the coldest air meets the outlet (cold) process stream, ensuring a high overall temperature driving force. However, for high pour-point services, this arrangement results in low tube wall temperatures at the cold end, raising the risk of solidification.
- A shift to co-current flow was analyzed. In this arrangement, the hottest process fluid is exposed to the coldest air, while the low-temperature outlet fluid encounters already warmed air. Although this results in a reduced log mean temperature difference (LMTD) and requires a larger heat transfer surface, it effectively ensures that tube wall temperatures remain above the pour point, enhancing safety and reliability.



2. Fan Speed Control Enhancement

- The existing design incorporated 50% variable speed drive (VSD) fans, limiting operational flexibility during cold weather.
- It was recommended to adopt 100% VSD fans, providing operators greater control in regulating air flow. By reducing air flow during low ambient conditions, the dependence on steam preheating is minimized, thereby cutting down on steam consumption.

3. Steam Coil Operation Optimization

- The distribution and control of steam across coils was reviewed. Enhanced monitoring ensured uniform heating across the air stream, preventing cold spots.

- Integration with process control systems improved steam usage efficiency, eliminating excess consumption without compromising thermal safety margins.

By adopting a combination of co-current flow arrangement and upgraded fan speed controls, the refinery achieved a substantial reduction in steam consumption while maintaining safe operating conditions. More importantly, the risk of hydrocarbon solidification within the tubes was effectively mitigated. This case highlights that winterization of air coolers handling congealing services cannot rely solely on conventional methods. A holistic approach that considers flow configuration, fan flexibility, and steam coil operation is essential for ensuring both energy efficiency and operational reliability.

Conclusion

The troubleshooting experiences presented illustrate that heat exchanger performance is governed not only by design codes but also by thermal–hydraulic interactions under real operating conditions. In the vibration case, local cross-flow velocities, two-phase flow regimes, and adverse temperature gradients were the root causes, demonstrating the need for detailed velocity profile mapping and flow regime analysis to ensure tube wall stability.

For expansion bellow challenges, the critical factor was differential thermal expansion between shell and tube metals, which, when excessive, resulted in mechanical overstress and leakage. By reassigning fluid sides, adopting U-tube configurations, or replacing steaming-out with water flushing, the effective metal temperature differentials were reduced to within safe limits, eliminating the requirement of expansion bellows.

In the winterization case, the key parameter was maintaining minimum tube wall temperature above the pour point of the process fluid. The switch from counter-current to co-current arrangement, combined with variable speed fan control and optimized steam heating, ensured that thermal driving force was preserved while preventing subcooling of congealing streams.

Across all three cases, a common theme emerges: heat transfer analysis must extend beyond average duty calculations to incorporate local velocity distributions, phase behavior, and transient temperature profiles. By focusing on these detailed thermal–hydraulic aspects, engineers can preempt failures, minimize energy penalties, and achieve more reliable exchanger operation under varying field conditions.

7. INTEGRATION OF GH2 WITH REFINERIES: THINKING BEYOND THE GH2 PLANT DESIGN

Mr. Shourya Kumar is a Business Development Manager at Hygenco Green Energies , has been serving the energy industry for six plus years. At Hygenco, he has worked extensively on assessing domestic green hydrogen demand in the refinery sector, particularly in the context of emerging policy mandates.

Introduction

In select applications, hydrogen can serve as a substitute for conventional fuels or be utilized directly for thermal energy. However, its most compelling value emerges in processes where the hydrogen molecule itself is essential for enabling specific chemical reactions, rather than merely serving as an energy carrier. Among such sectors, the refining industry stands out as a predominant consumer of hydrogen, accounting for a significant share of global hydrogen demand.

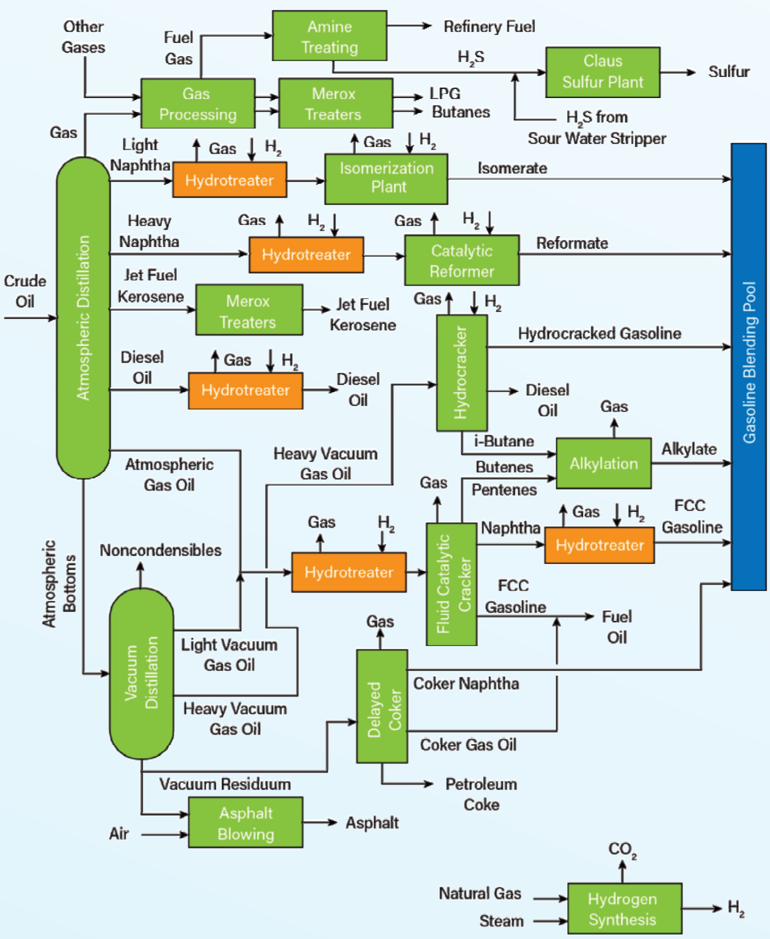


Fig. -1 Hydrogen consumption in refining application

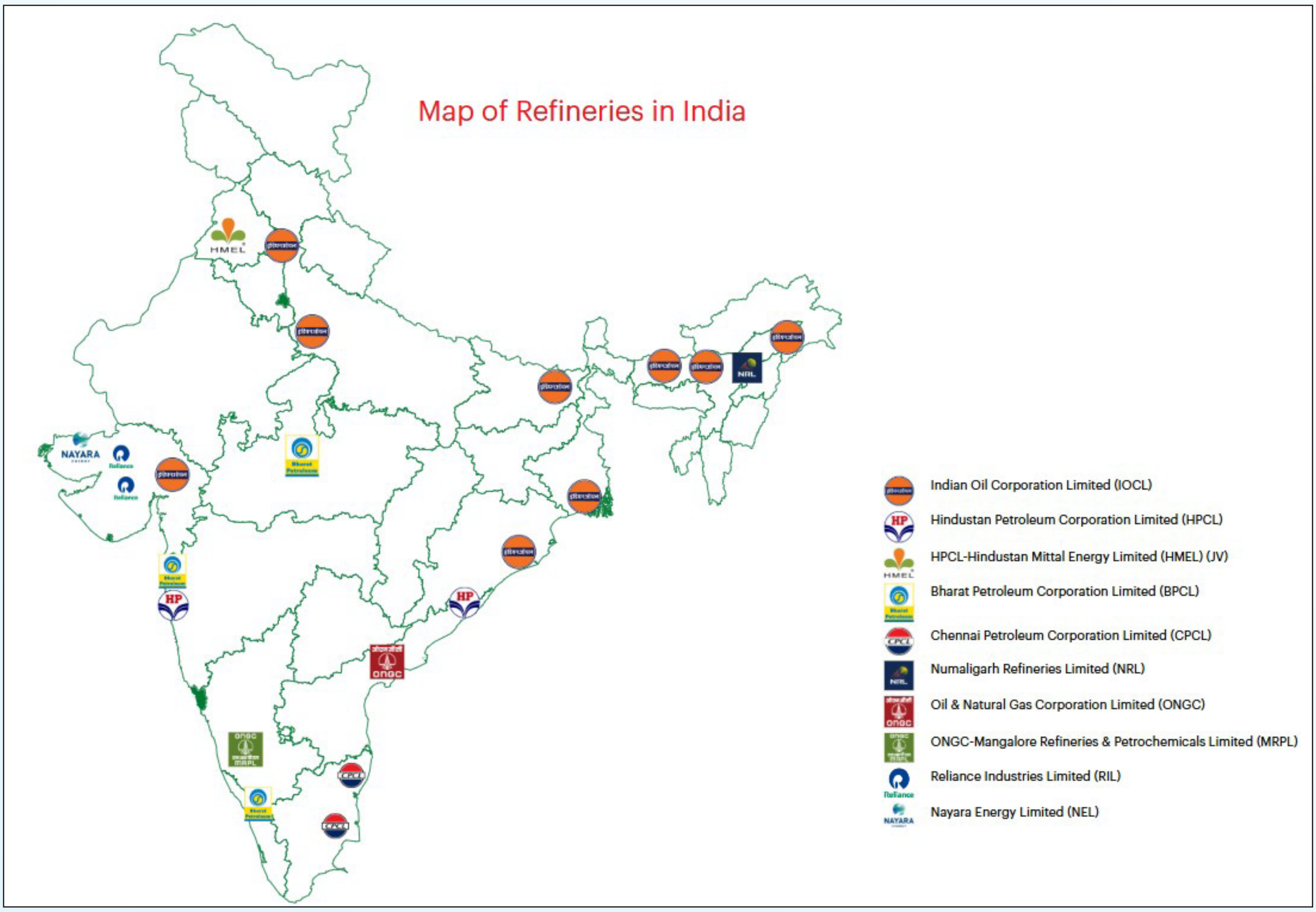
Consumption of H2 in refining

1. **Hydrotreating & Hydrocracking** process accounts for 90% of the hydrogen consumption in refinery.
2. **Hydrotreating:** To Remove impurities (like sulphur, nitrogen, metals) from petroleum fractions.
3. **Hydrocracking:** Breaking down (crack) heavy hydrocarbons into lighter, more valuable products (like diesel, jet fuel, naphtha).
4. **Isomerization:** Hydrogen keeps the process clean, the catalyst healthy, and the octane high. Very less H2 consumption in this

Global hydrogen demand reached approximately 97 million tonnes (MT) in 2023, marking a 2.5% increase from the previous year. This demand continues to be heavily concentrated in established applications, primarily in refining and industrial processes where hydrogen has long been produced using unabated fossil fuels.

The refining sector alone consumed around 43 MT of hydrogen in 2023, underscoring its dominant role in global hydrogen usage. As countries pursue increasingly stringent decarbonization targets, the integration of green hydrogen into refinery operations either through direct substitution for grey hydrogen or via blending strategies presents a critical pathway for emission reductions. The evolving landscape of carbon markets, including access to carbon credits, is expected to further incentivize this transition, making green hydrogen adoption an economic as well as environmental imperative for refineries worldwide.

India holds the position of the fourth-largest refining capacity globally, currently standing at 256 million metric tonnes per annum (MMTPA), with projections to reach 309.5 MMTPA by 2030. It is also the seventh-largest exporter of refined petroleum products, highlighting its strategic importance in global energy markets.



In the Indian refining sector, grey hydrogen is predominantly produced using natural gas (NG). Assuming an NG price of USD 10/MMBTU and a hydrogen yield of 3.3 kg per MMBTU, the cost of grey hydrogen is estimated at approximately USD 3/kg. With green hydrogen priced at around USD 4.5/kg, blending offers a transitional decarbonization strategy. The following table illustrates the blended hydrogen cost and impact on Levelized Cost of Hydrogen (LCOH) for varying green hydrogen blend ratios:

Green H_2 %	Grey H_2 %	Blended Cost ($/kg)	%age increase in LCOH
10%	90%	3.15	5%
20%	80%	3.30	10%
30%	70%	3.45	15%
40%	60%	3.60	20%
50%	50%	3.75	25%
60%	40%	3.90	30%

Note: The calculations above exclude carbon costs. Factoring in carbon pricing would further erode the cost competitiveness of grey hydrogen, enhancing the relative economics of green hydrogen. As the green hydrogen blend ratio increases, the effective carbon burden decreases, amplifying the financial and environmental benefits.

Current refinery tenders in India are typically targeting a modest green hydrogen blending ratio of 5–10%, supported by the Government of India's **SIGHT Mode 2B** incentive scheme, which promotes green hydrogen adoption in industrial sectors. While low-percentage blending is already economically viable under current market dynamics, achieving higher blending levels or full replacement of grey hydrogen will require significant cost reductions in green hydrogen production. Such advancements are essential to enable deep decarbonization across India's refining infrastructure.

A milestone for India's green hydrogen transition, the **10 KTPA green hydrogen project at IOCL's Panipat refinery,** tendered on a Build-Own-Operate (BOO) basis, has achieved a highly competitive price discovery of **INR 397/kg (incl. GST), ~USD 4.60/kg** through reverse auction. This tender marks a breakthrough in integrating green hydrogen with refinery operations, a critical step toward decarbonizing one of the most challenging industrial sectors. The successful response from multiple developers reflects that the market is maturing rapidly, with players equipped to handle technically complex and commercially demanding projects.

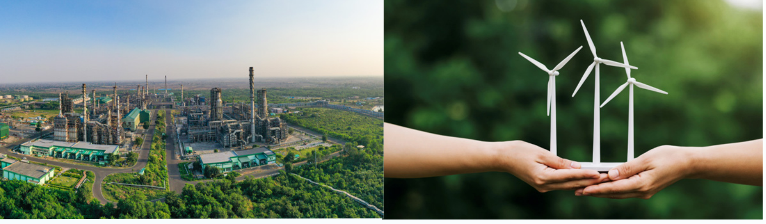
This not only sets a clear price signal for upcoming projects but also reinforces confidence that India's clean energy ecosystem is ready to scale.

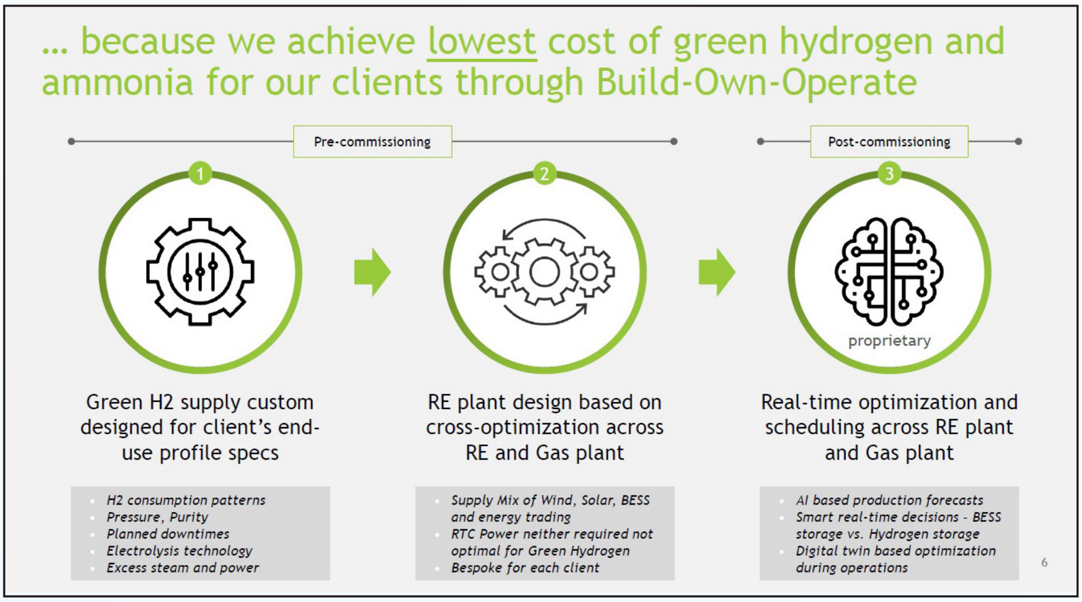
"Economics can't quarrel with physics"

Green hydrogen is costly (at best, $4-5 a kg); the two key drivers of costs — **electrolysers and electricity** — are the focus of research, but economics can't quarrel with physics. There is only so much room to drive costs down through conventional means. However, the next leap in cost optimization may not come solely from hardware, but from **advanced digital technologies.** The integration of **AI and machine learning** can play a transformative role in improving **system efficiency, dynamic load management, predictive maintenance, and real-time optimization—** unlocking operational savings that were previously out of reach.

How can we further optimize our solutions for the refinery specific use case?

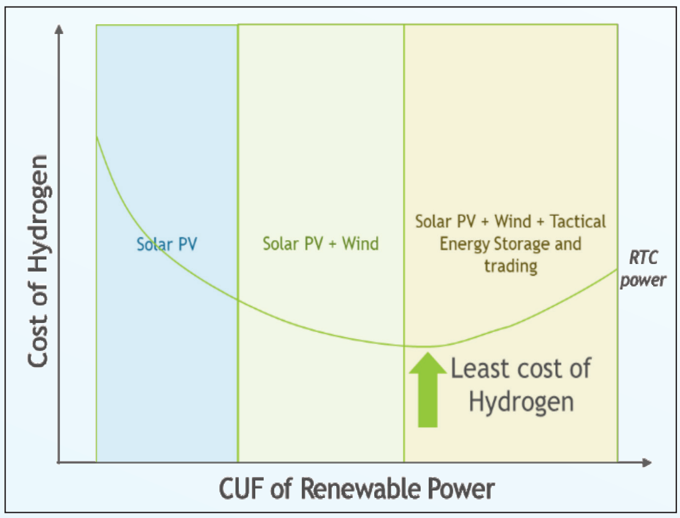
LCOH is closely linked to the performance of both the renewable energy plant and the hydrogen production facility. Optimization is required across both assets, not just in the design and sizing phases before commissioning, but also during long-term operations. Smart control systems that manage power flows, forecast demand, optimize storage, and respond dynamically to external conditions can help unlock significant efficiency gains. In this context, digitalization is not merely a support function—it is becoming a strategic enabler for scalable and economically viable green hydrogen integration in refineries.





The first step is to see the most optimized way to get the lowest LCOE (specific to the design)

The first step in reducing hydrogen production costs is optimizing for the lowest Levelized Cost of Electricity (LCOE), tailored to project-specific design and site conditions. This requires selecting the right renewable energy mix and sizing it efficiently to match electrolyser demand. AI-based modeling tools can streamline this process, enabling rapid assessment of design scenarios and helping to align energy generation with operational efficiency. A low LCOE directly lowers the Levelized Cost of Hydrogen (LCOH), making green hydrogen more viable for refinery integration.

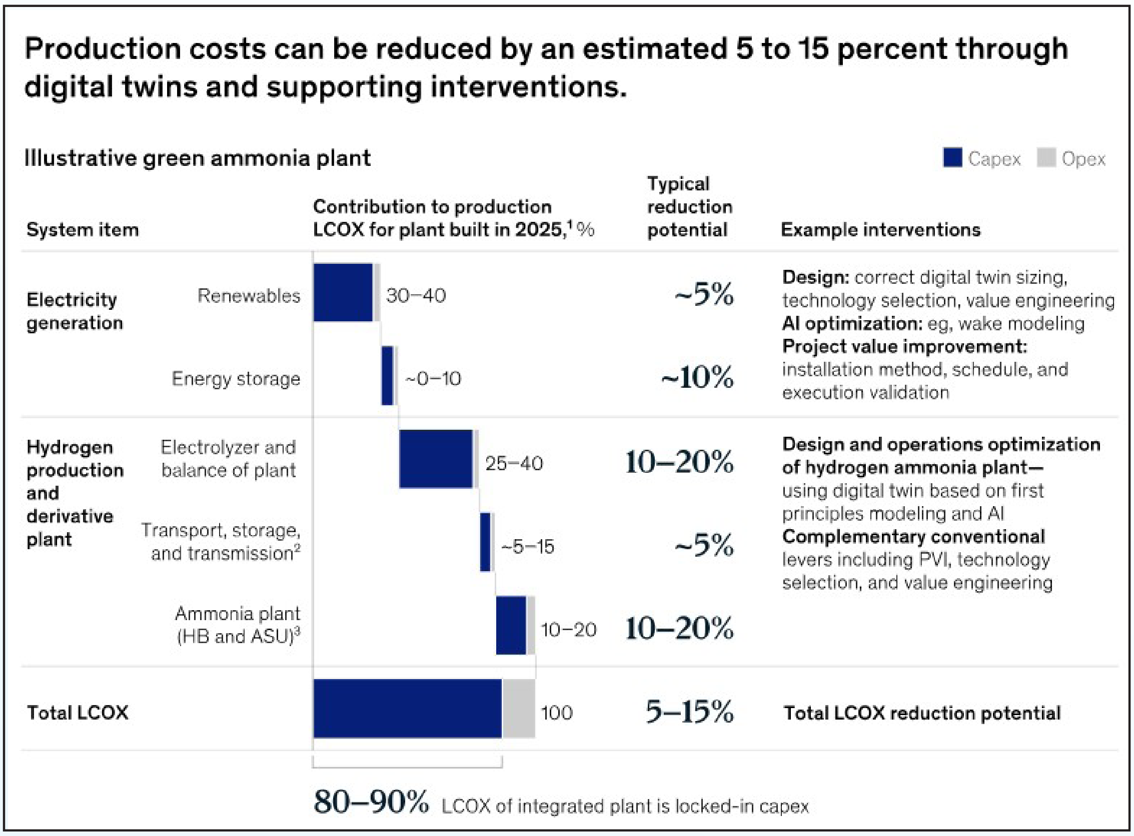


How Hygenco solves this optimization problem?

- Gas plant optimization: Hygenco integrates the gas plant with fluctuating RE for seamless operation.
- RTC energy cost: RTC boosts utilization but increases green energy costs.
- No linear input: Hygenco eliminates linear power input and banked power fees.
- Non-RTC + storage: By combining non-RTC power and storage, Hygenco cuts hydrogen costs.
- Real-time RE use: Hygenco matches RE supply in real-time, reducing LCOH and avoiding power banking.

The second step is Cost Optimization using IOT, AI/ML

A new pathway is opening to tame recalcitrant costs — artificial intelligence AI & ML. In many pilot projects, AI usage has achieved efficiency gains of 5-15 per cent; this could go higher with more operational data.



End to end integration of technology (IOT, AI/ML) at plant will involve the following steps:

1. Integrating IoT sensors in GH2 plants for real-time data capture and autonomous decision-making.

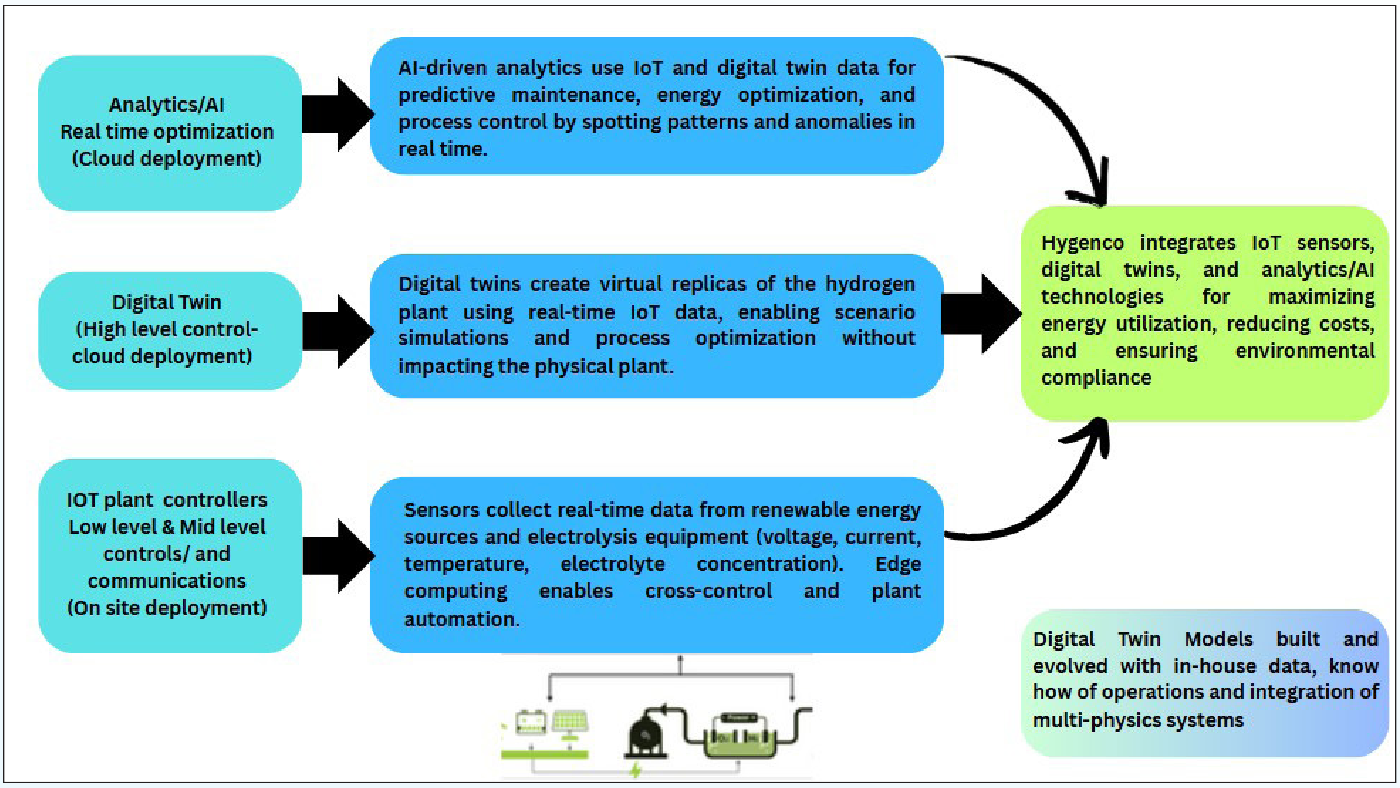
RE Side →

- IoT sensors are installed across solar, wind, and BESS assets to monitor hundreds of parameters, enabling accurate generation forecasting and optimized RE dispatch planning.
- Hygenco implements "autonomous" real-time decisions (algorithms developed in-house) to achieve high efficiencies and tight coupling with Gas plant dispatch to deliver cost- competitive H2 to the end clilents while ensuring highest standard of "green"

Gas Side →

- IOT Sensors installed at each stage to measure multiple process parameters per single stack equivalent hydrogen unit
- To ensure each parameter is captured accurately, several sensors are added in each component leading to higher accuracy of information.
- Hygenco does optimization on the gas side.

2. Integration Of In-house Developed AI / Digital Twin Technology



Leveraging probabilistic advanced analytics (AA) and generative-AI (gen AI) techniques, digital twins can help clarify project viability by quantifying the impact of external factors on the economic performance of a potential project design over its operating lifespan. By fully embracing digital twins, production costs LCOH could be reduced by 5 to 15 percent.

Global companies are incorporating 'reinforcement learning' (RL), a type of ML, to enable online tuning of over 70,000 parameters for their electrolysis process to achieve 8-10 per cent enhancement

Digital Twin – Digital twins integrate data across the plant's lifecycle, offering a multi-visual, contextualized experience from project to operations. AI enhances this by providing insights beyond sensors, running simulations, predicting future values, and detecting anomalies. This boosts situational awareness, enabling agile, sustainable decision-making.

Power of Digital Twin

- Digital twins quickly evaluate plant complexities, optimize setups, and compare alternatives within constraints (e.g., green hydrogen regulations). They explore design options, including storage sizes, electrolyser configurations, and BOP setups, using AI optimization for process modeling.
- Digital twins can simulate and compare electrolyser performance under varying conditions, boosting confidence in plant design. Some projects may benefit from oversizing electrolyser capacity, while others may need to balance electrolyser and storage capacity.

Conclusion

To conclude, the strategic optimization measures aimed at achieving the lowest LCOH form a robust foundation for the successful integration of green hydrogen within refineries. The adoption of non-RTC power, coupled with innovative energy storage and trading techniques, ensures cost efficiency and operational flexibility. Moreover, as policies evolve to support green hydrogen, particularly through incentives and regulatory frameworks, these advancements create a highly favourable environment for refineries to expand green hydrogen integration into their operations, covering a substantial percentage of their total hydrogen requirements. The recent IOCL tender price discovery, with its competitive pricing, further demonstrates the growing market maturity and cost-effectiveness of green hydrogen. This expansion not only drives sustainability but also enhances the long-term economic viability of green hydrogen, solidifying its potential as a key energy solution for the refining industry.

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4. https://ppac.gov.in/infrastructure/location-of-refineries

8. Enzyme Assisted CO_2 Capture Technology (eCO_2Sorb)

Dr. K. B. Srinivas is the Chief Research Manager at the Technology Implementation Cell of Indian Oil Corporation, R&D Centre, in Faridabad, India. His core technical expertise lies in Process Modeling and Simulation of refinery processes, specifically focusing on reactor modeling for key units like Hydro processing, FCC, and Steam Reforming. He also specializes in Heat Integration studies utilizing Pinch Analysis for sections such as the FCC/ Hydrocracker Gascon. Currently, Dr. Srinivas leads decarbonization initiatives by driving improvements in process efficiency and implementing Carbon Capture and Utilization (CCU) technologies. His impactful work is demonstrated by 1 US Patent and 2 International publications.

01. Introduction

The major reason for global warming is due to increasing atmospheric concentrations of green house gas emissions (GHG). This is one of the major challenges today's society has to face. Specifically, CO_2 emissions have been identified as major contributor to these GHG emissions. The major sources of these emissions originate from chemicals, refineries, petrochemical, power industries etc. The capture, sequestration and utilization of CO_2 is a key strategy that the companies can adopt to reduce these emissions. Therefore, all the companies announced their plans to reduce their emissions and meet net zero target.

Indian Oil, one of the largest oil companies in India, is committed to achieve net-zero operational emissions by 2046. The company has undertaken various initiatives to reduce its emissions and has already made significant strides in this endeavour. As part of these efforts, Indian Oil's Research and Development division (IOCL R&D) has developed an advanced enzyme assisted solvent-based CO_2 capture technology known as eCO_2Sorb using a combination of proprietary enzyme and solvent. The enzyme used in the process improve the absorption and desorption of CO_2 from the solvent and lowers the regeneration energy as compared to conventional processes, leading to overall reduction of energy requirement with better economics. This breakthrough technology has transitioned successfully from laboratory testing to commercial demonstration. Demonstration of the technology was considered in two-stage process. Initially, due diligence was carried out in the pilot scale (5 kg/day CO_2 capture) to demonstrate the performance of process and subsequently demonstrated in a commercial plant. An existing commercial CO_2 capture plant in southern India was selected for the demonstration considering the lower CAPEX and faster execution. This has significantly reduced the lead time of ~2-3 years for a new grassroots unit. Modifications were carried out in the existing unit and replaced the structured packing with Immobilized enzyme (enzyme loaded on packing). The start-up of the plant was carried out employing the IndianOil's proprietary solvent. This indigenous technology can be used as cost effective solution for capturing CO_2 from gas streams containing CO_2.

2.0 Pilot Plant Experiments

The eCO_2Sorb technology relies on a patented blend of enzymes and solvents, which work together to amplify the effectiveness of traditional amine-based CO_2 capture methods, simultaneously decreasing the energy needed for regeneration and improves efficiency of absorption. Hence, the development of the correct solvent composition and a stable enzyme is crucial for achieving the goal of energy-efficient CO_2 capture.

i. Development of robust biocatalyst (enzyme) and proprietary solvent system

The enzyme 'Carbonic anhydrase (CA)' is one of nature's fastest active enzymes and can dramatically improve the economics of carbon capture under demanding environments. But its sensitivity towards harsh process conditions (like high temperature, pH, etc.) makes its option limited for CO_2 capture. Therefore, it is imperative to design and develop a thermo-stable enzyme that can withstand the harsh process conditions for efficient CO_2 capture.

Using high-throughput screening, 3,06,964 potential mutants were identified and were subjected to genomic shuffling to develop thermo-stable enzymes. Further, by chemical modification of the active sites of CAs were manipulated to obtain two different variants of enzymes. (a) Variant-1 is responsible for promoting CO_2 absorption (in absorber column) and (b) Variant-2 is used to improve regeneration of CO_2 at low temperature (in stripper column). Enzyme isolation/ modification and extraction were patented. Some of the key characteristics of the enzyme are as follows:

a) Thermal stability of enzyme is an important parameter for enzymatic CO_2 capture as the CAs need to be stable at high desorption temperature. The two CA variants (Variant-1: and Variant-2: are highly stable over others and can tolerate temperatures of up to 110 °C and a wide range of pH from 4 to 14.

b) Based on the experimental data, it is noted that these CA variants demonstrated superior catalytic activity as compared to commercially available CAs.

c) The enzyme can be readily immobilized within a support matrix and demonstrates stability in the operating regime. Additionally, it demonstrates resilience against impurities such as SOx, NOx, and H2S commonly found in flue gas.

In enzymatic CO_2 capture, it is very important to select a biocompatible solvent system. The test of solvents for enzyme compatibility were carried out using Droplet Digital Polymerase Chain Reaction (DDPCR) at various conditions. After screening suitable biocompatible solvents, the next strategy was to use the time-tested and widely studied commercial solvents as base amine with additional solvents as accelerators and overcome the shortcomings of time-tested solvents to make them successful. For the same, 208 different combinations were prepared and based on maximum CO_2 uptake, optimized combinations were selected. Further, the requirement of desorption energy is an important parameter for solvent evaluation. It is highly desirable to reduce the energy for regeneration to make CO_2 capture process more economical. In enzymatic CO_2 capture process, Varient-2 reversibly catalyzes the reaction and regenerates the solvent at 90-95°C as compared to 120-140°C in case of conventional amines. Based on the laboratory testing and optimization of solvent composition, suitable enzymes (Variant-1 for absorber and Variant-2 for stripper) along with biocompatible solvents were finalized. The CO_2 capture efficiency of selected solvents was tested in an enzymatic CO_2 capture pilot plant having 5 kg/day CO_2 capture capacity.

ii. Outcome of pilot plant study:

- Using the enzyme catalyzed process, it is possible to achieve a lower amine recirculation rate to have greater than 90% CO_2 capture efficiency at the same condition compared to uncatalyzed process resulting higher energy saving.
- Further, the desorption was achieved at 90-95^{0}C with using enzyme catalysis in amine compared to 120^{0}C in uncatalyzed process resulting energy saving in terms of heat duty (~25-30 % reduction on desorption energy).
- No degradation of enzyme activity up to 3000 h of pilot plant operation.
- Very minimum Heat Stable Salt (HSS) formation and low foaming tendency observed.
- Solvent degradation was minimal, leading to a substantial decrease in the makeup rate required.

3.0 Commercial demonstration of eCO_2Sorb technology

Commercial demonstration of the technology by setting up of grassroots units, laying of pipelines for transportation of captured CO_2 for utilization would have longer lead time. Therefore, it was felt prudent to look for alternate avenue where the issue utilization of captured CO_2 is addressed. After search in this direction, IOCL identified a company in southern India having commercial CO_2 capture plant and conversion of CO_2 to soda ash. Accordingly, IOCL held discussions with the company for demonstration of eCO_2Sorb technology in the existing plant. In view of the availability of basic hardware for CO_2 capture and its subsequent utilisation at same premise, the demonstration of eCO_2Sorb technology at commercial scale could be carried out at lower cost within lesser time. Modifications were carried out in the existing unit for demonstration of the technology. During the demonstration period, specific steam consumption of 1.85 MT steam/ MT of CO_2 was achieved (~ 20% reduction as compared to regular operation). The capacity of CO_2 capture demonstrated is 150 TPD (~50% enhancement in CO_2 production from regular operation).

4.0 Conclusions

Demonstration of eCO_2Sorb technology is a showcase of indigenous technology as all the activities, from concept to technology development followed by preparation of process package, modifications and commissioning was carried solely by IOCL R&D Centre. The successful implementation of eCO_2Sorb technology boosted the confidence in deploying the technology in IndianOil refineries and licensing to other companies in India in line with the true spirit of 'Atmanirbhar Bharat'. This will be the stepping stone for subsequent deployment of this much needed technology in various refineries and locations of not only IndianOil but also in other companies in multiple sectors (Energy, Steel, Power, etc.) in the journey towards net zero.

9. An Essential Software for Real-time Corrosion Progression Visibility on Bottom Plates of Crude Oil Storage Tank

Mr. Ashutosh Kumar, Technical Head of Corrosion Intelligence Private Limited has led the conceptualisation, development and deployment of real time corrosion visibility software in the crude oil storage tanks and the overhead column of the crude distillation units.

Executive Summary:

Corrosion Intel is a deep-tech startup founded in North East India, dedicated to revolutionizing industrial asset management through advanced artificial intelligence (AI) solutions. We focus on providing AI-based, real-time insights to industries, enabling them to visualize and monitor their critical high-value assets—assets that are otherwise challenging for humans to inspect. Our technology empowers businesses to detect corrosion, wear, and other potential issues before they escalate, helping them enhance operational efficiency, reduce downtime, and improve safety standards.

Introduction:

The petrochemical industry is at war with corrosion. The diversity of petrochemicals appears the same to an untrained eye. Underneath their diverse composition affects the metallic assets at different rates. The interaction between metallic assets and petrochemicals leads to unprecedented health, safety and environmental consequences. Uncontrolled interaction leads to corrosion, significantly increasing these risks. The interactions in inaccessible environments possess risk of prolonged unobserved deterioration, due to corrosion, resulting in unexpected interruption of operations and economic loss. In addition to the economic losses there are environmental losses. Hence creating a requirement of real time visibility into corrosion progression. We have developed artificial intelligence powered software for providing real-time corrosion visibility into the metallic surface.

The software builds on the knowledge base of chemical reaction simulation and flow simulation. The novel approach of chemical reaction simulation helped us to start with a chemical reaction database of the last 4 decades. During the process of building the software, we incorporated a knowledge base of more than 193 crude oils. The knowledge base of flow and deposition of crude oil was built with the design and behaviour analysis of 57 crude oil storage tanks.

The knowledge base is continuously evolving with availability of new data sources. Our software wraps up the knowledge base, with user friendly input and output graphical user

interface. The software, Corrosion Intel SAM, helps in centralised, customisable and real time visibility of corrosion progression in crude oil storage tanks. The software is protected with 4 Intellectual Property Rights. It has been successfully demonstrated for a crude oil storage facility at Indian Oil Corporation. It is active development for refinery applications.

Genesis:

Our endeavour to build a software for real time corrosion visibility began on the foundations of data driven chemical reaction modelling and data driven fluid simulation leveraging advanced deep learning (Artificial Intelligence) algorithms. This initiative was driven by the pressing need to rejuvenate ageing oil fields, which present diminishing returns as they mature, and to make them more productive, cost-efficient, and environmentally sustainable. Our endeavour acquainted us with the pervasive challenges of corrosion progression in the interior of crude oil storage tanks. We believed fluid simulation and chemical reaction modelling can help us with the desired real time visibility.

We were working with chemical reaction modelling for expediting enhanced oil recovery. We started working on the problem statement in the mid of 2020. Primarily because chemical enhanced oil recovery is a very time and resource consuming process. While working on this problem statement we attended Abu Dhabi Petroleum Exhibition and Conference, to learn about the importance of crude oil storage. The crude oil storage and processing had an inherent challenge of corrosion associated with them. This insight came as a natural progression to the chemical reaction modelling endeavours that we have already undertaken.

We began development on chemical reaction modelling and corrosion forecasting (fig. 1- fig. 4) with available data from the American Shipping Bureau.

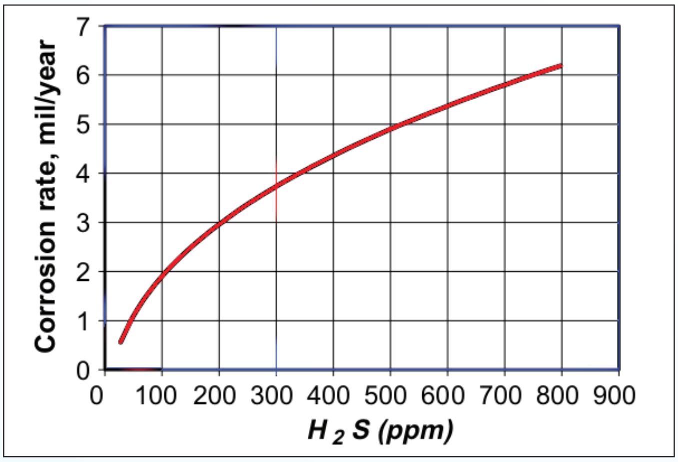


Fig. -1: Contribution of corrosion rate due to presence of Hydrogen Sulphide, crude carrier ship

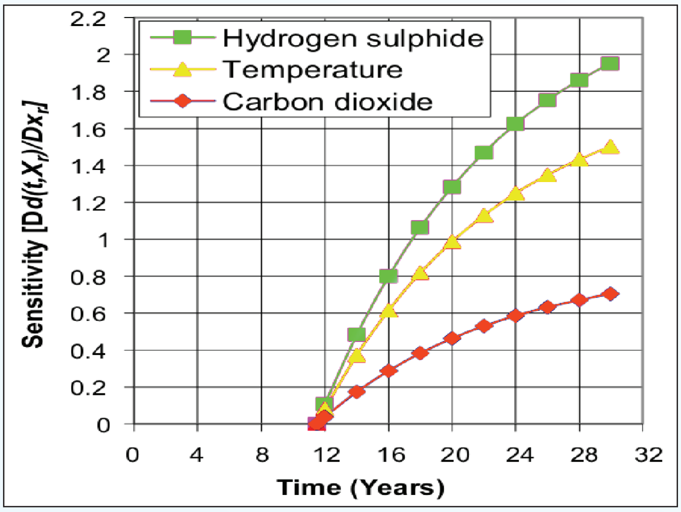


Fig. -2 Sensitivity of the corrosion rate as dependent on its composition, crude carrier ship

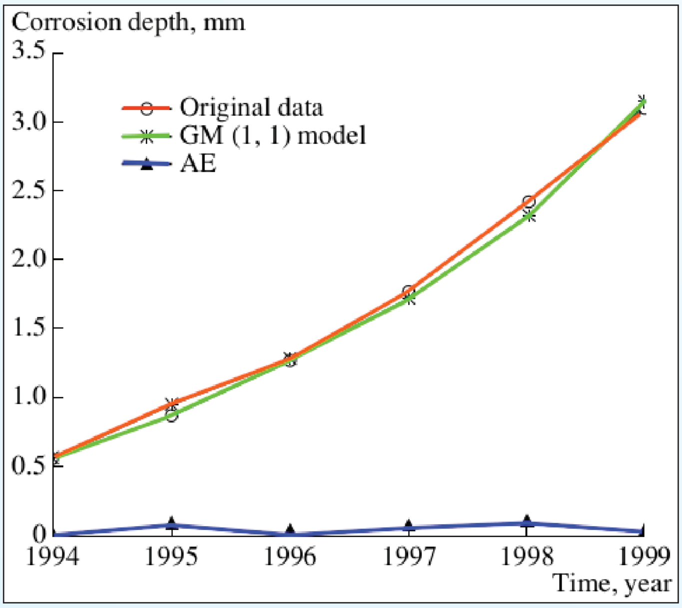


Fig. -3 Fitting curve to the corrosion rate obtained over 5 years, crude carrier ship

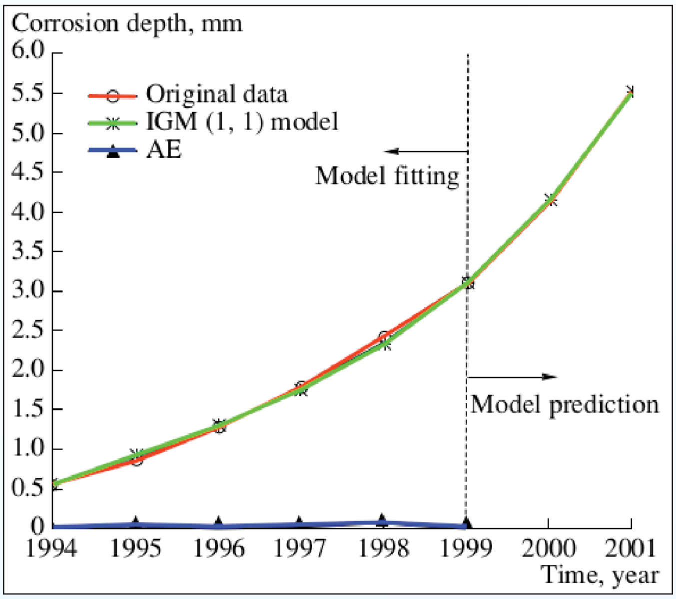


Fig. -4 Using the fitted curve to forecast the corrosion rate for next 2 years , crude carrier ship

The work on modelling corrosion progression in large crude carriers helped us to propose the technology for corrosion modelling in crude oil storage tanks.

The AI Engine:

The artificial intelligence engine of SAM has a knowledge base (fig. 5) of reactions and corrosion propagation due to the crude oil that has been received by Indian Oil Corporation tanks farms in the last 24 years. SAM has knowledge of their flow and deposition behaviour as well.

In real time, the engine interfaces with the input output functions as per requirement of the business stakeholders.

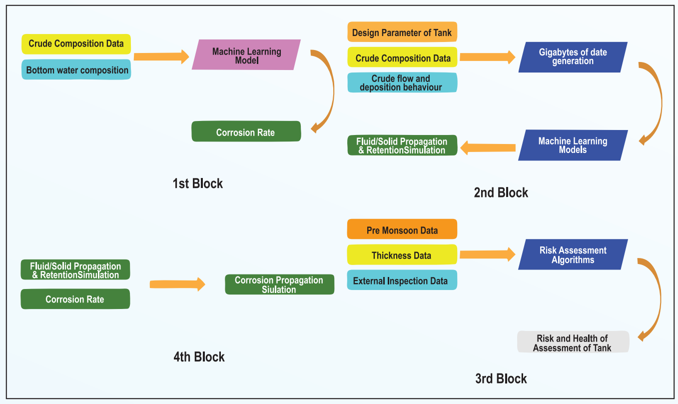


Fig. -5 Schematic diagram of the software

Parameters and Software Inputs:

For real time corrosion visibility in the bottom plate of crude oil storage tanks we have considered the following parameters as per their availability with the industry stakeholders:

Dataset Name	Parameters	Frequency of data
Premonsoon	Foundation, Shell, Roof, Roof Drain System, Roof Appurtenances, Stairways, Platforms, Rolling ladder	Once in 3 years
External Inspection	Earthing connections, Peripheral seals, Roof Drain System, Roof Appurtenances, Surface Drains and Hume Lines	Annual
Thickness survey report	Product drain pipe, water draw pipe, Roof drain pipe, TRV outlet line, TRV inlet line, Staircase plates,	
Bottom water testing	pH, Test Temperature, Dissolved oxygen, Dissolved H2S, Dissolved CO2, Total dissolved solids, Total suspended solids, Oxidising power (redox potential), Total Alkalinity, Buffer capacity; β=Δ(change in base) / Δ(per unit change in pH), Chlorides (Cl-), Bicarbonates(HCO3-), Sulfate (SO42-), Carbonates (CO32-), Hydroxide (OH-), Sodium (Na+), Potassium (K+), Calcium (Ca2+), Magnesium (Mg2+), Iron (Fe2+), Langelier Saturation Index (LSI), Stiff-Davis Index (SDI), Sulphur Conductivity, Sulphate Reducing Bacteria (SRB)	Twice a month

Dataset Name	Parameters	Frequency of data
Crude Assay	Crude Name, Density, Pour Point, Nitrogen, Water Content, B.S.&W, Sulphur, Asphaltene, Wax Content, Kinematic Viscosity at 40°C, Kinematic Viscosity at 60°C, Total Acid Number, Hydrogen SUlphide Content	Every batch of crude
Engineering drawing of Storage tank	NA	Once

Table 1. Dataset and parameters used by SAM

Algorithms, Modelling and Methodology:

The software provides a knowledge-base of collective decision making on multiple crude oil storage tanks (fig. 6).

Fig. -6 Centralised access to insight on multiple storage tanks

The software processing is divided into 4 modules for the ease of understanding:

- The corrosion rate calculation module: SAM's artificial intelligence module has features of predicting the corrosion rate associated with every batch of the crude oil. This is achieved by using the crude oil assay (fig. 7).

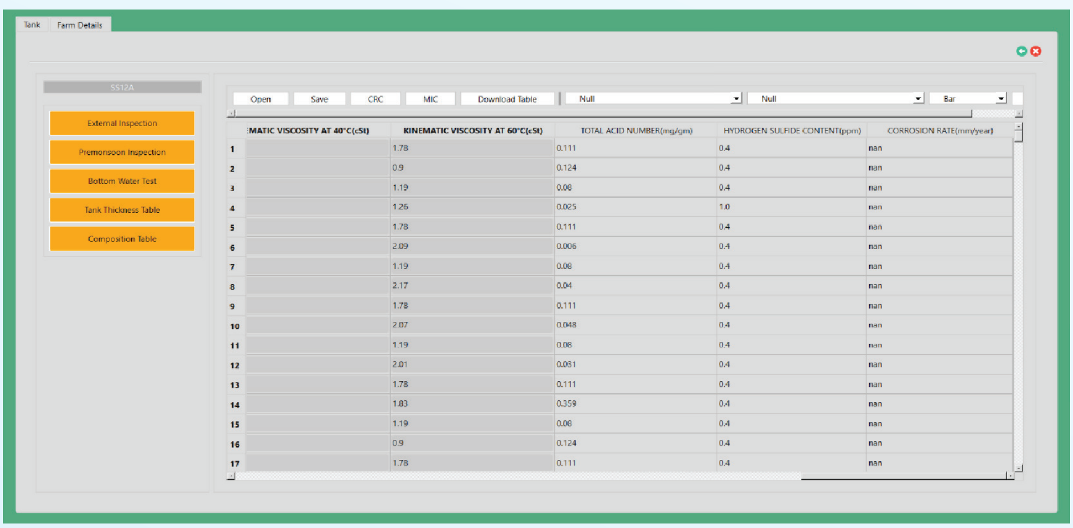


Fig. -7: 3 of 59 parameters used for Calculating Corrosion rate. Right most column for holding corrosion rate, button on top (CRC) for calculating corrosion rate.

- The fluid simulation module: Trained with terabytes of data, SAM has ability to simulate flow and deposition of crude oil in storage tanks. Inspired by the *Deep Minds' paper on Learning to Simulate Complex Physics with Graph Networks (fig. 8 & fig. 9).

After every batch update, the crude composition and operational parameters are used by SAM to simulate the flow and deposition. The flow and deposition is inherently used by SAM's artificial intelligence engine to calculate the spatio-temporal effect of the crude oil on the bottom of crude oil storage tank.

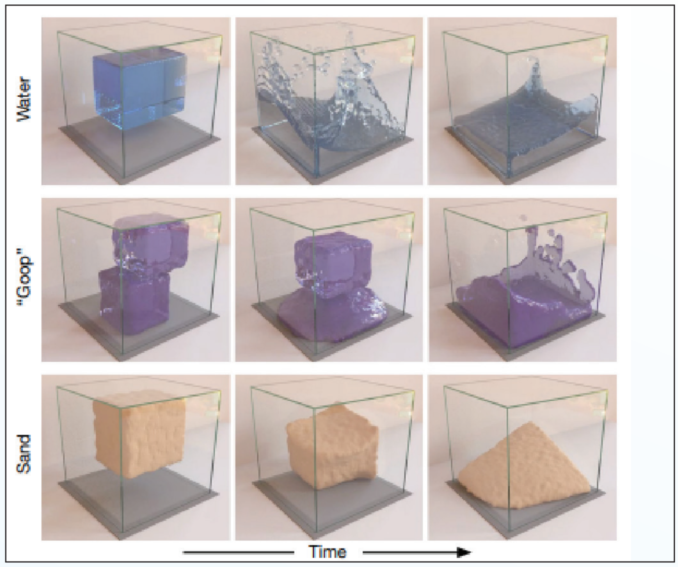


*Fig. -8. Fluid (material of varying hardness) flow representation**

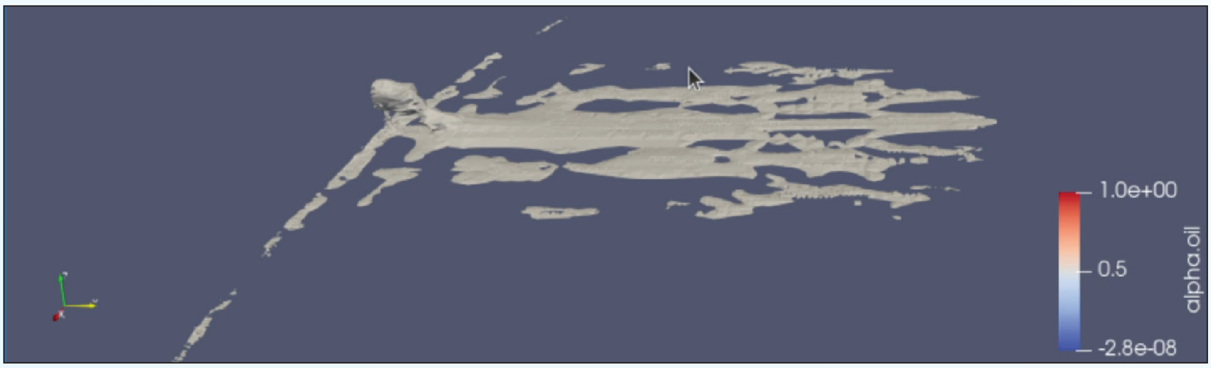
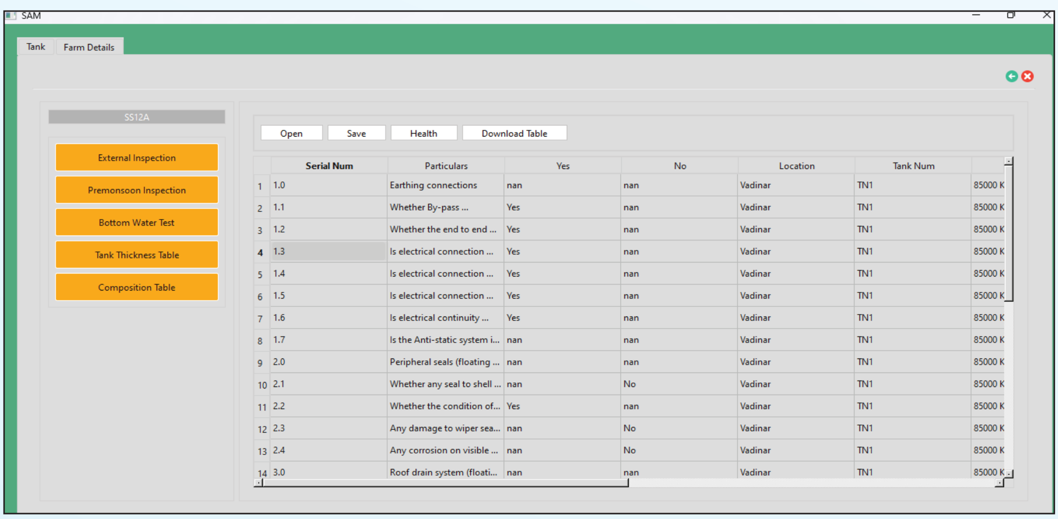


Fig. -9 Crude Oil flow simulation in storage tanks

- The risk assessment module and data visualisation module:
  - The pre monsoon data (fig. 10), thickness data and external data is read by proprietary algorithms of SAM to assess the risks (fig. 11) associated with the. The Algorithm can easily be customised as per requirement of the clients' priorities.



	Serial Num	Particulars	Yes	No	Location	Tank Num	
1	1.0	Earthing connections	nan	nan	Vadinar	TN1	85000 K
2	1.1	Whether By-pass ...	Yes	nan	Vadinar	TN1	85000 K
3	1.2	Whether the end to end ...	Yes	nan	Vadinar	TN1	85000 K
4	1.3	Is electrical connection ...	Yes	nan	Vadinar	TN1	85000 K
5	1.4	Is electrical connection ...	Yes	nan	Vadinar	TN1	85000 K
6	1.5	Is electrical connection ...	Yes	nan	Vadinar	TN1	85000 K
7	1.6	Is electrical continuity ...	Yes	nan	Vadinar	TN1	85000 K
8	1.7	Is the Anti-static system i...	nan	nan	Vadinar	TN1	85000 K
9	2.0	Peripheral seals (floating ...	nan	nan	Vadinar	TN1	85000 K
10	2.1	Whether any seal to shell ...	nan	No	Vadinar	TN1	85000 K
11	2.2	Whether the condition of...	Yes	nan	Vadinar	TN1	85000 K
12	2.3	Any damage to wiper sea...	nan	No	Vadinar	TN1	85000 K
13	2.4	Any corrosion on visible ...	nan	No	Vadinar	TN1	85000 K
14	3.0	Roof drain system (floati...	nan	nan	Vadinar	TN1	85000 K

Fig. -10 Screen for loading, visualisation and assessment with pre-monsoon data

Yearly Inspec...		Health Data			
		Components	Year	Health	Risk
2025	1	Earthing connections	2025	7.2857	2.7143
	2	Peripheral seals (floating ...	2025	7.75	2.25
	3	Roof drain system (floating...	2025	7.0	3.0
	4	Roof appurtenances	2025	6.7143	3.2857
	5	Surface drains & hume lines	2025	7.0	3.0

Fig. 11 Screen for yearly risk assessment based on pre-monsoon data

The software provides visualisation (fig. 12 & fig. 13) of 2 desired parameters in 4 different preferences of plots.

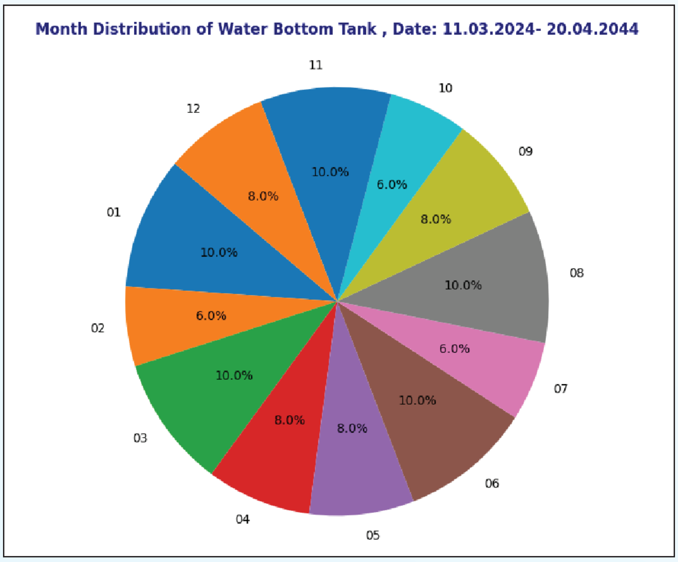


Fig. -12 Pie chart showing distribution from bottom water data

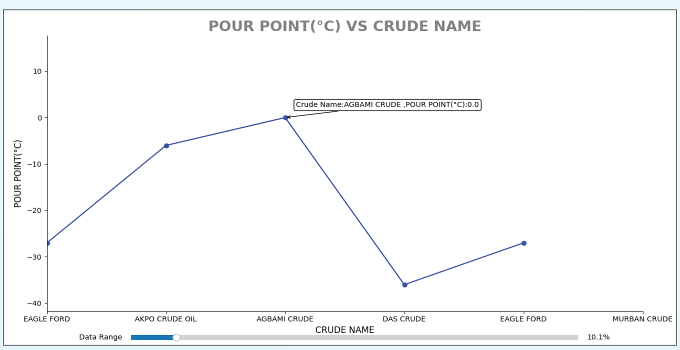


Fig. -13 Line plot showing pour point values associated with different crude oil

- Corrosion progression and visualisation module:
- The software shows the collective effect of crude oil on a yearly basis(fig. 14). Colour representation shows the metal loss at specific locations in the given year.

Key Results and Insights:

Corrosion Rate to Thickness Reduction:

The thickness reduction observed in the bottom plate of the large crude oil storage tanks. Simulations done give us an overview on the volume fraction of sludge that is deposited on the surface of the bottom plate . This in turn is used to calculate the corrosion rate of the bottom plate . The corrosion rate is an average value that changes accordingly with respect to the amount of sludge and the composition of the crude oil . The composition that affects the most

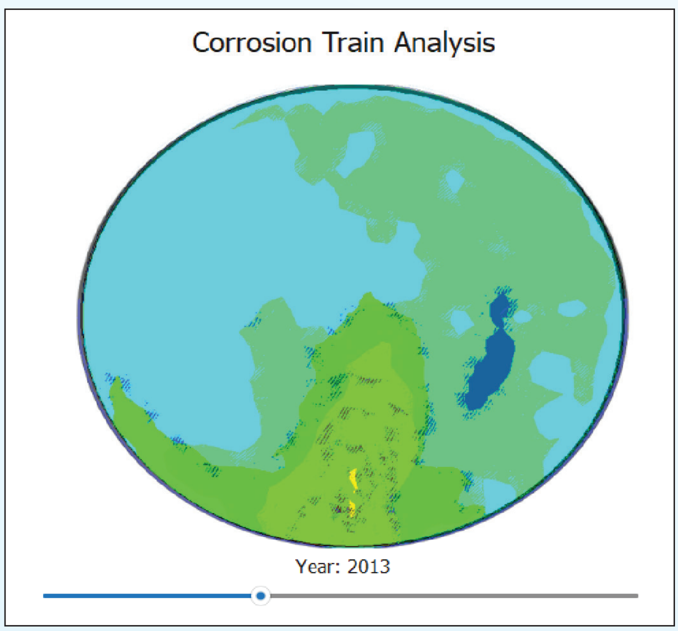


Fig. -14: Yearly effect of different crude oil handled by the storage tank on its bottom plate

are mentioned above and captured successfully in the software data entry framework. These parameters give rise to a factor that accelerates the corrosion in the bottom plate and is named 'acceleration rate' (AR). This AR value further affects the bottom plates in a manner where there can be pitting , holes , structural damage and rust formation in the weld areas . From this we can get the thickness reduction and the mass loss that occurred in due course of time .

Thickness Reduction and Mass loss:

According to the API 650 the minimum bottom plate thickness before the corrosion allowance needs to be 6mm and the minimum corrosion allowance to be 2.5mm. According to the UT tests reports the Bottom/Sketch plates readings observed were from 7.9 mm to 8.3mm. Other results include Maximum wall reduction of 88% (7mm) and minimum wall reduction 23% (1.8 mm). There are around 512 plates in total and the variation in thickness reduction is mentioned below

%Wall Loss	Wall Loss (mm)	No of Plates
<20%	<1.6mm	40
21%-30%	1.68-2.4	91
31%-40%	2.48-3.2	175
41%-50%	3.28-4	115
>50%	4.08-7	80

Table 2. The plate thickness reduction, obtained by the UT

The simulated results include the average corrosion rate of specific areas of the bottom plate :

From the table we can see that the average corrosion rate at the end of the 15th year is around 6.85045 mm/year . Now this value is used to annotate the different contour areas with their specific average corrosion rate as the simulation has given us the volume fraction of the particular contour which correlates to the corrosion rate .

Now this corrosion rate is used in turn to evaluate two crucial values i.e., Thickness Reduction and Mass loss .

For Mass Loss , the formula is as follows

$$CR = \frac{k \cdot m_{loss}}{A \cdot t \cdot \rho},$$

Above:	For this case:
CR = corrosion rate (mm/year) ,	*CR = 6.85045 mm/year = 7.8201484e-5 cm/hr*
K = constant 8.76×10^4 ,	
m_{loss} = mass loss (grams) ,	*k = 8.76×10^4*
	A = 198,556,509.688 cm^2
t= time (hours) ,	
ρ = density of the material (g/cm^3) ,	*t = 1,31,490 hours (15 years)*
	ρ = 8.05 g/cm^2 (Low carbon alloy steel)

For Thickness Reduction ,

$$CR = T_{reduction} / t$$

Where ,

$T_{reduction}$ = Thickness Reduction (mm),

CR = Corrosion Rate,

t= total time (years)

For this intermediate calculation, in the 15th year the avg corrosion rate is 6.85045 mm/ year. Therefore, the average thickness reduction observed in the tank is around 6.85045 mm . Similarly for the different areas the minimum thickness reduction in the last year observed from the simulation is around 23.58% which equals to 1.6153361 mm and a maximum of 77.4477% which equals to around 5.305 mm. This values of thickness reduction are simply the values covering a certain area of the tank i.e., the average values of those areas but the actual value would be greater at a few areas and lower at certain areas as these are the mean values .

%Wall Loss	Wall Loss (mm)	No of Plates	Colour Coding		
23%<	<1.6mm	84			
30%-40%	1.7038-2.351	173			
40%-50%	2.4-3.51	120			
50%-65%	4.39-5.18	115			
>65%	>5.305	20			

Table 3. Range of thickness reduction values, associated colour and number of plates

Plate number	UT wall loss %	Corrosion Intel: SAM wall loss %	Remark
1	44	40-50	In range
2	45	40-50	In range
3	44	40-50	In range
4	48	40-50	In range
5	50	40-50	In range
6	44	40-50	In range
7	50	40-50	In range
9	38	40-50	in range
12	50	40-50	In range
13	48	40-50	In range
14	48	40-50	In range
20	44	40-50	In range
21	44	40-50	In range
22	44	40-50	In range
23	44	40-50	In range
24	44	40-50	In range
399	70	>65	In range
400	64	>65	In range
406	64	>65	In range
407	64	>65	In range
408	41	40-65	In range
409	50	40-65	In range
412	63	40-65	In range
413	63	40-65	In range
414	50	40-65	In range
416	56	40-65	In range
417	63	40-65	In range
418	63	40-65	In range
419	63	40-65	In range
420	50	40-65	In range
421	44	30-40	~8% deviation
422	44	30-40	~8% deviation
11	38	40-50	~4% deviation
411	38	40-65	~4% deviation
15	63	40-50	~26% deviation
17	63	40-50	~26% deviation
19	63	40-50	~26% deviation
410	75	40-65	~20% deviation
415	75	40-65	~20% deviation
10	31	40-50	~18% deviation
16	31	40-50	~18% deviation
8	58	40-50	~16% deviation
18	58	40-50	~16% deviation

Table 4. Comparison of the plate thickness reduction, obtained by the UT vs by SAM

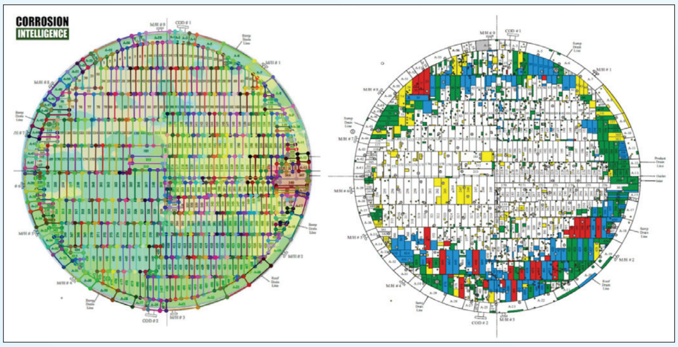


Fig. -15 Side-by-side comparison of the results obtained by version 0.1 of SAM and UT result

Software Output and Benefits : Comparison with the conventional UT Results:

Our Software Benefits	Ultrasonic Testing Results
Non-Invasive technology solely based on prediction of results from legacy data	Tanks need to be opened and cleared off fluids every time
No need to open the tanks	Need to open the tanks
Can be done at any stage of tank life and while in service	Impossibility of usage while tank in service
No external instruments used, still produces well defined outcomes over entire surface area	Ultrasonic instruments are used
Aids in maintenance decision making before opening the tank and prioritising one tank over another without opening the tanks	Is helpful in decision making only after the tank has been opened
Real time visualisation possible, across service life. Can be initiated at any stage of life.	Tests performed once in 15 years, after decommissioning and cleaning of tanks.
Ease of visualisation without inspection. Quick report generation and sharing.	Involves planning, operations, execution and data exchanges for visualisation
Plate to plate exact reports can be derived after every batch of crude oil handled	Platewise result available only after tank is out of service after 15 years
BoM can be estimated to certain accuracy before hand while planning the maintenance job	Does not facilitate BoM estimation
Manpower required in inspection can be estimated	Does not facilitate estimation of manpower requirement
Can be used in heat exchangers, pipelines, distillation columns, desalters and storage tanks	Can not be applied because of the complexity of asset and inaccessibility in the operational environment
Can be used in modelling corrosion in large crude carriers and very large crude carriers	Can not be used because of extensive service period and inaccessibility of the asset for inspection
Can be integrated with various assets across the organisation in different location through a common platform to plan and prioritise operations at management level	Have to be done by different service providers in different areas. Cannot be integrated centrally.
Numerical values of corrosion for each plate similar to UT data. Assessment and visibility is independent of operational complexity.	The assessment and visibility of assessment result is inversely proportional to the complexity of the operational environment and design of the asset.

Conclusion and Way Ahead:

Large storage tanks and pipelines are integral to the infrastructure of the oil and gas industry, but they face numerous challenges throughout their lifecycle. Issues such as shear stress, deformation, fractures, pitting, thermal defects, and structural instability often lead to the degradation of assets, primarily in the form of corrosion and fractures. These problems incur significant financial burdens due to escalating maintenance costs and operational downtime. In India, the economic impact of corrosion is particularly severe, with annual losses ranging between $100 billion and $110 billion, constituting around 2-3% of the country's GDP. Given this context, effective corrosion monitoring is vital to mitigating these challenges and reducing their impact on both industrial operations and the broader economy.

Our innovative solution leverages AI-powered predictive models to offer real-time insights into the health of critical assets like storage tanks, with a unique selling proposition rooted in its integration of Machine Learning. This advanced technology enables the modeling of complex chemical processes and provides valuable insights in areas where manual inspection is impractical or unsafe.

Looking ahead, our goal is to continue advancing our corrosion monitoring solution, expanding its application across various industries to improve asset longevity, operational efficiency, and safety. We aim to further refine our predictive models, integrating more complex data sources, and expanding our solution's reach to both domestic and international markets. By scaling our technology and forging new partnerships, we aim to play a pivotal role in reducing corrosion-related economic losses and contributing to a more sustainable and resilient oil and gas infrastructure.

10. Estimating Debris and Wax Deposition in Oil and Gas Pipelines: A Pressure Transient Analysis Approach

Dr. Pranab Narayan Jha is the Co-founder of Bharat Flow Analytics, a startup dedicated to creating innovative products for the energy industry. With 15 years of experience in the oil and gas sector and academic research, he has worked with Fortune 500 companies in both Houston, USA, and India. Dr. Jha has developed industry-leading products, authored multiple papers in international journals, and holds one patent. He earned his PhD and MS in Mechanical Engineering from the University of Houston and his B.Tech. from NIT Hamirpur. His expertise includes Computational Fluid Dynamics (CFD), Machine Learning, Flow-Induced Vibration (FIV), and Finite Element Analysis (FEA).

Introduction

Pipelines are the most economical and preferred method for transporting crude oil and petroleum products, forming a critical component of the global energy infrastructure. Maintaining their integrity is paramount for stable energy supply chains and economic stability. Moving beyond reactive or preventive approaches and adopting predictive maintenance strategies are essential to minimize flow restrictions and ensure safe and continuous operation. Advanced anomaly detection technologies are vital for sustaining energy supply and economic competitiveness.

Wax deposition is common in pipelines transporting high-wax crude oils, occurring when oil temperature drops below its Wax Appearance Temperature (WAT). Precipitated paraffin components form a solid or gel-like layer on the pipe wall, trapping liquid oil and reducing flow area.

Debris includes solid materials like corrosion and erosion products, water hardness scales, emulsions, hydrates, and produced sand fines. These accumulations reduce effective internal pipe area and increase roughness.

Other anomalies that compromise pipeline integrity may include geometric deformations such as dents from external impacts, wrinkles, buckles from axial movement, and excessive unsupported spans. In gas pipelines, liquid Pools may also occur due to accumulation of liquid hydrocarbons which hinder flow. [1]

Wax, debris, and other anomalies impose significant operational and economic burdens. The primary impact is a reduction in internal flow area and increased roughness, leading to higher pressure drop and increased pumping costs. Figure 7 shows that a 1% diameter reduction due to wax can increase pumping costs by 5%, and a 5% area reduction can decrease throughput by 30%. Also, severe blockages cannot be detected only by monitoring pressure drop across a section of pipeline. A localized 50% ID reduction will result in only 5% change in pressure drop, calculated for a sample 28" pipeline flowing crude oil at 1000 m^3/h. Traditional pressure drop methods does not provide the local deposition profile information.

A critical consequence is the increased probability of stuck pigs during cleaning or inspection. A stuck pig causes prohibitive pipeline downtime and expensive retrieval operations, on top of the lost value of productive time. Debris also leads to high maintenance costs due to abrasion and promotion of corrosion mechanisms like Under-Deposit Corrosion and Microbial Induced Corrosion (MIC), compromising structural integrity. Structural anomalies reduce fatigue life and overstress connections.

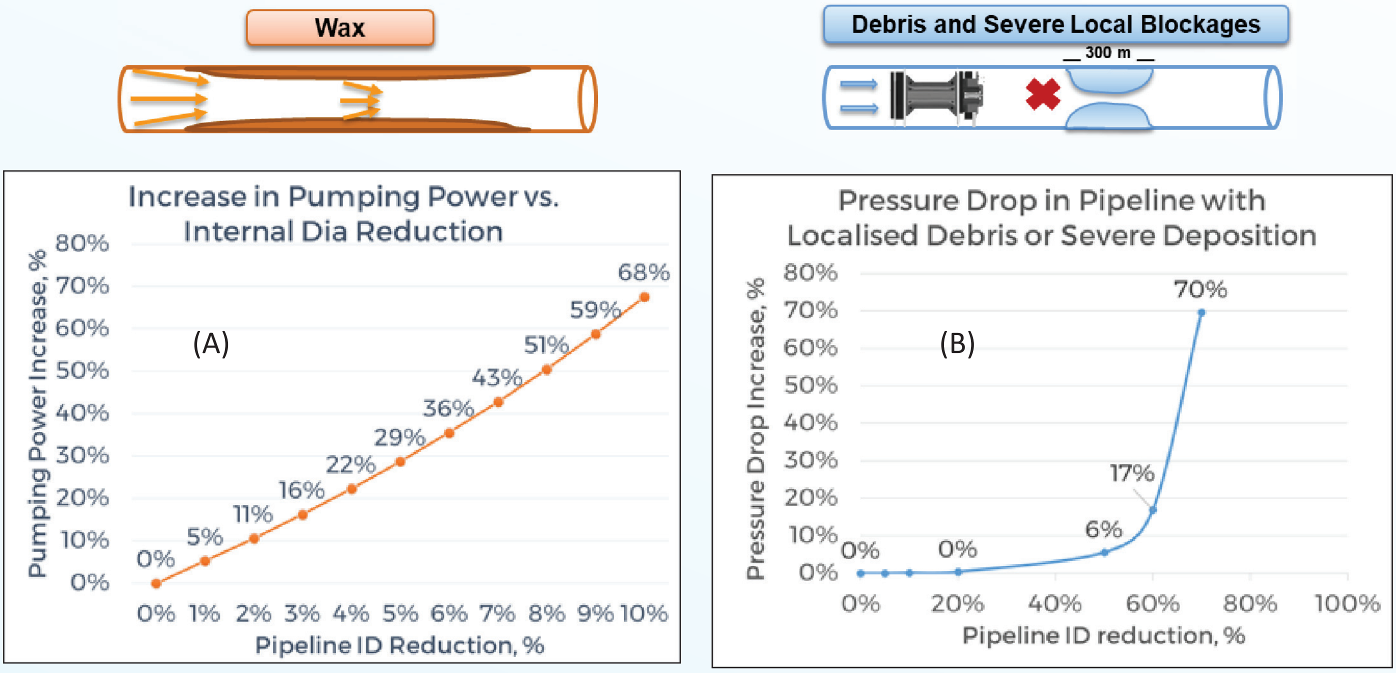


Fig. -7 (A) Wax deposition in pipeline and pumping power increase due to ID reduction. (B) Severe blocak/ge or localized debris in pipeline and associated pressure drop increase vs pipeline ID reduction.

Pipeline Anomaly Detection Technologies

Early and accurate detection is crucial for optimizing maintenance and preventing failures. Various technologies are employed such as Smart Pigs (Inline Inspection, ILI tools). These are devices traveling inside the pipeline to collect data. These include Magnetic Flux Leakage (MFL) tools for metal loss and deformations, Ultrasonic tools for wall thickness and geometric irregularities, and Electromagnetic Acoustic Transducer (EMAT) tools for crack detection. Fiber Optic Sensors (Distributed Fiber Optic Sensing, DFOS) provides continuous monitoring, detecting leaks, third-party intrusion, and pig tracking by sensing vibrations and temperature changes along the fibre optic cable itself.

Pressure Transient Analysis (PTA) is a non-intrusive technique based on pressure wave propagation, effective for estimating wax deposition, locating blockages, and detecting leaks. The reflection of acoustic (pressure) wave from discontinuities indicate anomaly location and size.

The industry is shifting towards non-intrusive, real-time monitoring solutions like PTA and fibre optics, which minimize operational interruption and provide rapid data, reducing overall costs. A holistic integrity management strategy often combines these technologies, leveraging their unique strengths for comprehensive data and synergistic insights.

This paper reviews pipeline anomalies and advanced detection methods. It details wax deposition mechanisms, introduces Pressure Transient Technology (PTA) and its applications, and focuses on the enhanced iPTran technology. Practical efficacy is demonstrated through case studies, concluding with key findings and future advancements.

Guidelines for Pipeline Pigging

OISD (Oil Industry Safety Directorate) guidelines for pigging, as outlined in OISD-SOP: Standard Operating Procedure for Integrity Assessment of Petroleum and Natural Gas Pipelines, or standards like OISD-STD-141 (pertaining to Liquid Hydrocarbons), OISD-STD-214 (LPG pipelines) and OISD-STD-226 (Natural Gas pipelines and City Gas distribution) emphasize the importance of pigging for pipeline integrity management, particularly in detecting metal loss in pipelines. OISD-SOP outlines the recommended frequency for scrapper pigging for various pipelines during design life span (25 years) as follows:

Pipeline type	Crude oil	Non-ATF Petroleum Product Pipelines	ATF pipelines also carrying other products	Dedicated ATF Pipelines	Two phase / multiphase flow	Dry gas	LPG
Frequency (once in every)	3 months	6 months.	3 months	1 year	1 year (or more frequently if there is significant liquid hold-up)	5 years	1 year

The SOP also mentions that "If there is an increase in quantity of muck /corrosion product, other corrosive indications, such as sulphur, pH, H2S etc. the pigging frequency should be increased and corrosion rate should be determined."

This indicates that there is scope for change in frequency of pigging depending on the result of each scraping/cleaning operation.

It needs to be mentioned that globally accepted API standards and recommended practices do not stipulate any specific frequency for cleaning pigs. They allow the pipeline operators to choose a frequency as per their requirements for optimizing operations and maintenance costs.

This article focuses on methods to estimate wax depositions and debris in pipelines and location of heavy blockages and stuck pigs.

Wax Deposition Mechanisms

Wax deposition is a complex phenomenon impacting waxy crude oil transportation. It begins with the precipitation of high molecular weight n-Paraffins when crude oil temperature drops below its Wax Appearance Temperature (WAT). These precipitated wax molecules form a gel-like layer on the pipe wall, trapping liquid oil.[2]

Molecular Diffusion is the dominant mechanism for wax deposition, driven by a radial thermal gradient where wax molecules diffuse from warmer bulk fluid to the cooler pipe wall. Secondly, Gravitational Settlement also leads to denser wax crystals settling under gravity, especially in low-flow or static conditions. A third important mechanism – Shear Dispersion – occurs under shear stress, causing wax molecules to migrate from high-shear to low-shear regions, depositing on the surface.

Other mechanisms include:

- Brownian Motion: Random movement of wax molecules or particles due to thermal energy, leading to adherence to the pipe wall.
- Gelation: Precipitated wax crystals form a 3D network, trapping liquid oil and contributing to deposit bulk.
- Aging Mechanism: Time-dependent changes in the deposit layer's structure and properties, affecting adherence and hardness.

This complexity, coupled with crude oil's non-Newtonian behaviour, makes accurate prediction challenging, highlighting the value of AI/ML integration in detection systems to learn from real-world data.

Debris and Other Pipeline Anomalies

Beyond wax, pipelines are susceptible to other internal and structural anomalies. Debris comprises various solid materials accumulating within pipelines [3]. These include:

- Corrosion and Erosion Products: Byproducts of chemical reactions or physical wear (e.g., iron oxides, sulphides).
- Water Hardness Scales: Mineral deposits from water content.
- Emulsions: Stable mixtures of immiscible liquids forming viscous deposits.
- Hydrates: Crystalline solids from natural gas and water under specific conditions, causing blockages.
- Produced Sand Fines: In oil production systems, particulate matter like small diameter sand particles (425 microns or less) that flow from the reservoir and settle in low-flow areas.

Pipelines can also suffer from structural and geometric integrity issues such as Dents (Localized inward deformations from external impacts) and Wrinkles and Buckles (Localized folds or larger structural instabilities from axial movement).

Operating parameters, fluid consistency, and environmental conditions dynamically evolve, necessitating detection systems that assess co-occurrence and combined severity, which AI/ML systems can provide, utilizing historical operational data from the pipelines.

The collective impact of anomalies is profound. A primary consequence is a reduction in effective internal diameter and increased roughness, leading to increased pressure drop and higher pumping costs. This can escalate to complete blockages, posing severe risks.

A critical operational challenge is the increased probability of stuck pigs during cleaning or inspection, leading to prohibitive downtime and expensive retrieval.

Debris and deposits also accelerate internal corrosion, including Under-Deposit Corrosion and MIC, compromising pipe wall integrity. Structural anomalies reduce fatigue life and overstress connections.

These issues result in significant economic liabilities: increased pumping and maintenance costs, high pig retrieval costs, and substantial losses from lost production and downtime. Environmental risks from leaks and spills incur hefty fines and reputational damage.

Pressure Transient Technology for Anomaly Detection

Pressure Transient Analysis (PTA) is an advanced and effective non-intrusive technique for detecting and characterizing pipeline anomalies. PTA relies on pressure wave transients in fluid-filled conduits. A pressure wave, generated by a controlled event (e.g., valve operation), propagates along the pipeline. Reflections from anomalies (depositions, blockages, stuck pigs) occur due to changes in cross-sectional area or impedance discontinuities, and these transient pressure changes are recorded by high-sampling rate pressure transmitters.

Theory

Pressure transients in pipelines can be described using a set of fluid flow equations as below, that essentially balance mass and momentum in the system.

Continuity equation (conservation of mass):

Momentum equation:

$$\frac{\partial H}{\partial t} + \frac{a^2}{gA}\frac{\partial Q}{\partial x} = 0 \qquad (1)$$

Here: $\frac{\partial Q}{\partial t} + gA\frac{\partial H}{\partial x} + \frac{fQ|Q|}{2DA} = 0$ (2)

Q=AV is flow rate, H = p/ρg is the pressure head, V(x,t) is velocity, *p(x,t)* is pressure, a is the acoustic velocity, g is gravity, D is pipe diameter (corresponding to internal diameter), A is the cross-sectional area, x is the coordinate along the pipeline length, t is time and *f* is Darcy friction factor that accounts for pressure drop due to flow. *f* is Darcy's friction factor, calculated as:

$$f = \frac{64}{Re} \text{ for } Re < 2200$$

$$f = -1.8 \log\left[\left(\frac{\frac{\epsilon}{D}}{3.7}\right)^{1.11} + \frac{6.9}{Re}\right]^{-\frac{1}{2}} \text{ for } Re >= 2200 \quad (3)$$

The second expression above is known as Haaland's correlation (there are many other correlations that are used across the industry with varying applicability and benefits). Here, is the non-dimensional Reynolds number, given as *Re=VD/* and is the kinematic viscosity of the fluid.

Solution Methodology: Method of Characteristics (MOC)

The non-linear governing equations are solved using the Method of Characteristics (MOC) over a grid constructed in x and t dimensions and using a finite difference method. MOC transforms partial differential equations into ordinary differential equations along characteristic lines in the x-t plane. The pipeline is discretized into sections and equations are solved with discrete time steps using a computer code. An in-house software that implements this setup for various operating conditions has been developed by Bharat Flow Analytics Pvt. Ltd. (BFAPL). The accuracy of the software depends on how finely the pipeline is discretized – smaller the sections, higher the accuracy but it increases the required computational power and time.AI/ML integration in systems like iPTran helps compensate for these complexities and uncertainties by learning from real-world data.

Applications of PTA in Oil and Gas Pipelines

PTA is versatile for pipeline maintenance operations.

- Estimation of Internal Diameter Reduction and Blockages

PTA directly estimates internal diameter reduction and precisely locates blockages by analysing reflected pressure waves from cross-sectional area changes. A "clean pipe" simulation is compared to actual measured pressure data; the difference indicates deposition. An optimization approach iteratively adjusts effective diameters to minimize discrepancies, mapping the deposition profile.

Pipeline operators in USA have been using PTA for blockage detection mainly for upstream industry. It has been used in both oil and gas pipelines [4], and liquid pools in gas pipelines [1] to detect blockages and stuck pigs using pressure profiles.

- PTA can also be used to locate stuck pigs and tracks moving pigs.

A pressure transient can be used to locate a pig that is not moving. Moving pigs generate pressure transients and vibro-acoustic noise from velocity fluctuations, friction, and passage over internal features. The pipeline acts as an acoustic waveguide, allowing sensors kilometres away to detect these signals. [5]

- Leak Detection Principles and Implementations

PTA has also been implemented to detect leaks by identifying the imperfections in the pressure profile when a transient pressure wave hits a leak and reflects/transmits the associated pressure signal. Inverse Transient Analysis (ITA) uses optimization to determine leak parameters (number, location, size) from measured pressure data.[6]

It must be noted that one potential shortcoming of PTA is that very small changes in diameter (2% or lower) cannot be detected using this technology, as pressure wave is subject to dissipation and attenuation. However, estimations using empirical methods are used to overcome this challenge in application.

iPTran: An Enhanced Pressure Transient Technology

iPTran is a non-intrusive enhanced Pressure Transient Technology for accurate wax and debris estimation in oil and gas pipelines. It provides on-demand pressure monitoring, internal diameter profiling, and precise location of debris and stuck pigs. Figure 8 shows a schematic of how the data collection and analysis works. Building on PTA being used by US-based oil companies, BFAPL has improved on it and applied iPTran to cross-country transportation pipelines in India.

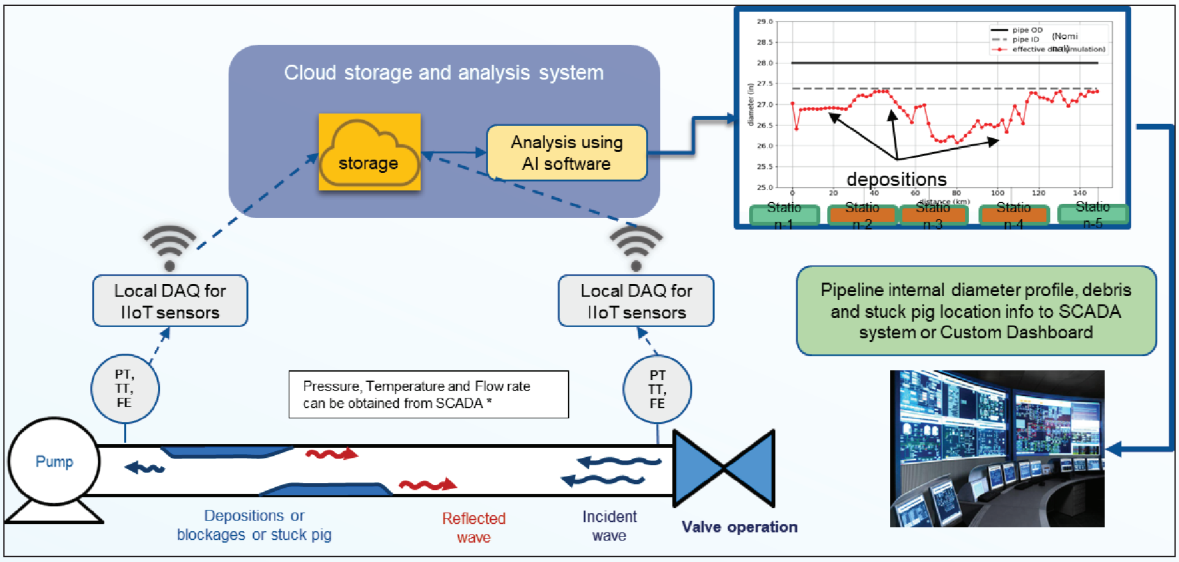


Fig. 8 Schematic of iPTran - data collection and analysis

Integration of Artificial Intelligence (AI) and Industrial Internet of Things (IIoT)

iPTran's core innovation is its integration of pipeline hydraulics models with AI and Industrial Internet of Things (IIoT) sensors for advanced data collection, analysis, and prognosis.

BFAPL, iPTran's developer, automates pipeline monitoring using Industry 4.0 AI and IoT-enabled solutions for non-intrusive wax estimation and blockage/stuck pig detection.

IIoT Sensors: iPTran uses IIoT sensors and local Data Acquisition (DAQ) systems to collect real-time pressure, temperature, and flow rate data, or seamlessly obtains it from existing SCADA systems.

BFAPL has developed an Edge Device for collection of data at high sampling rate (10-100 Hz) (Figure 9). It also performing data analysis after collection from the pressure transmitter, that helps improve accuracy of wax estimates to within 10% of actual weight and within 100 m of location of stuck pig. This device incorporates a microprocessor-based data collection and analysis module, and a GSM module for data transfer to the cloud.

AI Software: Enhanced physics models are augmented by AI algorithms, improving accuracy, sensitivity, reliability, and robustness over traditional PTA. AI algorithms, trained on historical and simulated data, accelerate the determination of the internal diameter array, synthesizing large data volumes quickly to provide predictive insights. Collected data is processed and stored in a cloud-based system, providing pipeline internal diameter profiles and anomaly locations, which can be integrated into SCADA or custom dashboards.

Fig.-9. IIoT Edge Device for faster data collection and cloud integration

This analysis provides critical data to the pipeline operator to make an informed decision about the next cleaning operation – when to schedule the pigging run. This data-driven predictive maintenance optimizes pigging schedules and pre-empts stuck pigs, leading to substantial cost savings and minimized downtime. This aligns with industry trends where AI and IoT systems are helping to revolutionize pipeline operations and predictive maintenance.

Key Advantages of iPTran

iPTran offers compelling advantages:

- **Non-intrusive Technology:** No internal instrumentation needed and no pig is to be inserted into the pipeline, minimizing operational interruption and pigging complexities.
- **Industry 4.0 Solution:** Leverages IIoT and AI for enhanced accuracy, sensitivity, reliability, and robustness. The entire software development and hardware assembly has been carried out in India, thus furthering the Make in India initiative.
- **Quick Turnaround Time:** Analyses 100+ km sections in minutes (e.g., 148 km in <5 minutes).
- **Cost-Effective:** Lowers Total Cost of Ownership (TCO) by optimizing pigging programs and enabling predictive maintenance. Compared to Optic Fiber technology, iPTran costs are significantly lower.
- **High Accuracy and Sensitivity:** Improved by IIoT sensors and AI algorithms.
- **Enhanced Predictive Maintenance Capability:** Helps pre-empt stuck pigs by identifying debris/blockage location and severity.
- **Broad Application Areas:** Applicable to onshore and offshore oil and gas pipelines. iPTran can be installed easily on both new and existing pipelines, without the need for any downtime.
- **Flexible Software Options:** Available as cloud-based or desktop application, or a hardware + software package with SCADA integration.

Optimizing pigging runs can result in significant savings in operation and maintenance costs. Avoiding stuck pig incidents by proactively planning the next cleaning run also mitigates unwanted expenditure on pig retrieval and downtime costs. This demonstrates that advanced detection technology enables operational efficiencies that directly enhance profitability.

Case Studies of iPTran Application

iPTran's practical efficacy is demonstrated through the following case studies.

Wax Profile Estimation on VKPL Crude Oil Pipeline of IndianOil

This demonstration was on a 148.3 km section of a 28-inch diameter Viramgam-Koyali Crude Oil Pipeline (VKPL) [7]. The objective was to estimate the wax deposition profile using SCADA data.

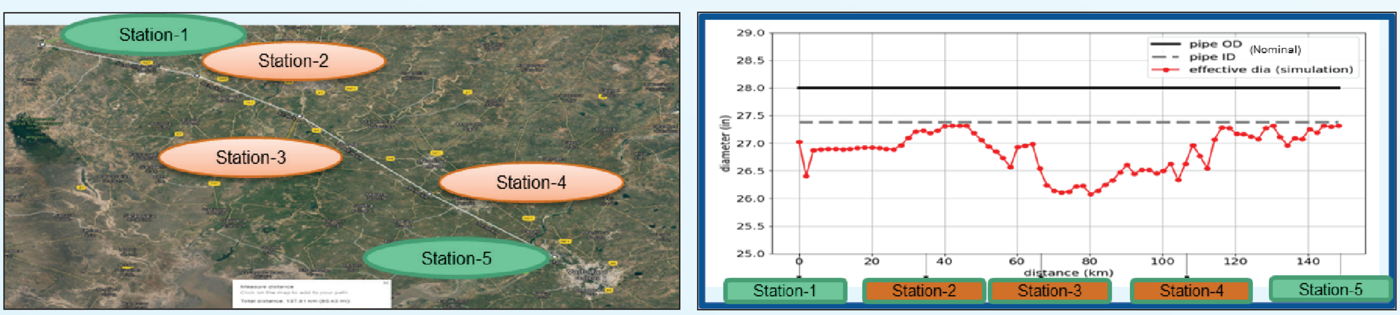
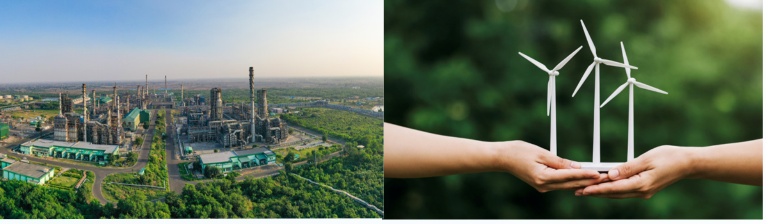


Fig. -10 (A) VKPL pipeline stations (B) Wax estimated profile (low accuracy estimate using SCADA data)



Methodology: A pressure transient wave was generated by closing a valve at the outlet (Station-5) for ~90 seconds. Data was collected from five locations (Station-1, -2, -3, -4, -5) using the existing SCADA system (5-second sampling rate), completed in ~5 minutes. An in-house Python code, using Method of Characteristics (MOC) and an AI/optimization algorithm, simulated a "clean pipe" pressure response. It then iteratively calculated the effective internal diameter profile by minimizing the difference between simulated and actual SCADA pressure readings. Acoustic velocity was estimated at ~987 m/s.

Results: Analysis mapped a deposition layer along the pipeline length. The analysis was validated by using Station-1 data. The accuracy of this analysis was low as SCADA data was used. This could be improved by using a higher sampling-rate data acquisition system (now developed by BFAPL).

Implications: Rapid wax deposition profiling provide critical information for optimizing pigging programs and predictive maintenance. Operators can shift to condition-based pigging, leading to substantial economic benefits.

Total Wax Estimation on CPCL Crude Oil Pipeline

This study estimated total muck/deposition in a 12.5 km, 42-inch diameter crude oil pipeline from Chennai Port to Manali Refinery. The pipeline typically underwent quarterly pigging with low muck retrieval.

Methodology: The iPTran system estimated the total muck weight. Data collection took ~5 minutes. The iPTran estimate was then compared to the actual muck weight retrieved during a subsequent pigging operation.

Results: iPTran estimated 28.1 kg of muck, closely aligning with the actual retrieved weight of 30 kg, an approximate 6% difference. This was deemed an "Accurate estimation" given the limited resolution offered by SCADA data (5 s sampling rate).

Implications: This satisfactory accuracy reinforces iPTran's capability to provide reliable quantitative data for pipeline health assessment. Accurate data supports pre-inspection services for pig type selection and enhances chemical treatment efficiency.

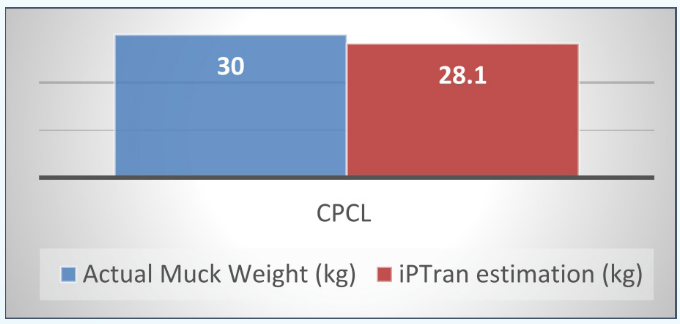


Fig. -11 iPTran estimate vs actual muck weight comparison

Stuck-Pig Location on Trichy-Madurai Product Pipeline of IndianOil

This case-study addressed a stuck pig incident in a 155 km, 10-inch diameter product pipeline from Trichy to Madurai.

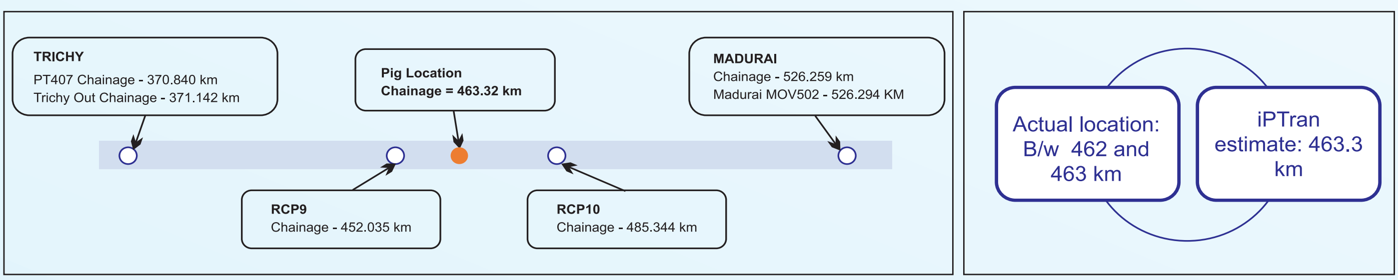


Fig. -12. Stuck pig location estimate using iPTran (~1 km resolution using SCADA data)

Methodology: iPTran technology was deployed to pinpoint the stuck pig's location, leveraging its pressure transient analysis capabilities to detect the impedance discontinuity. SCADA data of 1 s sampling rate was used.

Results: iPTran successfully located the stuck pig with a high degree of precision, achieving an accuracy of 1 km. iPTran located the pig to be at approximately 463.3 km chainage. Actual location was found to be between 462 and 463 km chainage, verified physically by personnel.

Implications: Accurate and rapid stuck pig location is paramount for minimizing pipeline downtime and mitigating severe economic consequences. iPTran's capability not only helps pre-empt stuck pigs through early blockage detection but also provides precise location information if an incident occurs, enabling quicker intervention and restoration of operations.

Conclusion and Future Works

The safe and efficient operation of oil and gas pipelines is vital, yet constantly challenged by internal anomalies like wax deposition, debris, and structural defects. These issues lead to increased costs, reduced throughput, and risks of stuck pigs and catastrophic failures. The economic impact is substantial, costing billions annually.

Pressure Transient Analysis (PTA), a non-intrusive technique based on pipeline hydraulics model, effectively detects these anomalies by analysing pressure wave reflections, providing a mechanistic understanding of internal conditions.

iPTran, developed by BFAPL, significantly enhances traditional PTA by integrating Artificial Intelligence (AI) and Industrial Internet of Things (IIoT) technologies. This synergy provides a robust, accurate, and rapid solution for pipeline integrity management. IIoT sensors enable real-time data acquisition, while AI algorithms process this data to deliver precise internal diameter profiling, quantitative wax/debris estimation, and accurate stuck-pig localization.

Real-world case studies validate iPTran's efficacy and highlight iPTran's contribution to proactive, data-driven approach to improve pipeline operational efficiency and profitability.

Further refinement of AI algorithms is crucial to enhance accuracy and sensitivity, especially in complex multiphase flow regimes where acoustic velocity variation is wide and frequent.

Adoption of technologies such as iPTran by oil companies shall also play a key role in advancing the innovation ecosystem for the energy industry, both at a national and global stage.

Deeper integration of iPTran data with other pipeline integrity management systems, such as SCADA, GIS, and other ILI tools, is a significant future direction. This convergence aims for a holistic "digital twin" approach, providing a unified, real-time view of asset health.

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11. Servo Miracle Grease Technology

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1.0 Introduction

Grease, a versatile semisolid lubricant, plays a crucial role in the majority of dynamic machinery, particularly those equipped with bearings. Grease consists of three components base oil, additives and thickener. Thickener plays vital role in determining many properties of greases. First patented in the 1940s, lithium greases captured major market share due to their superior performance and ease of manufacturing over comparable technologies. Lithium-based greases are established as a multipurpose product, commanding a market share exceeding 69% in global and ~84% in Indian subcontinent.

Recently, the demand for lithium has expanded beyond lubrication industries, driven by the growing need for alternative energy in the energy-intensive society, particularly in the transportation sector for EVs. In recent past lithium price increased in manifolds and availability is also a concern to grease producers due to increased demand for lithium in other industries. Intensive use of lithium in batteries and recent classification of lithium hydroxide being classified as a reprotoxin by EU made grease manufacturers to look for alternate sustainable grease thickener solutions.

Other existing alternative thickener technologies such as calcium, calcium complex, sodium, aluminum, aluminum complex, calcium sulfonate, calcium sulfonate complex and polyurea have certain excellence in specific properties and at the same time have some limitations to reach the level of lithium greases to suit as multipurpose greases. Numerous lithium alternate grease thickeners have been developed, each presenting distinct advantages and disadvantages.

IOCL's pursuit to develop lithium alternate thickener has led to the development of sustainable India Centric Grease Thickener based grease making technology. This technology christened as "Miracle" grease is a patented technology. It is based on novel hybrid metal soaps. Technology is based on preparation of grease from carefully balanced 'multifunctional soap' prepared with a transition metal, fatty acid and complexing acids in base oil. Miracle grease technology has potential to break Lithium grease technology monopoly.

2.0 Developmental program

The developmental program of the new thickener technology included a systematic scanning of periodic table to search for the metal which is abundant in Indian subcontinent and is able to saponify fat and also perform complexing with dibasic acids. Once metal was identified, an exhaustive search on the published literature and patents was carried out. The patentability search resulted in zero patents on greases made by using identified metal. Hence, further development of the new thickener technology based on identified metal initiated.

3.0 Experimental

3.1 Grease manufacturing

All greases were prepared through batch process. Commercially available base oils, fats (castor oil based derivatives) and a large number of dibasic acids were used for complexing. A typical grease batch was prepared as follows: In a pressure reactor base oil, fats, metal oxide, alkali and dibasic acids were added in optimized sequential manner. Reactor charge was cooked under pressure (typically 4-6Kg) for a period one hour and was then blown to an open processing kettle where grease was finished by passing through a homogenizer operating under 1000-1500psi pressure. For reference lithium greases were also prepared by following similar manufacturing process using similar base oils and fats. Scale up was done by preparing 5 Kg (bench scale), 20 Kg (lab scale), 50 Kg (pilot plant scale) and 9MT (commercial scale) batches. Commercial scale up was done at IOCL's Grease plant located in Vashi, Navi Mumbai. Manufacturing process was optimized in such a way that existing infrastructure (reactors/ kettles/ homogenizers) could be easily used. Batches covering broad range of NLGI grades: from 000 to 3 grades were made to assess technology suitability for commercial applications. Each batch was tested for physicochemical properties vis-à-vis lithium greases. Performance testes were carried out only on the batches performing better or equivalent to the Lithium greases.

3. 2 Physicochemical testing

As a standard test protocol, each batch was allowed to settle for 48hours after preparation before testing physicochemical properties. Penetration, mechanical stability , drop point, water was out, Roll stability, copper corrosion , rust preventive characteristics tests, etc. were carried using standard test equipments by following BIS / ASTM / IP test methods.

3.3 Performance testing

Selected batches that performed better or equivalent to Lithium batches were chosen for performance testing. Wheel bearing leakage, 4-ball weld load, 4-ball wear scar diameter, Oxidation stability, Dynamic rust tests, etc. and grease life at high temperature tests were carried out. Finally to simulate the actual use of grease in the application / field , high temperature and bearing life of the miracle greases were established through tribology rig evaluation by following ASTM / DIN methods.

3. 4 Analytical testing

Microstructure of the grease matrix was determined using Scanning Electron Microscope(SEM). FTIR was used to monitor the reaction kinetics and completion. Pressure differential scanning calorimetry (PDSC) was employed to determine the oxidation induction time of various thickener based greases.

3.5 Commercialization and benefits

Miracle grease technology was demonstrated at IOCL Grease Plant, Vashi Navi Mumbai by taking multiple commercial supply batches of 9MT each. Commercial batch products (various products based on Mircale thickener technology) were supplied to various major industries such as steel, cement, mining, transport, etc. for trial/application in their machineries.

4.0 Results and Discussion

4.1 Grease Manufacturing

Typically, a lithium grease manufactured through the batch process mentioned in experimental section takes nearly 7-8hours to finish from material charging in reactor to barrel fill. For Miracle technology this process was completed in half of the time taken by lithium grease batch. The key differences are –Firstly, lithium grease requires reactor material to be heated to >200 °C whereas for Miracle grease heating upto only 150 °C is required. Thus, considerable amount of energy and time is saved with Miracle technology. Secondly, after reactor material is blown to the processing kettle, dehydration of lithium grease typically requires 2-3 hours for a 8/9MT batch. Miracle grease being inherently water-repelling in nature gets dehydrated after blow in just half an hour. Thus scope 2 emissions (200 Kg CO_2 for lithium compared to 125 Kg for Miracle batch) are reduced considerably with Miracle technology and this also gives grease manufacturer more production capacity per working shift. This is also to be borne in mind that processing of Mircale grease base metal emits 7 times less CO_2 than lithium metal.

4.2 Physicochemical testing

Table 1 gives comparative data for Lithium EP 2 (fortified with EP additives), Lithium complex 2 (higher performance than lithium EP grease) and Miracle 2 greases (All greases are of same NLGI grade 2, prepared in VG 220 mineral base oil by following batch process). Physicochemical properties of Miracle grease are comparable to lithium greases.

Property	Test Method	Lithium EP 2 Grease	Li- Complex 2 Grease	Miracle 2 Grease
Appearance	Visual	Smooth	Smooth	Smooth
Color	Visual	Brown	Brown	Brown
Texture	Visual	Homogeneous	Homogeneous	Homogeneous
NLGI Grade	ASTM D217	2	2	**2**
Worked penetration, 0.1mm	ASTM D217	285	287	**284**
Drop Point, °C	ASTM D2265	198	262	**265**
Water wash out, %wt.	ASTM D1264	3.8	2.7	**1.8**
Mechanical stability, unit change in penetration	ASTM D217	+27	+30	**+21**
Copper corrosion test, Rating	ASTM D4048	1a	1b	1a
Rust preventive characteristics, Rating	ASTM D1743	Pass	Pass	Pass

Table1: Comparative properties of Lithium and Miracle greases

From the data given in Table 1, it is evident that Miracle grease has better drop point (higher) and mechanical shear stability (lower change in penetration value upon working). Higher drop points relate to the ability of the grease to withstand higher temperatures during application. This property is solely attributable to the thickener with which grease is made. Thus, the newly developed Miracle thickener has better high temperature workability that lithium thickener. Less change in consistency upon mechanical shearing is always desirable. This is directly proportional to the grease life in application. Thus, Miracle based greases are expected to have a better life than that of the lithium greases. Lower water wash out value of Miracle grease indicates that the grease is comparably more water resistant in nature. This property makes it an ideal choice for water ingress prone applications commonly encountered in steel and paper industries. These superior properties of the Miracle grease are attributed to the unique microstructure of Miracle grease matrix, Fig 1 (irregular honey comb type) compared to lithium greases matrix, Fig 2 (liner fibrous) as seen under scanning electron microscope. Other properties such as copper and steel corrosion protection are comparable to lithium greases.

Fig. 1: SEM of Lithium grease

Fig. 2: SEM of Miracle grease

The thickener fibers of lithium grease matrix gradually align to the direction of the shear/rotation upon shearing. Longer fibers break into smaller fibers loosing oil, resulting in to the loss of consistency (oil bleed and thinning of the grease). In case of the miracle grease the densely stacked honey comb grease matrix retains shape and oil in it and resulting structure integrity for longer periods under shear. Based on the analysis and ingredients used the proposed microstructure of the Miracle grease matrix is given in Figure 3.

4.3 Performance testing

Table 2 shows the comparative performance data of the lithium vs Miracle greases of the same NLGI grade 2. In the first glance of the data, it becomes evident that Miracle grease performance is superior than that of the lithium greases. Better load carrying capacity (higher weld load), antiwear characteristics (lower wear scar diameter) and better high temperature rolling shear stability (less change during rolling shear) make it ideal choice for heavy duty industrial and automotive applications. These facts was further strengthened by conducting tribological rig tests on lithium and Miracle greases for wheel bearing and high temperature life.

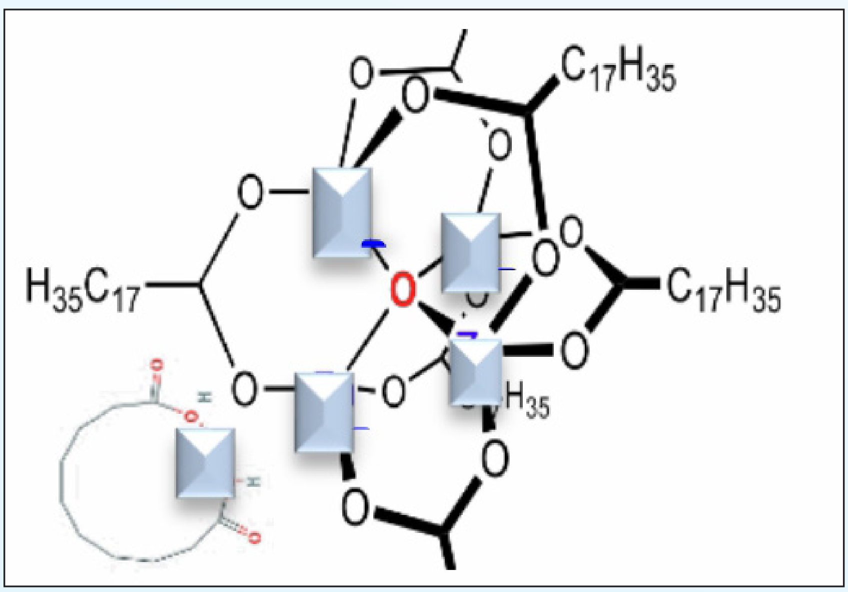

Fig. 3: Thickener matrix of Miracle grease

Performance Property	Test Method	Lithium EP 2 Grease	Li- Complex 2 Grease	Miracle 2 Grease
4- Ball weld Load, Kg	IP 239	250	315	**450**
Wear Scar Diameter, mm	ASTM 2266	0.6	0.6	**0.50**
EMCOR rust test, Rating	IP 220	0,0	0,0	0,0
High Temp Roll Stability, 80°C, 96h	ASTM D1831	28%	17%	**16%**
Wheel Bearing Leakage, g	ASTM D1263	1.7	2.0	**1.6**
Wheel bearing life, 160°C, hrs	ASTM 3527	40	81	**84**
FAG FE9 L50 life , 140°C, hrs	DIN 51821	112	261	**294**
High Temp Bearing Life, 160°C, hrs	ASTM D3336	18	42	**92**

Table 2: Comparative performance properties of Lithium and Miracle greases

Miracle grease not only had better wheel bearing life (critical to be used as a wheel and hub grease) but also performed better in most stringent FE 9 life rig test. This test establishes life of greases for high temperature industrial and automotive applications where the rpm is typically > 5000. Thus superiority of the Miracle grease was established through performance evaluation tests before proceeding for the commercial batches production. The superior performance of the Miracle grease was attributed to – its unique grease matrix structure (retaining oil and resisting structure degradation under shear or at high temperature), multi-functional nature of grease thickener (acting as extreme pressure, anti-wear, water resistant and corrosion protecting component) and synergistic effect of additives with thickener matrix.

4. 4 Analytical testing

Based on the data presented in previous sections, it is hypothesized that Miracle grease is expected to last at least twice as long as lithium grease. To support this, Pressure differential scanning calorimetry (PDSC) was employed to determine the oxidation induction time of various thickener based greases. Figure 4 depicts the oxidation induction time (OIT) in minutes for various greases in PDSC test. The oxidation of grease is directly related to its functional life. Higher the OIT longer the grease life. It can be easily observed from the Figure 4 that Miracle thickener based grease has nearly twice OIT compared to lithium grease. Other thickener based greases are even inferior to lithium greases. This firms the previous findings on the performance evaluation of the lithium vs Miracle greases.

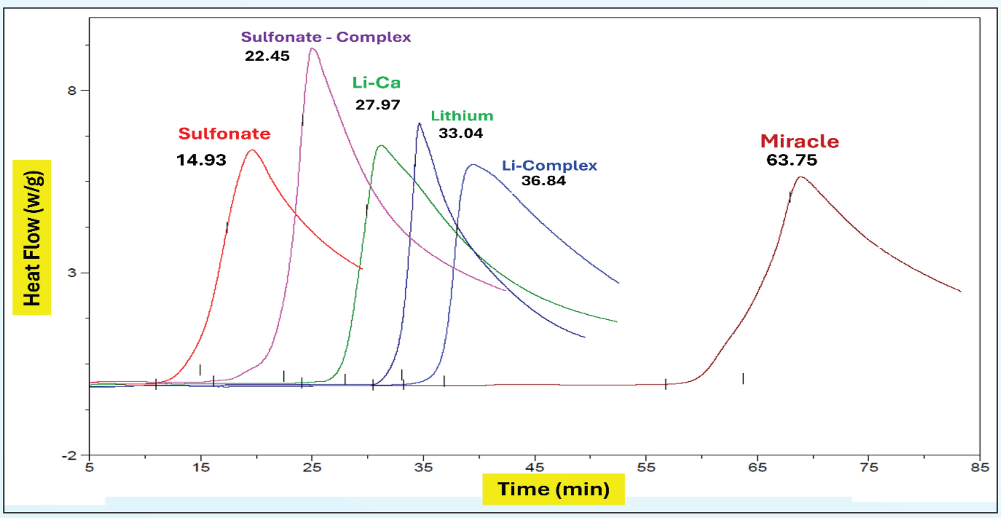

Fig. 4: Oxidation induction time (OIT) in minutes of various thickener based greases as per ASTM D5483 at 180° C

4.5 Commercialization and benefits

During scale up done at IOCL Grease Plant, Vashi, Miracle thickener based batch manufacturing process resulted in grease batches with consistent properties. Miracle grease was formerly launched by IOCL on June 5, 2023. Since then, approximately 1500 MT Miracle grease has been sold to the market. A large variety of the industries such as Steel, cement, mining, refinery, sugar, construction, earthmovers, power, state transport, etc. have used Miracle greases and confirmed its superior performance. Miracle greases users have reported less grease consumption and longer life compared to lithium greases.

As referred in Section 1: Introduction; nearly 70% of the global and 84% of Indian grease production is based on lithium thickener technology. Consideration of 2% use of lithium hydroxide for a typical lithium grease batch manufacturing, simply translates to saving of Rs 2071 crores (for lithium) for global and ~Rs 300 crores worth lithium imports for Indian context. Switching to Miracle grease technology can directly save lithium import costs. This perfectly aligns with the "Atmnirbhar Bhart" vision of the nation. Moreover, India being a powerhouse of the production of chosen metal for making Miracle grease thickener (4th in the global production), the technology is sustainable. By adopting Miracle technology, IOCL has already increased its non-lithium grease production by 6% within a year.

5.0 Conclusions

Miracle thickener grease technology is easily customizable with respect to consistency, dropping point, weld load, grease life and solid additive requirements. Other than the comparative performance evaluation, commercialization and cost considerations, Miracle technology has the following distinct advantages over lithium thickener grease technology –

i. Sustainability - Inputs are abundantly available in India. This alternate technology will help to preserve precious Lithium ore or make it available for EV technology.

ii. Ease of Manufacturing – Miracle greases can be manufactured in both open kettle and or in reactor by using existing infrastructure.

iii. Energy Efficient Manufacturing - Miracle grease manufacturing requires low processing temperatures compared to Lithium. This saves time, energy and increases production/shift resulting in reduced scope 2 emissions.

iv. Flexibility- Miracle greases can be made in any NLGI consistency with tailor made dropping points. Technology has good additive response.

v. High temperature operability - Typical drop point of Miracle grease is around 270 °C whereas for Lithium base soap it is ~190 °C.

vi. Superior Features- Miracle technology alone can perform better than conventional Lithium EP or Lithium complex greases. Thus, it is a single solution for both Industrial and automotive applications.

vii. Easy inventory management – Since Miracle grease can perform in variety of industrial and automotive applications, it is a single solution, thus requires to maintain low inventory at customer's end.

viii. Superior water repellency - Miracle grease is inherently 40% more water-repellent than conventional Lithium grease.

ix. Long lasting performance – Miracle greases give longer service life than Lithium /Lithium complex greases.

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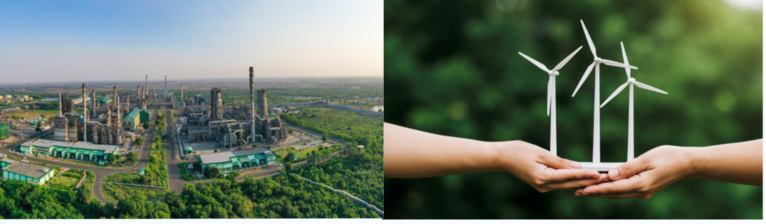

12. BIO HYDROGEN AND BUTANOL FROM PADDY STRAW IN A STATIC REACTOR EMPLOYING CLOSTRIDIUM SPECIES

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Introduction

The growing demand for sustainable and renewable fuels has intensified research into bio-based alternatives to conventional fossil fuels. Among these, bio-butanol has emerged as a promising candidate due to its high energy content, compatibility with existing fuel infrastructure, and potential as a versatile chemical feedstock. Bio-butanol can be produced via microbial fermentation of biomass, where carbohydrate-rich substrates are converted into organic acids and subsequently reduced to butanol through microbial metabolic pathways (see Fig. 1).

In this research work, we have undertaken novel approach using static fermentation compared to the conventional dark fermentation pathway thereby avoiding the microbial stress encountered with high stirring during fermentation which has enhanced and quickened the butyric acid conversion process to butanol. It is called dark fermentation for the reason that strictly anaerobic conditions warrant it to be a closed bioreactor without leaving an iota of doubt for atmospheric air to enter, thereby creating a dark scenario. By introducing the cellulose microbe ternary complex formation technology through CMT reactor (see Fig. 2), more sugars can be produced from carbohydrate and this can be fermented for maximum hydrogen liberation and butyric acid formation which is used for butanol production of > 30% (w/w) is observed making this process highly efficient compared to conventional dark fermentation.

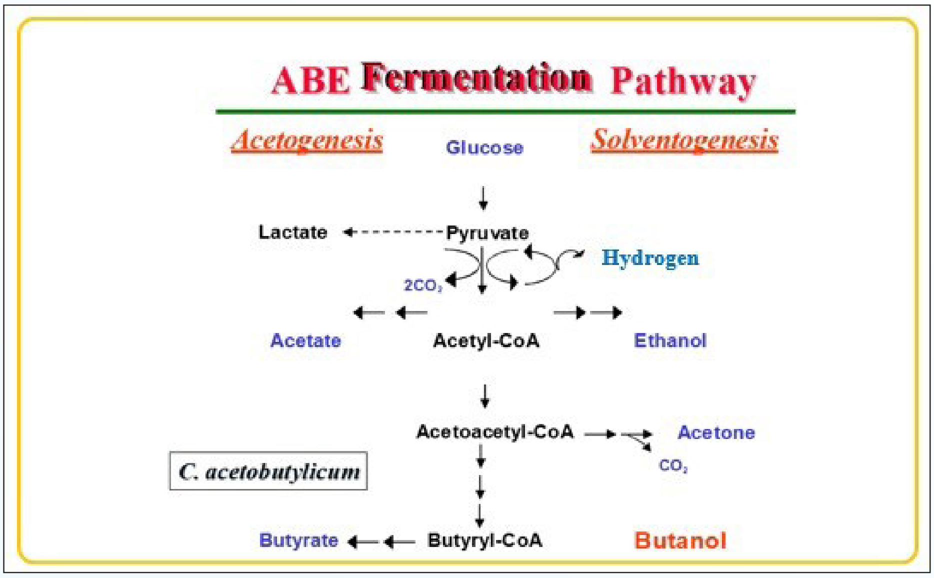

Fig 1. Two stage fermentation with distinguished phases Bio-Hydrogen - butanol yield from cellulose derived sugars.

This research work brings together carbohydrate and bacteria to work in tandem in their optimal pH and temperature conditions paving way to remove hydrogen from the butyric acid hydrolysate in the bioreactor. In the present research work on two-stage CMT fermentation process for butanol production from rice straw , we also added a small quantity of corn syrup to provide the bacteria with required energy until the cellulose is disintegrated into fermentable sugars. Static environment in the fermentation process enhanced the solventogenesis phase by minimizing the energy consumption by the bacteria. This new concept of stationery 2 stage fermentation was studied in phase I. Further optimization of dilution factor, pH management strategy and butanol separation methods were investigated in phase II. Fermentation enters the 1st stage of acidogenesis where carbohydrates in the biomass are converted into organic acids in the presence of CMT complexes and then as the acids build up , the microbial reaction changes to solventogenesis in the 2nd stage. In this stage the acids are hydrogenated by hydrogenase enzymes produced by clostridium species at a very low pH <5.0 to produce solvents like butanol . Other parameters like temperature , initial Clostridium load and other medium compositions were also observed to vary the overall butanol concentration produced. "It is observed that 37^{0}C is most suitable for efficient metabolic activity of Clostridium" (Soni and Goma, 1987).

Bio-hydrogen gas is generated during the first stage of the fermentation while the pH is still above 5.0 while butyric acid is being produced by biomass break down by Clostridium and it is a promising high energy renewable fuel of the future. Hydrogen's molecular formula of H2 which is a very light gas with a with a very high yield of 122 kJ/g of energy, compared to fossil fuels and petroleum products hydrogen gas generates 2.75 times higher calorific value.(Pattra et al. 2008; Chong et al. 2008; Chong et al. 2009; Classen et al. 2010). "With only water as by-product , combustion of hydrogen is far better than any petroleum derived fuels" (Fields 2003; Pattra et al. 2008).

Butanol is produced during the process owing to the acid shift reaction during the fermentation of cellulosic sugars forming an intermediate butyric acid and then eventually with the help of hydrogenase enzyme produced by Clostridium on the surface of the hydrolysate utilizing the produced hydrogen gas as a negative charge provider for the butanol formation. Probing this mechanism with various feed stocks like paddy straw, paddy husk, further pre-treatment with KOH was carried out followed by different steps to produce two types of hydrolysate namely washing with water for lignin to obtain only cellulose and without washing to retain lignin and cellulose. These two different hydrolysates are subjected to dark fermentation in a static reactor employing Clostridium butyricum. Hydrogen gas and butanol production is compared. .

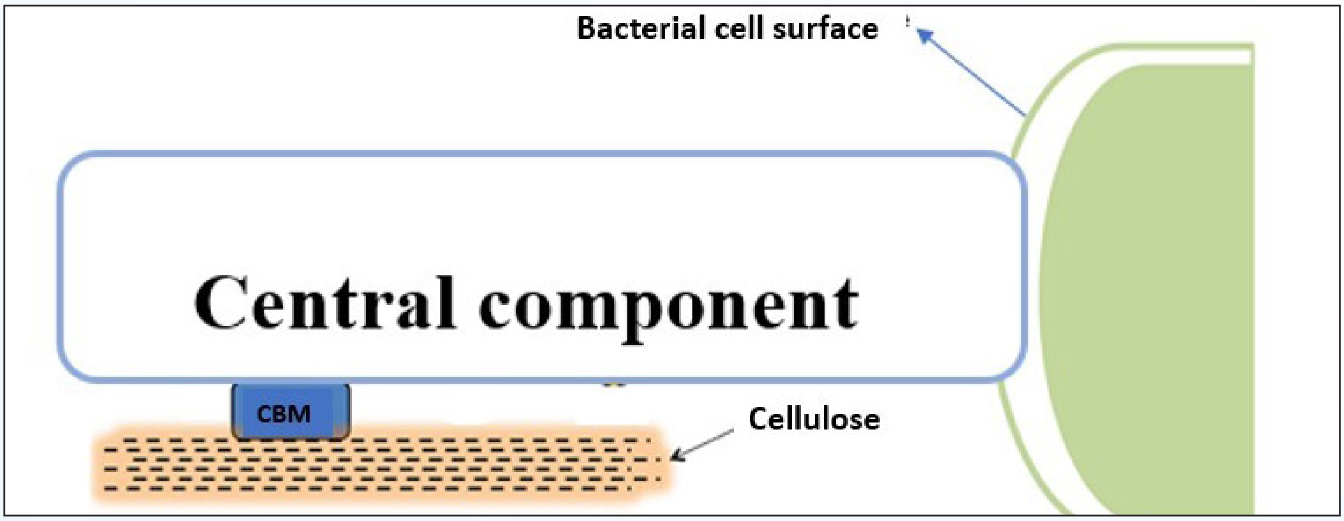

Fig 2. Structure of Cellulosome. The central component of cellulosome is bound to the peptidoglycan layer of C. tyrobutyricum. Central component also contains a cellulose binding module (CBM), which locates lignocellulose for digestion of hemicellulose and cellulose.

STUDY METHODOLOGY:

Sequential Production and Conversion:

Step 1: Hydrogen Gas production

Acid Production: During the initial fermentation phase, Clostridium species produce butyric acid as a metabolic byproduct. At the same time, hydrogen gas (H_2) is generated as a byproduct of this fermentation process. In a two-stage fermentation reaction, one of the pathways for hydrogen production from glucose is through fermentation by Clostridium butyricum (Li, X., Mao, Y., Wu, Y., & Bao, G. 2013). The simplified reaction for hydrogen production can be represented as:

$$C_6H_{12}O_6 + 2H_2O \rightarrow 2CH_3COOH + 2CO_2 + 4H_2$$

This reaction shows that 1 mole of glucose ($C_6H_{12}O_6$) can produce 4 moles of hydrogen gas (H_2). Also, during the dark fermentation reaction butyric acid formation is also observed by Clostridium butyricum in a simplified reaction represented as :

$$C_6H_{12}O_6 \rightarrow C_4H_8O_2 + 2CO_2 + 2H_2$$

This reaction shows that 1 mole of glucose ($C_6H_{12}O_6$) theoretically produce 1 mole of butyric acid ($C_4H_8O_2$) and 2 moles of hydrogen (H_2)gas. In the biomass – Clostridium spp. hydrolysate , hydrogen gas is formed by various pathways as above.

Step 2: Butyric Acid to Butanol

Solvent Production: In the later phase of fermentation (solventogenic phase), the same or different Clostridium strains utilize the butyric acid and hydrogen gas to produce butanol and other solvents. This phase involves a shift in metabolic pathways where the bacteria convert acids into alcohols represented by the reaction:

$$C_4H_8O_2 + 2H_2 \rightarrow C_4H_{10}O + H_2O$$

This reaction shows that 1 mole of butyric acid ($C_4H_8O_2$) produces 1 mole of butanol ($C_4H_{10}O$) (Wang, Y., Li, X., & Blaschek, H. P. 2013).

NOVELTY - One pot fermentation study:

With a single addition of bacteria culture and no further addition of enzymes or other microorganisms, we term this technique as one pot fermentation process. Mainly in solventogenesis phase the fermentation kinetics was studied with CMT reactor with cellulose hydrolysate – (washed on pre-treatment) and cellulose + Lignin (unwashed on pre-treatment) as seen in fig 3. With the butyric acid broth under strict anaerobic condition. The impact of pH ranging between 5.5 to 6.5 and dilution factor at 20 was considered with a constant temperature of 37°C in CMT reactor. The reactor efficiency at various dilution rates were studied. The Hydrogen gas evolution was observed by the substrate upward movement in the reactor. With continuous medium movement and bubbling gas production in the fermentation broth, the reactor is sufficiently mixed as seen in Fig 4.

Fig 3. Left flask is the washed feedstock (paddy straw – cellulose only)from whereas the right flask is the unwashed feedstock (paddy straw – cellulose with hemicellulose retained in the lignin liquor).

Fig 4. The substrate (cream in color) is seen rising from the bottom of the flask and touching the top media surface.

Analytical Procedure:

Every 3 hours , 20 ml of sample was drawn aseptically. The pH was measured with a pH meter and adjusted to 6.1 up to 42 h. At the end of 80 h , removing the bacterial cells by centrifugation at 6000 rpm for 20 min, the clear fermentation broth of about 200 ml was subjected to rotavapor (Fig 5) with a vacuum pressure of 75 mBar , temperature of 43 oC and 100 rpm. The distillate was collected on the condenser side of the rotavapor equipment . Further the obtained clear solution (crude butanol) is them subject to liquid -liquid extraction with Dichloro methane – DCM absorption in a 10 ml centrifuge tube and then the phase separation happened . 1.5 ml of the DCM phase was analysis for product concentrations in GC instrument. Butanol, ethanol, acetic acid and butyric acid was determined by using a gas chromatograph (Agilent model 18890 equipped with a flame ionization detector and column : DB-1MS(part No. 122-0132).

Fig 5. Rotavapor equipment for vacuum Distillation Model BUCHI R300

Below are the GC parameters used for the analysis: injection volume: 0.2 ul; column liner temperature: 250 oC; Column Flow: 1 ml/min Nitrogen; Column DB -1MS ; Oven temp.: 40 °C starting holding for 3 min then increasing to 200˚C with heating rate of 40 oC /min; FID temp: 300˚C; Air : 300 ml/min; H_2 : 40 ml/min: Makeup (N_2): 25 ml/min; split ration: 20:1. Similarly, hydrogen gas collected in the balloons were injected to the GC (Agilent model 8890 with Thermal Conductivity Detector, with Column: Carbo plot P7 (part No. CP7514). Below are the GC parameters used for the analysis: Injection volume: 1500 ul; Column liner temperature: 50˚C; Column Flow: 5 ml/Min helium; Column: Carbon Plot P7 column (cp7514); Oven temp: 80˚C starting holding for 10 min; TCD Temp: 180˚C; Reference Flow: 10.5 ml/min; Makeup flow: 2 ml/min; split ratio: 10:1.

Experimental Setup

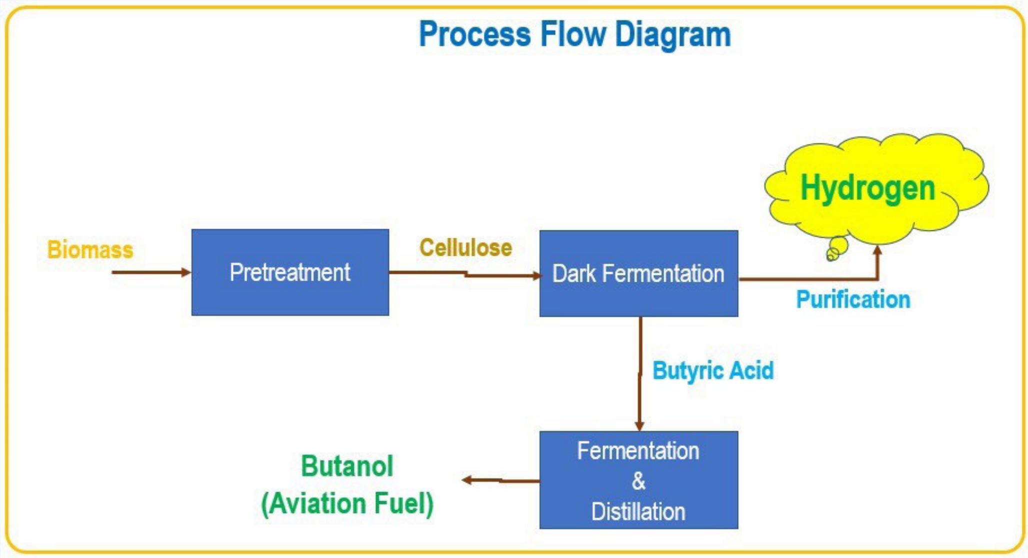

Fig 6. Process flow diagram for Bio-hydrogen & Butanol from Paddy straw

Materials Used:

Paddy straw collected from the nearby farms around Indian Institute of Technology Tirupati was first powdered to 3-5 mm particle size and was subject to 5% KOH treatment with a 20 dilution with R O water.at 90ºC in a hot air oven for 2 hours. The pretreated paddy straw slurry is then washed with tap water to wash away the lignin and separate the Carbohydrate. The solid carbohydrate residue can be subjected for Carbohydrate microbe ternary reaction by C butyricum procured from an industrial bacterial Clostridium butyricum supplier SK Bio, Gujarat, India into fermentable butyric acid residue hydrolysate. This broth can be used as carbon source for Bio-hydrogen production and butanol by Clostridium butyricum .

Bacterial culture and media:

Clostridium butyricum was used for the study of Bio-hydrogen and butanol production from paddy straw as source of carbohydrate. This strain of bacteria is easily activated in bioreactor and was found to get adapted to tolerate higher butanol concentrations. The reactor C. butyricum was used for the study of hydrogen and butanol production from paddy straw as source of carbohydrate. The reactor medium suitable for this strain was provided with the following composition in 1 L of DI water: Cooked meat media , 2g; Corn syrup , 2g; 0.2 g of Clostridium butyricum powder culture with total viable count of 10 billion cfu/g. Here corn syrup as the nitrogen source was used along with the cooked meat media which is most preferable media for anaerobic gram-positive spore forming Clostridium butyricum . The temperature of the bioreactor was controlled at a constant 37 ºC. The microbial media is kept under controlled pH by adding 1 N KOH or 3% acetic acid solution as much required to adjust the pH to 6.0. While the RPM of the shaker incubator was maintained at static – zero which is a key strategy to avoid the microbial stress which enhanced the butanol concentration.

Results and Discussions:

pH Impact on Butanol production:

After 80 h, (Fig 9.A to G), the concentrations of butanol and ethanol were obtained with GC peaks for various trials; 1. Pre-treated paddy straw washed, unwashed; 2. Pre-treated paddy husk- washed, unwashed; 3. Glucose powder. It is observed that the in the initial 18 hour the pH drops as low as 4.3 to 4.6 along the minimal hydrogen gas production getting accumulated in the gas collector bag. As we proceed with experiment further 18 hours with pH adjustment back to 6.1 , the hydrogen gas starts to increase and stabilize by end of 40 hours. There is a continuous collection of gas with pH management in place. If the pH management is not uniform and left unattended the gas collection falters but can be brought back to constant gas collection again with constant 6.1 pH management. The drop in pH is mainly attributed to accumulation of butyric acid. Further at this low pH < 5.0, C. butyricum produces hydrogenase enzyme which catalyzes the hydrogenation of butyric acid to butanol. This particular phase of reaction is termed as acid shift reaction leading to a transition from acetogenesis to solventogenesis.

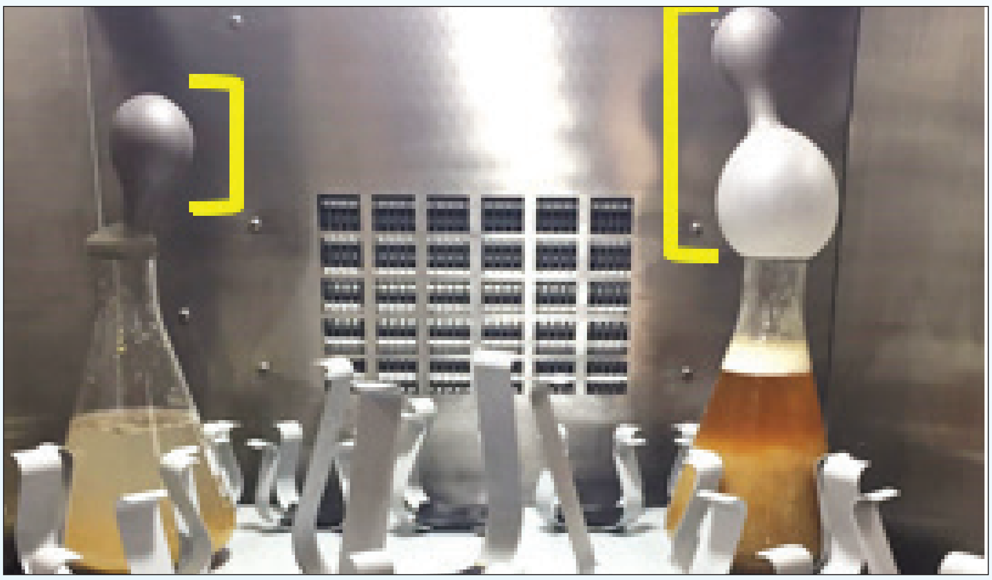

Fig. 7 Hydrogen Production Comparision

Fig 7. The left flask showing Hydrogen gas produced is less from the washed feed stock (paddy straw – cellulose only since hemicellulose is lost with washed lignin liquor) compared to the bigger balloon on the right with more hydrogen gas produced from the unwashed feed stock (paddy straw – cellulose with hemicellulose since hemicellulose is retained with the lignin liquor)

Paddy husk and paddy straw both unwashed showed more concentrations of butanol owing to the hydrolysis of both cellulose and hemicellulose . Whereas in the washed feedstocks it was only cellulose and hence the concentration of butanol was lower <1.5%. Similarly, the Hydrogen gas balloons were seen bigger for the unwashed feedstocks and smaller for washed feedstocks as shown in Fig . 7 and distinct peak for hydrogen gas in GC gas analysis with Thermal Conductivity Detector were recorded Fig 11.

Impact of pH on Hydrogenase Production:

Acidic Conditions (pH < 5.5): In more acidic environments, hydrogenase activity tends to decrease, and the overall metabolic pathways may shift from hydrogen production towards producing more organic acids like butyric acid. Extremely low pH values can also lead to enzyme inhibition or denaturation. Alkaline Conditions (pH > 7.5): In more alkaline conditions, hydrogenase activity also tends to drop. The enzyme structure may become unstable, and the bacterial metabolism may not favour hydrogen production.

Role of pH in Metabolic Shifts:

Acidogenic to Solventogenic Shift: In many Clostridium species, the shift from acid production (acidogenesis) to solvent production (solventogenesis) is associated with changes in pH. For example, during the early stages of fermentation (acidogenesis), the medium tends to become more acidic, which may suppress hydrogenase activity. As the pH gradually increases (usually around pH 5.5 to 6.0), solventogenesis becomes more favourable, and hydrogenase enzymes are more active, facilitating hydrogen use in reactions like butyric acid conversion to butanol.

pH Control in Industrial Processes: In industrial bioprocesses that use Clostridium for butanol production, pH is carefully controlled to maintain optimal hydrogenase activity. This ensures efficient hydrogen production and utilization, especially during the solventogenic phase when butanol is produced. The favourable pH for hydroge- nase enzyme activity in Clostridium species is typically between pH 5.5 and 7.0, with optimal activity often around pH 6.0 to 7.0. Maintaining this pH range is crucial for maximizing hydrogenase enzyme production and function, which plays a key role in hydrogen gas metabolism and the conversion of butyric acid to butanol. The GC re- sults (area under graph) for experimental trials undertaken are listed in Table 1 and Table 2. The results are plotted as shown in Figure 8 and Figure 10.

Bio-hydrogen and Butanol evolution plots analysis

Butanol Evolution @ 3.9 min retention time - G C Analysis

Sl. No.	Feedstock	Area unde the graph		
		Glucose Powder	Pandy Straw (Pre- treated)	Paddy Husk (Pre-treated)
1	Control	920327	NA	
2	Washed (only Cellulose)		30014	
3	Unwashed (Cellulose & Ligning)		524363	464480

Table 1. Butanol Evolution @ 3.9 min retention time - G C Analysis

Area under graph Plot for Butanol formation @3.9 min retention time- GC analysis

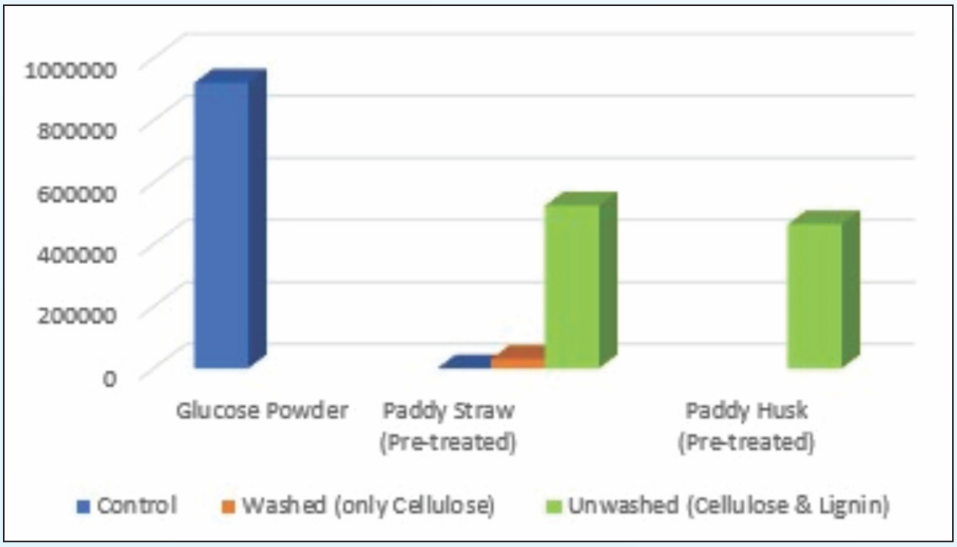

Fig 8. Butanol Evolution @ 3.9 min retention time - GC Analysis

GC results as obtained from the Mass Hunter software showing the peaks :

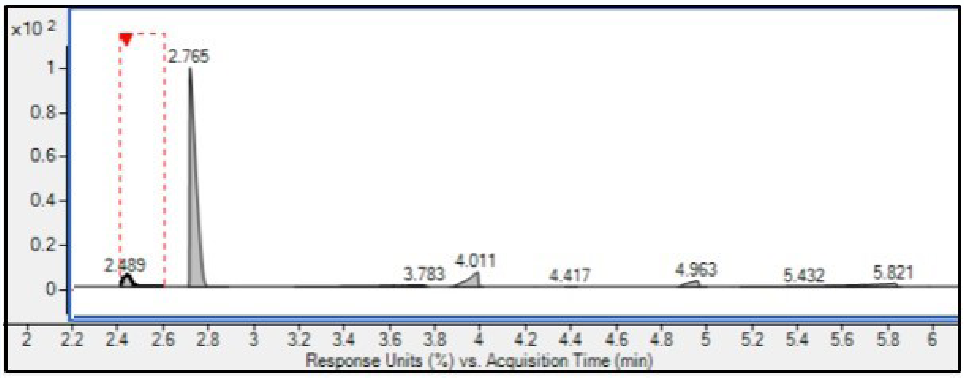

Fig 9.A: Pure Ethanol 1% (t=2.48), pure DCM 96%(t=2.76), Pure Acetic Acid 1%(t=3.78), Pure Butanol 1%(t=3.96 to 4.01), Pure Butyric acid 1%(t= 5.82); for compounds identification

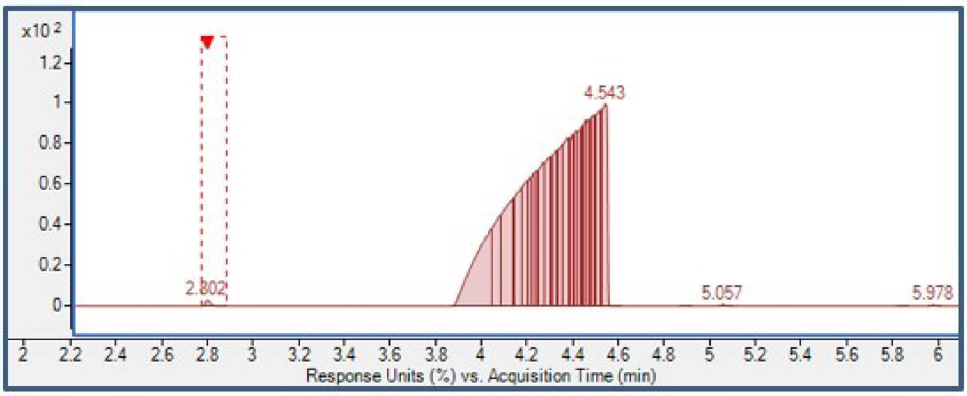

Fig 9.B.: Pure Butanol 10%; peak spreads from t=3.83 to 4..58; for product identification

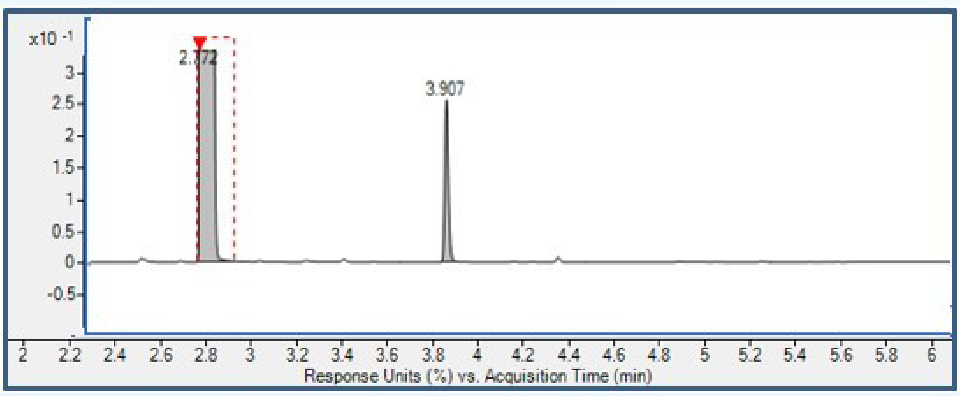

Fig 9.C.: Substrate- Glucose powder 16% W/v; Butanol peak at t=3.907 ; for control to check the bacterial strain viability

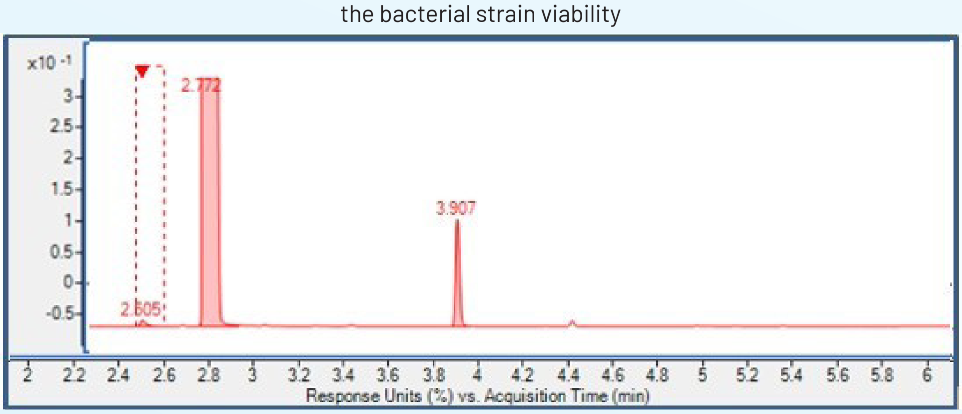

Fig 9.D.: Substrate – unwashed Paddy Straw ; Butanol peak t= 3.907, traces of ethanol at t=2.50

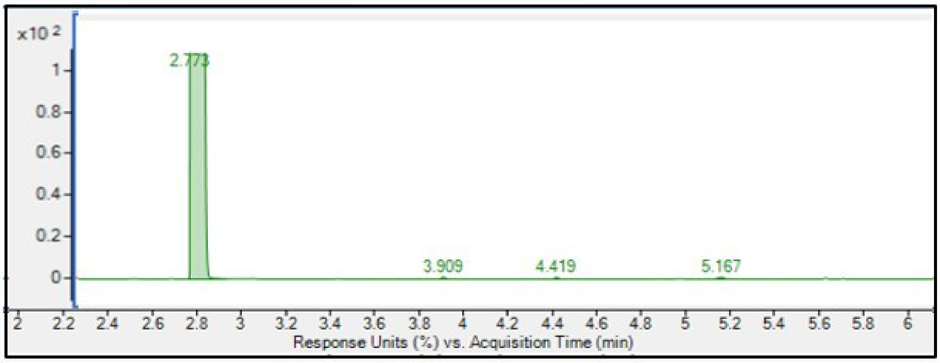

Fig 9.E.: Substrate – washed Paddy straw ; Butanol peak at t= 3.909

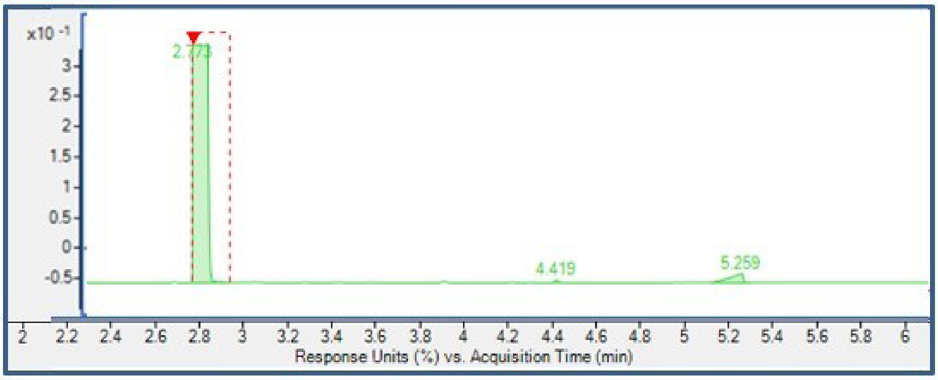

Fig 9.F: Substrate – washed paddy husk ; Butanol peak at t= 4.47

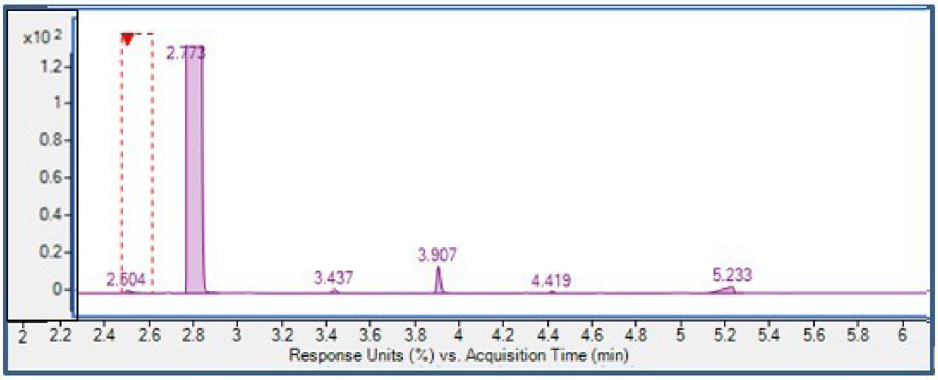

Fig 9.G.: Substrate – unwashed Paddy husk; Butanol peak a t=3.907

Table 2. Hydrogen gas evolution @ 1.4 min retention time – GC Analysis

Sl. No.	Feedstock	Area Under the graph	
		Paddy Staw (Pre-treated)	Paddy Husk (Pre-treated)
2.	Washed (only Cellulose)	1051	
3.	Unwashed (Cellulose & Lignin)	1420	1401

Area under graph for Hydrogen gas evolution @1.4 min retention time - GC Analysis

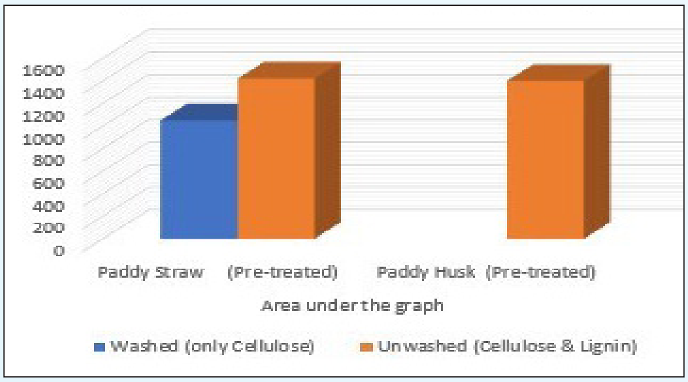

Fig 10. Area under graph- Hydrogen gas evolution @ 1.4 min retention time

Hydrogen gas analysis with GC - Thermal Conductivity Detector

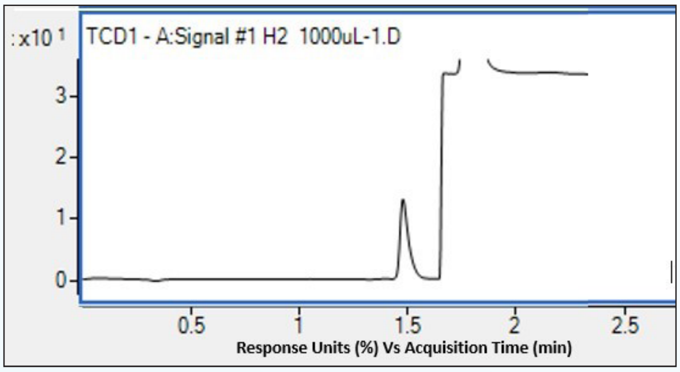

Fig 11.1 Pure hydrogen from cylinder for gas identification peak at 1.4 min retention - GC analysis

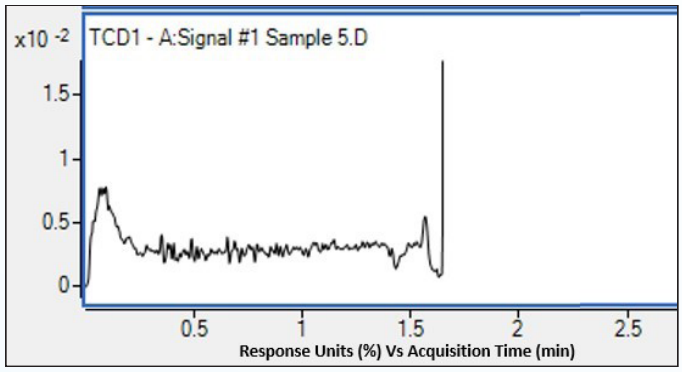

Fig 11.2: Substrate – washed Paddy straw; gas collected after 18 h, H2 peak at 1.4 min retention - GC analysis.

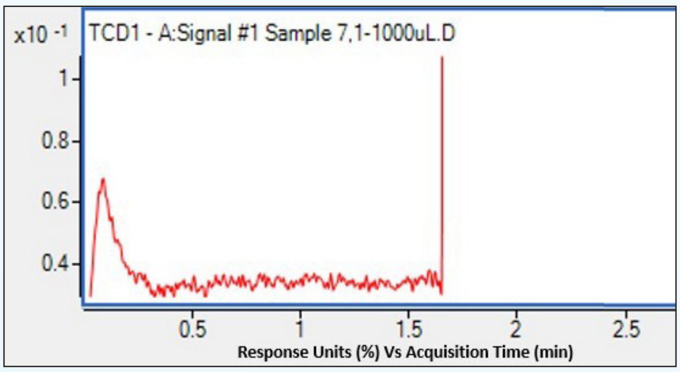

Fig 11.3: Substrate – unwashed Paddy husk; gas collected upto first 18 h, very small H2 peak at 1.4 min retention - GC analysis

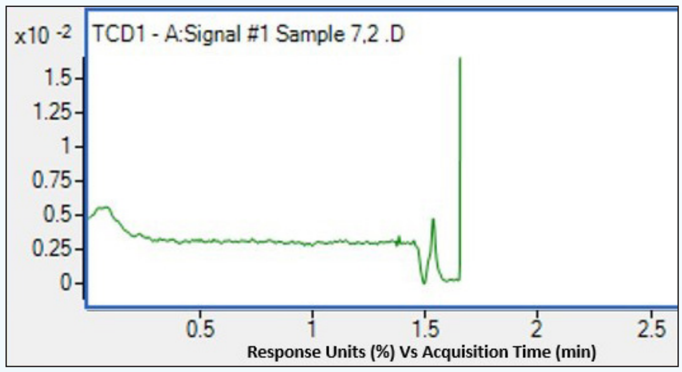

Fig 11.4: Substrate – unwashed paddy husk; gas collected after 18 h, H2 peak at 1.4 min retention - GC analysis

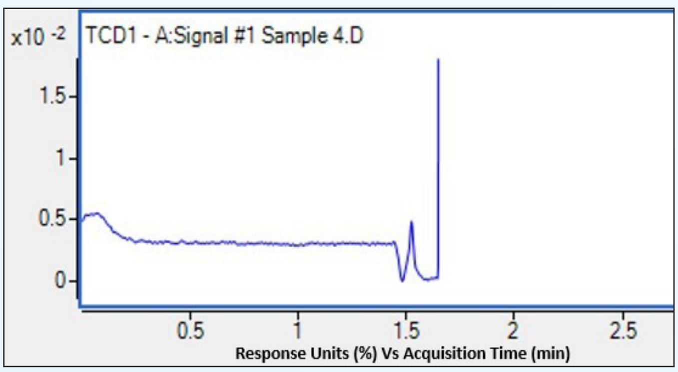

Fig 11.5: Substrate – unwashed paddy straw; gas collected after 18 h, H2 peak at 1.4 min retention - GC analysis

SUMMARY AND CONCLUSION:

Study Report Summary

Streamlining the key parameters in the fermentation process is an important area of focus in many research efforts so far. Traditionally, the profitability of fermentation is affected by the feedstock , bacterial culture dosage, media nutrient concentration , media dilution rate, temperature and pH management strategy and product recovery.

Butanol production is typically associated with the acid hydrogenation by hydrogenase enzyme and the availability of hydrogen at this juncture is a crucial aspect. Our efforts in the future will be build a continuous fermentation process that improve the butyric acid concentration with careful pH management strategy and a static media in the CMT reactor. Producing butanol by butyric acid conversion method proved to be efficient owing to high fermentable sugars available in the unwashed hydrolysate. Both paddy straw and Paddy husk have been proved suitable for butanol production. The experimented routes of pre-treatment followed by dark fermentation has shown different degree of butanol production. Broadly the yields of butanol can be ordered as unwashed pre-treated paddy straw is more than the washed pre-treated paddy straw. Mostly significant observation was that the gas produced during one pot fermentation is mainly Hydrogen as confirmed from Gas Chromatography and the hydrolysate at the end of 72 hours is confirmed as butanol from Gas Chromatography analysis. Butanol production is typically associated with the acid hydrogenation by hydrogenase enzyme and the availability of hydrogen at this juncture is a crucial aspect.

The pH management and product recovery has proven the key aspect of this one pot fermentation of lignocellulosic biomass employing Clostridium butyricum in a static reactor.

Conclusion

We term this fermentation as one pot fermentation process with C.butyricum since no other input like enzymes and other strains or species of microorganisms are used in the entire research work carried out for production of Bio-hydrogen and butanol from paddy straw with an improved yield of butanol from unwashed substrate (Cellulose and lignin) in static reactor, which can make one pot fermentation derived butanol economically competitive compared to synthetically derived butanol from Petroleum refineries. Commercialization of this one-pot fermentation technology can greatly benefit any nation who are importing fossil fuels for their energy needs. Hydrogen gas production management is investigated in this study which implies to collect and separate the produced hydrogen gas to avoid reverse reaction with hydrogenase enzyme to produce butanol from butyric acid. Hence the production of hydrogen gas is regulated by collecting it in a separate cylinder. Similarly, butanol production management is also investigated in this study which implies to allow produced hydrogen gas to be retained in the reactor enabling hydrogenase enzyme to convert butyric acid to butanol utilizing the hydrogen gas available in the top portion of the reactor. Precise pH management is the key to achieve desired products in this one pot fermentation by Clostridium butyricum in a static reactor. Also, this technology promotes the agricultural biomass based butanol production enabling aviation sector to achieve sustainability goals through SAF. Further, this provides a hydrogen supply chain for the fuel cells.

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13. Heat Recovery Steam Generator (HRSG) & Its Auxiliary Systems

Mr. Piyush Sharma is currently working with Fired Heater team as Assistant Manager (Heat Transfer) and the team is responsible for all the projects undertaken by Toyo Engineering India Private Ltd. and supporting Toyo Engineering Corporation for overseas Jobs in the field of petrochemical, refinery, fertilizers (ammonia, urea) and gas processing unit. He has amassed over 18 years of extensive global experience in thermal design of heat exchangers. Handled vendor proprietary items such as air-coolers, plate type heat exchangers, electric heaters, Heat Recovery Steam Generator (HRSG) package till PGTR as a single point responsibility and currently handling Fired equipment (fired heaters, cracking heaters, hot oil package, incinerator's).

HISTORY:

Design alternatives and procurement approaches for heat recovery steam generators, supplementary firing duct burners, auto-change over and ancillary steam systems are addressed in this report.

ABSTRACT:

A heat recovery steam generator (HRSG) is an energy recovery heat exchanger that recovers heat from the exhaust gases of a gas turbine (TEG) to an extreme degree. The heat is recovered in the form of steam which is served in a process (cogeneration) or used as the power source of a power-generating steam turbine combined cycle).

OBJECTIVE:

- To provide detailed, informative guidance for specifying and procuring HRSGs.
- To identify, define, and discuss key design parameters of HRSG design and procurement today.
- Type of HRSGs based on horizontal, vertical, and once-through steam generator designs and based on type of operations used.
- To provide design and operation information regarding pinch & approach, duct burner for supplementary firing & fresh air firing, auto changeover from TEG mode to fresh air firing (FAF), stack design such as deciding height, velocity inside stack, extent of modularization concept.

EFFICIENCY AND SUSTAINABILITY

One of the primary reasons for using a HRSG is to increase the efficiency of a system. For example, by recapturing waste heat from a combustion process, we reduce the amount of heat lost, and thus increase the system's overall efficiency. An increase in plant efficiency correlates with reduced operational costs and reduced environmental impact.

COST SAVINGS

Even though an HRSG may need a large initial capital investment (Capex), the investment is justified by the long-term efficiency improvements (Opex). The HRSG will pay for itself several times over during its service life, which might be more than 20 years. The high reliability of a HRSG also means that its operational time is high, this ensures a good return on investment.

FLEXIBILITY

HRSGs can be integrated into various industrial processes, offering flexibility in terms of application. Whether it's for power generation, process heating, or other industrial applications, a HRSG can increase system efficiencies considerably (because it recovers heat that would otherwise be lost). It also gives an operation flexibility to operate HRSG independently without GTG using fresh air firing mode when GTG is tripped or under maintenance.

1) INTRODUCTION:

HRSG- A Heat Recovery Steam Generator, commonly abbreviated as a **HRSG** is an energy recovery heat exchanger that recovers heat from the hot exhaust gases of a gas turbine (TEG – Turbine Exhaust Gas) to an extreme degree, such as a combustion turbine or other waste gas stream. The heat is recovered in the form of steam that can be used in a process (cogeneration) or used as the power source to drive a steam turbine (combined cycle).

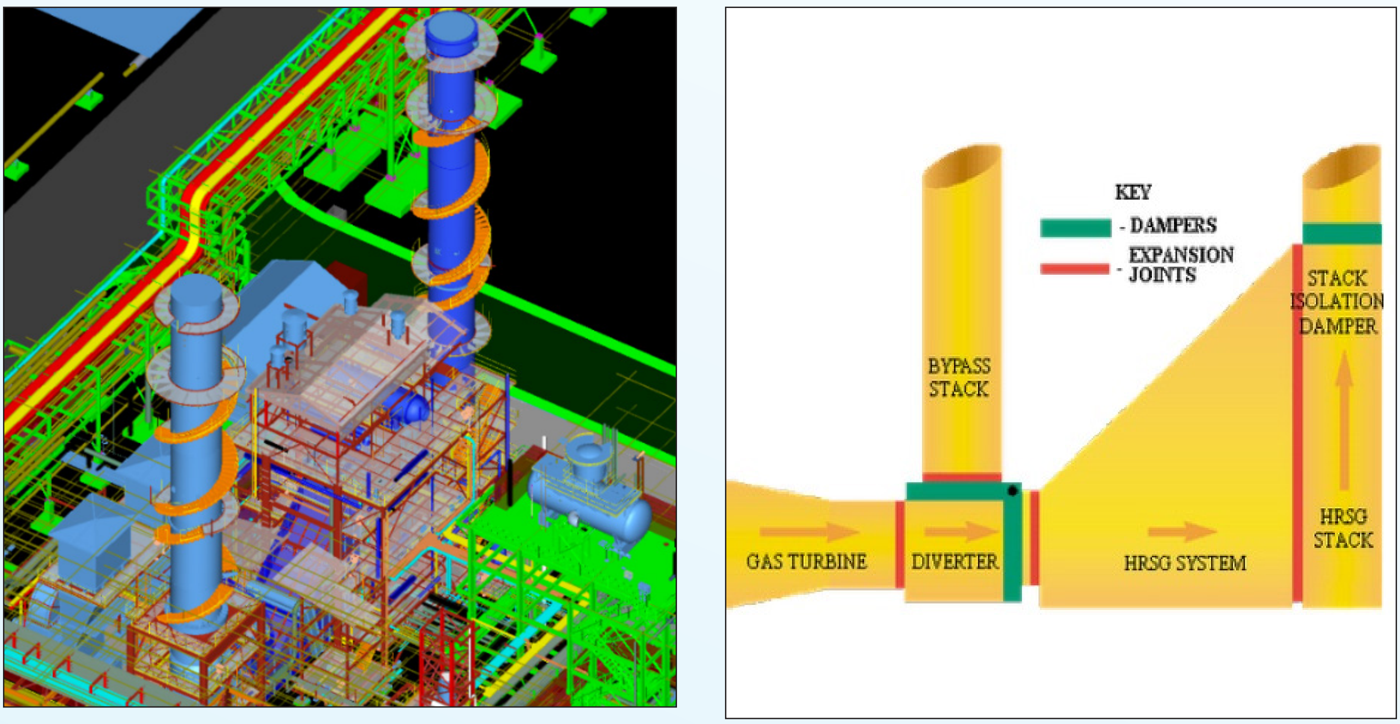


Fig 1: Heat Recovery Steam Generator schematic arrangement

So, to understand the HRSG and its types let's start it from the basics first.

Where the HRSG is Used

The HRSG can be used to drive a steam turbine for power generation, or to generate steam for factory processes or district heating. When used for cogeneration purposes, the HRSG-produced steam is for process applications such as Urea, Ammonia (fertilizer plants). In the combined cycle mode, the steam produced goes to a steam turbine generator for power generation. The two modes are demonstrated in the figure below.

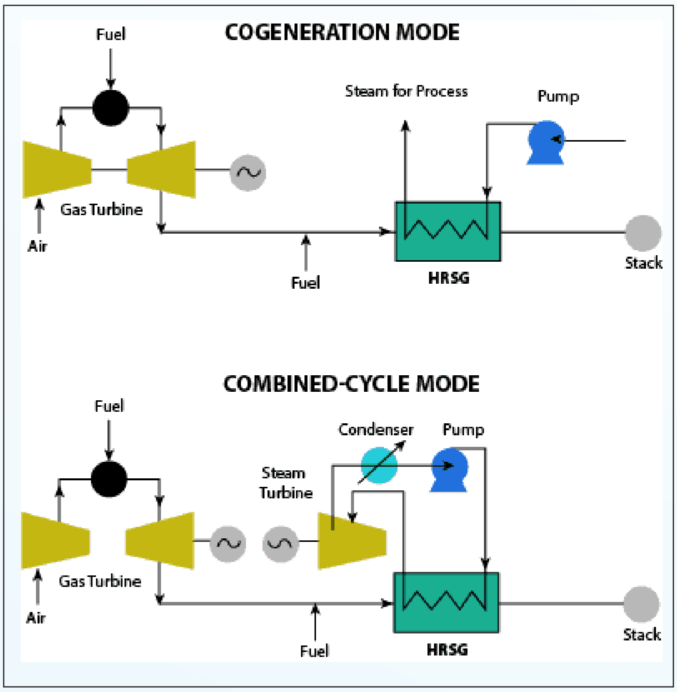


Fig 2: Cogeneration Mode and Combined Cycle Mode

2) TYPES OF HRSGS –

HRSG classification are mainly based on Circulation & Orientation, Operation, Application, or Design. This gives several types of these generators as described below.

2.1 HRSG Types Based on Circulation and orientation

Mainly three (3) types of HRSG's are used in industry

a. Natural Circulation HRSGs

Natural circulation units have vertical tubes and horizontal gas flow orientation. In natural circulation units, the difference in density between water and steam drives the steam-water mixture through the evaporator tubes and risers and back to the steam drum.

b. Forced Circulation HRSGs

Forced circulation units have horizontal tubes and vertical gas flow orientation. In forced circulation units, a pump is used to drive the steam-water mixture through the horizontal evaporator tubes.

c. Once Through HRSGs

Once-through units can have either a horizontal or vertical gas flow path. In once-through designs, there is no circulation system. Water enters at one end and leaves as steam at the other end of the tube bundle.

Client's preference may be advised by Capex and Opex, footprint area, maintenance, structural requirements and other factors that may vary,

2.2 HRSG Types Based on Operations

- **TEG (Turbine Exhaust Gas) mode:**

a) Unfired Mode

b) Supplementary Firing Mode

The second way of classifying HRSGs is to consider the heat input. Conventionally, HRSGs rely on exhaust heat alone. However, this becomes a challenge at GTG part loads operations. Ambient conditions also affect turbine performance (sometimes, VAM is installed for gas turbine inlet air cooling (TIAC) has long been the most commonly used method to improve the performance of gas turbine-based power plants which results in turbine gas exhaust with consistent temperature and relative humidity). That is why supplemental firing is often part of the system that not only elevate the turbine gas exhaust temperature and increase the steam generation when it is in demand and also burners serve the fresh air fan operation.

- **FAF (Fresh Air Firing) Mode:**

Fresh air firing is used to produce steam when the gas turbine is down (GTG tripped or GTG is in maintenance).

2.3 HRSG Types Based on Applications

a) Cogenerations (Process plants)

b) Combined-Cycle Mode (Combined Gas Based Power Plants)

2.4 HRSG Types Based on Design

a) Single Pressure

b) Multi Pressure

Classification on **pressure level** gives these two types of generators. With one steam drum, single-pressure HRSGs generate steam at a single pressure level. This is unlike the multi pressure type that features multi pressure circuits.

3) BASIC FUNDAMENTAL PARTS OF HRSG COMPONENTS (PRESSURE AND NON-PRESSURE PARTS)

Essentially, the HRSG is composed of several heat exchangers making it a large heat exchanger. The heat exchanger tubes are set in **different modules or sections,** popularly known as:

a. Preheaters (gas to polished water heat exchanger)
b. Economizers (gas to BFW water heat exchanger)
c. Evaporators (gas to wet steam heat exchanger)
d. Super heaters / Re-heaters (gas to dry steam heat exchanger)

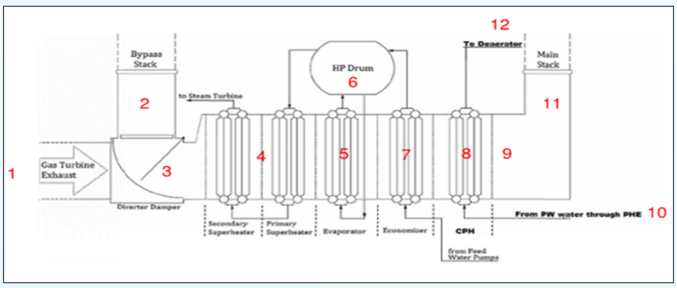


Fig 3: HRSG pressure part arrangements

3.1 Non-Pressure Parts

- **HRSG Inlet Transaction Duct (1)**

  It is a duct just after the GT to guide TEG towards bypass stack / HRSG.

- **Outlet Transaction Duct (9)**

  It is a duct just after the CPH coil to discharge TEG into the atmosphere through main stack

- **Bypass Stack / Main Stack Main (After HRSG) (11)**

  A stack applied just after the HRSG that allows combustion TEG to flow into the atmosphere

  Bypass (After GT) (2)

  A stack applied addition to and separate from the normal HRSG exhaust stack that allows combustion turbine exhaust gas to flow independently to the atmosphere when GTG operates in an open cycle.

- **IBD, CBD Tank**

  Intermittent blowdown tank and continuous blowdown tank to be kept at some elevation for natural circulation of blowdown coming out from HRSG pressure parts and steam drum.

3.2 Pressure Parts

- **HP Harps – Super heater, Evaporator, Economizer & CPH (4, 5, 7 & 8)**

  Main pressure part of HRSG system to be designed strictly in accordance with IBR

- **Steam Drum (6)**

  HP Steam drum take water from Economiser maintain the water level in Drum through 3 element control and deliver Steam to primary superheater.

- **Riser**

  Boling takes place inside the vertical tubes of evaporator and carry over the two-phase flow into the steam drum

- **Down Comers**

  Supply water to evaporator bottom header

- **Attemperator**

  It is also called as de-superheater where Steam temperature to be maintained by the spray of BFW water and installed in-between primary and secondary superheater.

3.3 Bought Out

- **Blow down cooler (S&T Heat Exchanger)**

  Shell and tube type heat exchanger to cool blowdown coming out from IBD tank to reasonable temperature prior to discharge blowdown in to the blow down pit.

- **PHE (10)**

  Plate type heat exchange to be introduced water at 50°C or more than 50°C.

at upstream of CPH coil to supply PW water at 50°C or more than 50°C.

- **Silencer**

  Silencer to be considered either by GT vendor or HRSG vendor to maintain the noise of high temperature TEG. If it is under HRSG Vendor scope then it should be kept in bypass stack just above the three-way diverter damper.

- **Dampers (3)**

  A valve or plate used for controlling draft or flow of Gases, including Air, Diverter damper in context of an HRSG system, is a damper that governs the flow of TEG flow towards HRSG or towards bypass Stack.

- **Duct Burners**

  A burner, mounted in a duct or discharging into a duct, used to heat the air, flue gas, or combustion turbine exhaust gas in the duct

- **Insulation**

  Proper insulating material to be considered with 10 SWG (Typical) SS liner

- **Expansion Joint**

  Appropriate expansion joints required to accommodate the thermal expansions and to prevent the stresses on the HRSG casing. 1 no. expansion joint is provided at outlet of each FD fan (1 W + 1S).

- **Scanner Cooling Fan, Seal Air Fans**

  Scanner cooling fans are generally used to cool flame scanners.

  Whereas seal air fans are used to provide 100 % leak proof damper operations to divert GT exhaust gases either in HRSG or in atmosphere through by-pass stack.

- **Blow down Pumps**

  Vertical pumps to be considered at blow down pit to supply blowdown into the ETP.

- **Deaerator (12)**

  Deaerator used to maintain the water quality prior to supply BFW into the Economiser.

- **Dosing Systems (LP and HP Dosing)**

  LP dosing skids for Deaerator and HP dosing skid for Steam drum

- **Valves**

3.4 Electrical & Instrumentation

- Transmitters, Control Valves
- Burner Management System (BMS)
- Gauges, Sensors
- Cables & cable trays, Impulse Tubing and accessories
- SWAS System (SWAS)
- Continuous emission monitoring system (CEMS)
- Push Button station, Electrical JB & earthing
- Aviation lighting
- Lightning Arrester

3.5 Stack Design Criteria

- Stack height shall be designed to meet 2D / 8D requirement of CPCB. Other criteria for deciding stack height are as follows:

a) Stack height is calculated using the formula H=14(Q)^0.33, where H is the height in meters and Q is the quantity of fuel in kg/hr multiplied by the sulfur content percentage divided by 100.

b) Stack height shall be minimum 30 m as per CBCB.

c) Stack height shall be decided considering the nearby structures and working platform.

d) Dispersion analysis.

e) EIA (Environmental Impact Assessment) study specifying minimum stack height, if any.

f) Minimum stack height requirement as specified in the ITB by the Customer.

- Stack Velocity Range: 0 to 30 m / sec.
- The work platform should serve the entire circumference of the stack (360-degree access). The minimum platform width shall be always 1.2 meters regardless of diameter of stack and no. of sampling ports as per CPCB requirement.
- Stack shall be provided with lightning arrestor. Also, aviation warning light shall be provided as per guidelines of Aviation Authority / ICAO standard.
- External insulation shall be provided on Main Stack.
- Consider adequate landing platform on stack depend on the height of stack.

4) HRSG DESIGN PHILOSOPHY

- Exchange heat from the exhaust gas to the fluid at the highest temperature difference available
- Accomplished by making the exhaust gas and the fluid (steam/water) temperature gradients as nearly parallel to each other as possible.

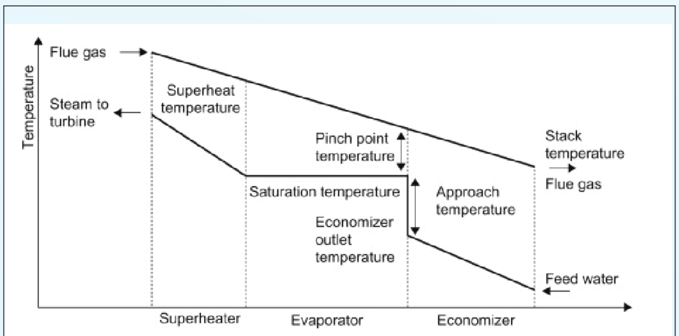


Fig 4: Pinch Point and Approach

Figure 4 shows the gas/steam temperature profile for the single-pressure stage HRSG. There are two design parameters of HRSG in the gas/steam temperature profile: pinch point temperature difference and approach point temperature difference.

The **pinch point** temperature difference is the difference between the exhaust gas temperature leaving the evaporator and the temperature of saturated temperature.

Approach point temperature difference is the difference between the temperature of saturated steam and the temperature of water leaving the economizer.

The pinch point temperature difference also affects the heat transfer surface area. Smaller pinch point temperature difference will require larger heat transfer surface area hence increasing the cost of production. Increase the approach point temperature difference also gives the same result as pinch point temperature case and it is greatly affecting the efficiency of single-pressure HRSG. if the value of approach point temperature difference is equal to zero, the water at the exit of economizer will tend to boil. This phenomenon is called steaming economizer. Zero value of approach point temperature difference means the gas temperature at the economizer inlet is equal to the temperature of water leaving the economizer. Steaming economizer will cause water hammer, vibration or deposition of salt in economizer tubes which can reduce the HRSG performance. There are several opinions about the temperature range for the pinch and approach point temperature difference. The typical pinch and approach point temperature difference that used in industry is 5˚C to 12˚C and 8˚C to 15˚C respectively.

HRSG Flow Path

Notice that water enters the HRSG at the coldest part (furthest from heat source) and is heated gradually as it progresses towards the heat source. Notice also that there is a standard flow pattern, which starts with the economiser, then the steam drum, evaporator, steam drum again, superheater, and finally to the steam turbines.

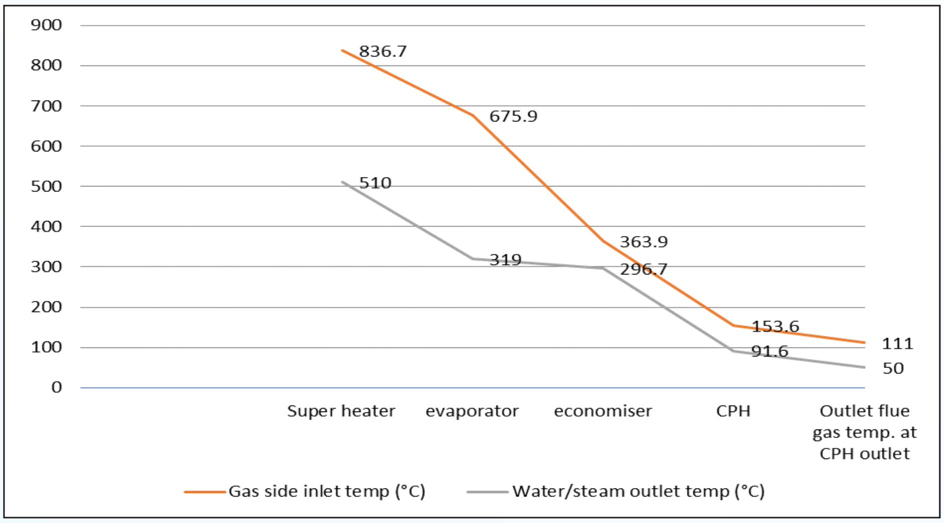


Fig 5: Pinch Point and Approach from past project reference (supplementary firing in all the cases)

The HRSG working principle is summarised below.

1. **Heat Recovery** – exhaust gases from a gas turbine or other heat source, typically at temperatures of 480°C to 600°C and in the range of around 850 °C (in case of supplementary firing and fresh air firing mode), are directed into the HRSG.

2. **Condensate Preheater** – The emphasis for the HRSG design shall be on maximizing waste heat recovery from exhaust gas. Hence condensate pre-heater can be added to utilize the waste heat and to lower the stack temperature but above sulfur dew point temperature. Other way to maximise the extent of recovery by deploying the multi pressure system (addition of steam drum).

   The HRSG, water is heated in the condensate preheater (CPH) which further routed to Deaerator as inlet water. Higher the CPH outlet temperature smaller the Deaerator sizing thus sometimes it uses to optimize the deaerator sizing.

3. **Economiser Preheating** – feedwater is preheated in the economiser. This process elevates the water temperature close to its boiling point, preparing it for the evaporator.

4. **Steam Drum** – water from the economiser is delivered to the steam drum, often also passing through a deaerator. Saturated steam is discharged from steam drums.

5. **Evaporator Steam Generation** – preheated water flows through the evaporator tubes and is heated by the hot exhaust gases. The heat exchanged results in the water boiling and changing state to steam.

6. **Superheating** – generated steam from the evaporator is directed to the superheater. Steam within the superheater is exposed to hotter exhaust gases due to it being closer to the heat source. The superheater may raise the steam's temperature which is what is required by a typical power station high-pressure turbine. Steam turbines require superheated steam because of its high energy content and reduced moisture content (dry superheated steam is what is delivered to a steam turbine).

   The amount of energy the steam contains corresponds to how much energy the steam turbine can extract, and consequently how much electrical power its generator can produce.

7. **Steam Turbine Power Generation** – dry superheated steam is discharged from the HRSG to one or more steam turbines. The steam turbine converts the heat energy of

the steam to mechanical energy and passes this to a generator (both are installed on a common shaft).

The generator converts the mechanical energy into electrical power (electricity).

8. **Exhaust Gas Discharge –** after the exhaust gases have transferred most of their heat energy to the water and steam systems, they are discharged to the atmosphere at a temperature of between 120°C to 150°C. It is important that the hot gas stream does not have an excessively low temperature because otherwise condensation may occur within the stack and a corrosive environment will be created.

   Good to know – a 'stack' is similar to a 'chimney' although 'stack' is the more common term used in engineering.

5) DUCT BURNERS AND SWITCH-OVER FROM GT TRIP TO FRESH AIR FIRING (AUTO-CHANGE OVER)

5.1 Duct Burners

A burner, mounted in a duct or discharging into a duct, used to heat the air, flue gas, or combustion turbine exhaust gas in the duct.

Use of duct burners in HRSG as follows –

- Add heat to the gas turbine exhaust stream
- Turbine exhaust gas typically has enough oxygen to sustain stable Combustion
- Steam demand increases without any change in the gas turbine exhaust
- Desired steam flow of final steam temperature cannot be achieved with the available heat from the gas turbine
- Gas turbine is completely down but steam is still needed (Fresh air firing)

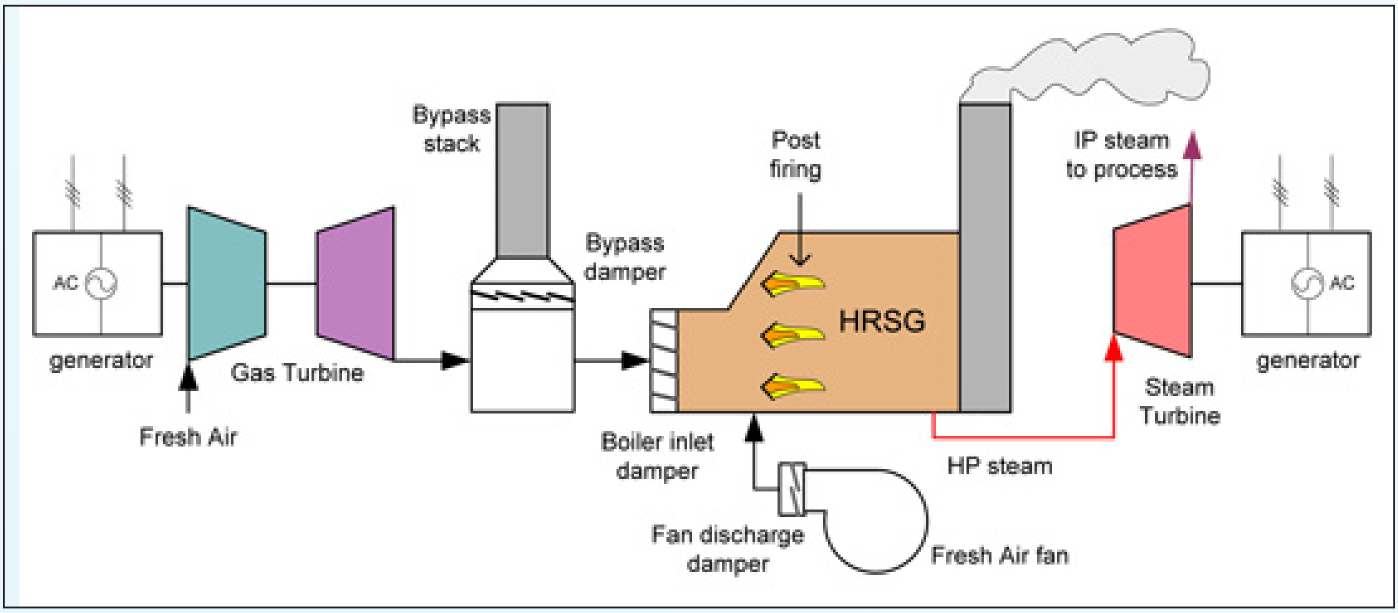


Fig 6: Typical Combine Cycle Scheme with HRSG

5.2 Auto Change Over Mode

he so-called 'fly switch over' (FTO). FTO consists of changing seamlessly from gas turbine operation to fresh air mode to FA operation while the HRSG is kept in service. It is usually desired when combustion turbine trips, automatic changeover logic will come in to action and Fresh air blowers will start running for fresh air fan operation.

The Auto changeover program will be initiated by the gas turbine trip signal and will comprise the following sequence:

- Start of the switch-over program
- Control of the fuel quantity to a fixed value (Burners at turndown and should be always on).
- Supply of fresh air
- FD fan Damper Open
- Separation of the gas turbine
- Ramp-up of the fuel quantity after successful change over from TEG mode to FAF mode

5.3 Pre-requisite for auto change over sequence

- GT trip creates black-out scenario and immediate power source is made available to immediately start the FD Fan/initiate the auto-changeover sequence.
- EDG will provide the required power for operating Fresh air FD Fans. Power supply to HRSG motor terminals shall be available from EDG in 30~35 seconds.
- HRSG operating with minimum firing to maintain purge credit during.
- Minimum 25% rated flow requirement to be ensured for purge credit as per NFPA 85.
- Emergency power made available to scanner cooling fans, HRSG low-low DP shall trip the HRSG/Burners within seconds from GT trip as there will be no power supply available to scanner cooling fans.

6) INSULATIONS IN HRSG

The insulation provides a means of keeping the heat contained in the HRSG where it can be absorbed by the pressure parts mainly sequence of heat exchanger tubes (superheater, evaporator, economiser etc.), resulting in higher overall efficiencies. The insulation also keeps the external casing cooler making it safe for operating and maintenance personnel to safely work around the equipment. Usually maintained casing temperature is around 60°C by considering 0 m/s wind velocity.

6.1 Insulation in Transition duct

Transition duct is subjected to high turbulent gases due to inherent characteristic of the GT exhaust gases. Ceramic Insulation and liner system design is preferred for inlet transition duct upstream of the duct burner and in the pressure part module section.

6.2 Insulation in Burner / Combustion zone

Instead of conventional refractory compressed ceramic modules are preferred in HRSG Burner area / combustion zone due to the following reasons:

- Suitability for high velocities.
- Compressed Ceramic Modules offer Low Thermal Conductivity thus less thickness of insulation than refractory lining.
- Density of compressed ceramic module is 1/10th of Refractory and accordingly weight would be very less thus overall weight of ducting remains very low and hence this reduces the foundation loads considerably.
- Compressed Ceramic Modules does not require curing. So immediate and faster start up is possible.
- Furthermore, the ceramic fibre blanket does not require "drying" in the field as would be required with the refractory.

7) CODES AND STANDARDS

Following standards or their equivalent shall be followed for HRSG:

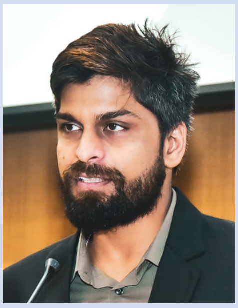
For design and fabrication	For Materials	For Performance Testing of HRSG and components	Statutory and Local codes
• Indian Boiler Regulation (IBR) • ASME • API • IS • ANSI • ISA • NFPA, NFPA 85 • AWS • IEC • NEC • NEMA • TEMA	• IBR • ASTM • ASME • IS	• IBR • ASTM • ASME • IS	• Indian Boiler Regulation (IBR) • OISD • Central Pollution Control Board (CPCB) • State Pollution Control Board • National Ambient Air Quality Standard • Environment (Protection) Amendment Rules, 2008 • CCOE, Factory Act & General Requirement of Law

Tab 1: Applicable Codes and Standards

8) CONCLUSIONS

One of the most important components in combined cycle and cogeneration power plants is the Heat Recovery Steam Generator (HRSG), which is sandwiched between the gas turbine and the steam turbine. In this article, we highlighted the basics of the HRSG and its importance in the industry. Consultants, plant engineers and generally anyone involved in projects will find this information relevant when making key decisions regarding the system from Capex, Opex, reliability, flexibility and relevant applications. One can also look for the extent of modularization which can be beneficial when there is sea to sea connectivity and there is no transportation limit constraint.

14. Fueling Clean Aviation: How Green Hydrogen Enables SAF at Scale



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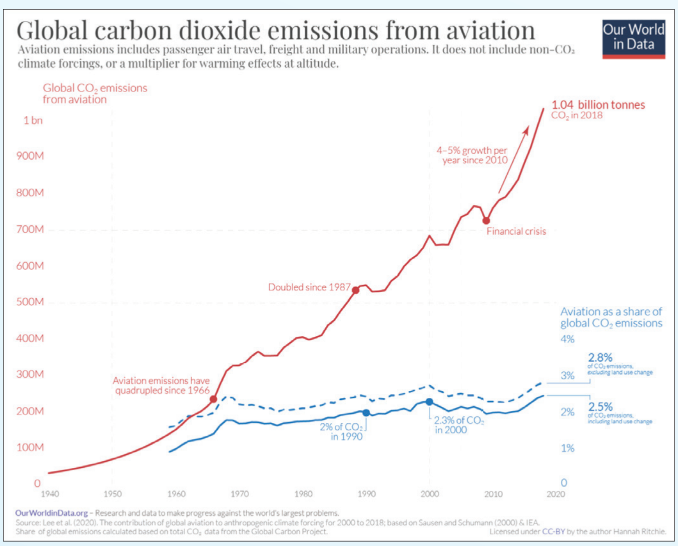
As the world accelerates toward net-zero emissions, the aviation sector faces a formidable challenge: how to decarbonise one of the hardest to abate industries without compromising its global connectivity and economic importance. Since 1990, it is estimated that the CO_2 emissions of the aviation sector have grown from 0.5% (500 MMTPA) to 2.5-3% (~900 MMTPA) of the global CO_2 emissions annually, and the emissions growth rate has surpassed other modes of transport.



This has led to growing regulatory pressures and an increase in voluntary environmental commitments from airlines across the world. In this backdrop, Sustainable Aviation Fuel (SAF) has emerged as the most promising solution to reduce the carbon footprint of aviation. Governments across the globe are now actively driving SAF adoption through mandates, incentives, and long-term decarbonization roadmaps. The European Union's ReFuelEU Aviation initiative mandates a minimum SAF blending requirement starting at 2% by 2025, scaling up to 70% by 2050. Further sub-mandate for e-SAF, i.e PtL has also been established by the EU, a blending at 0.7% in 2030 and increasing it to 35% in 2050. The United States, under the SAF Grand Challenge, aims to supply 3 billion gallons of SAF annually by 2030, with a goal of 100%. SAF by 2050. Countries like the United Kingdom, Japan etc have also outlined SAF blending targets and financial support mechanisms.

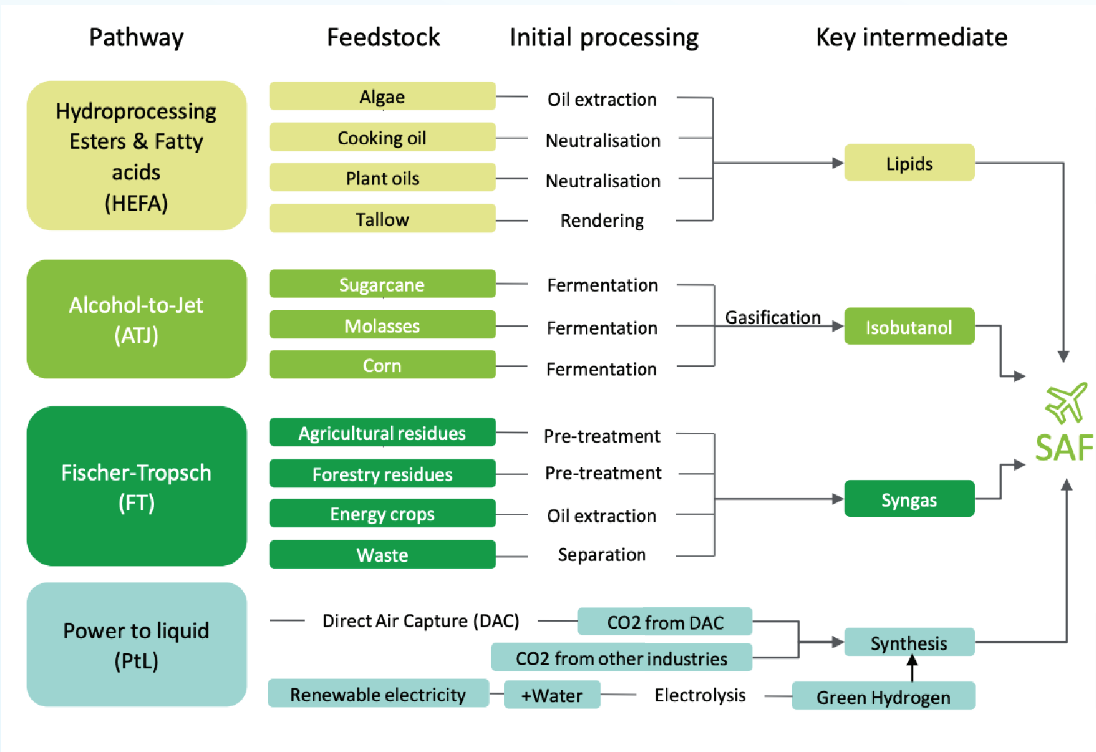
At the heart of this transition lies a critical enabler - green hydrogen. At Hygenco, our mission to revolutionise energy through clean hydrogen production places us in a unique position to contribute to the evolution and eventual scale-up of SAF.

What is Sustainable Aviation Fuel (SAF)?

SAF refers to a class of aviation fuels derived from sustainable feedstocks such as biomass, municipal solid waste, carbon dioxide, or renewable electricity. SAF can be used in existing aircraft engines and fueling infrastructure with minimal modifications. Critically, it offers a lifecycle emissions reduction of up to 80%, depending on the feedstock and production pathway.

There are 11 ASTM-approved production routes for SAF, out of which following are most important:

- **HEFA (Hydroprocessed Esters and Fatty Acids) -** Currently the most commercially used method, utilizing fats, oils, and greases.
- **Alcohol-to-Jet (AtJ) -** Producing SAF by converting bio-derived ethanol or isobutanol into jet-range hydrocarbons through dehydration, oligomerization, and hydrogenation
- **Fischer-Tropsch (FT) -** Using syngas from gasified biomass to produce hydrocarbons.
- **Power-to-Liquids (PtL) –** Converting green hydrogen and captured CO_2 into synthetic hydrocarbons via the Fischer-Tropsch or methanol synthesis routes.

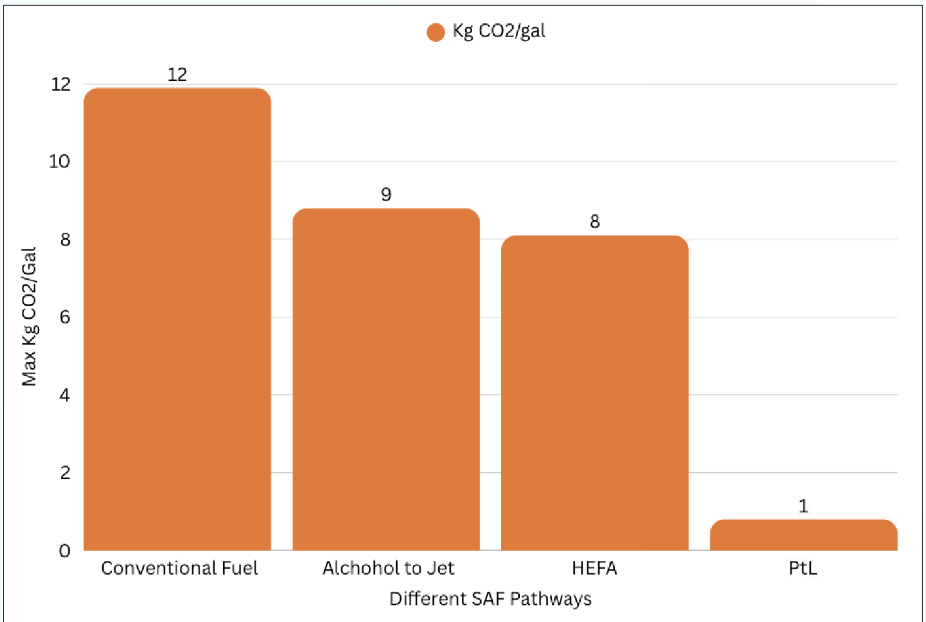


Sources: ICAO, EASA, World Economic Forum, Airbus

Some of these pathways are already established for industrial scale in a technological sense, whereas on the rest deep R&D work is underway. A detailed overview of the readiness is explained in table below:

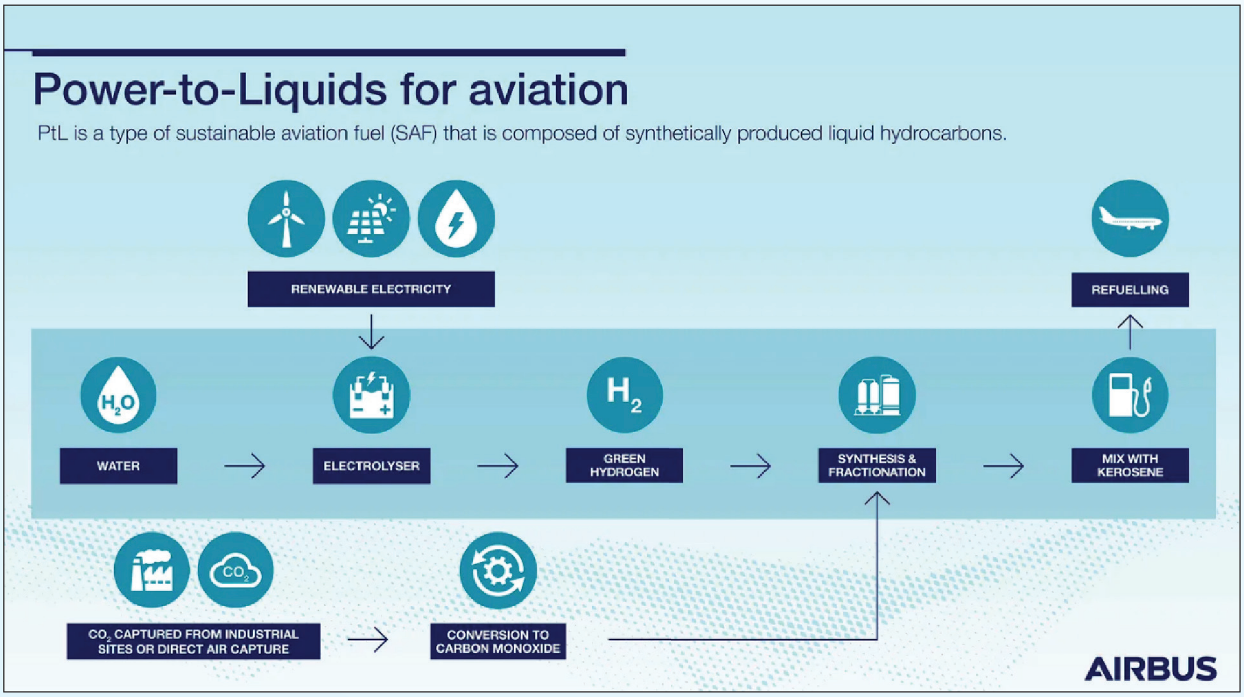
Pathway	Technology Readiness Status	Feedstocks	Challenges
HEFA	Mature	Used Cooking Oil, Oil Crops and other Fatty Waste	Feedstock Availability and Scalable Collection
Fischer Tropsch	Commercial Pilot	Biomass, Agri-waste etc	Feedstock Availability and Scalable Collection
Alchohol to Jet (AtJ)	Commercial Pilot	Corn, Sugarcane etc	Feedstock Availability
Power to Liquid (PtL)	In Development	CO2, H2	Technology is yet to Commercialize

Of these, Power-to-Liquids holds the greatest potential for scalability and climate impact, particularly in a future powered by abundant renewable electricity and green hydrogen. According to estimates PtL offers the maximum CO_2 emission reduction among other available SAF pathways as shown below:

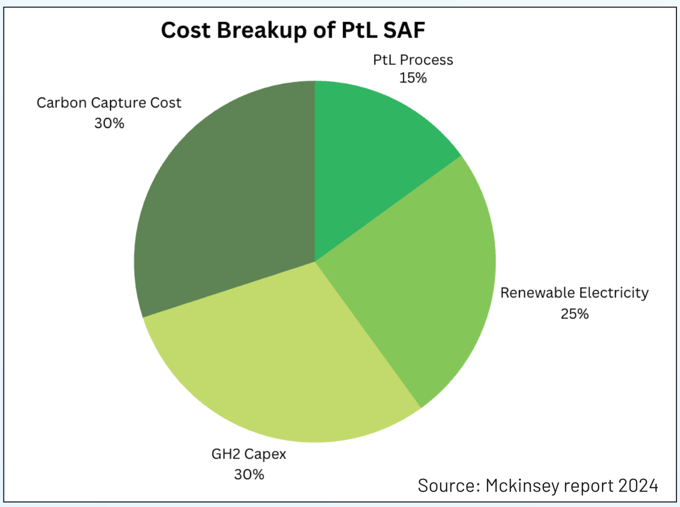


Source: https://www.twelve.co/post/what-is-power-to-liquid-saf

The PtL pathway relies heavily on green hydrogen i.e hydrogen produced via electrolysis using renewable electricity. In this process, hydrogen is combined with captured CO_2 to create synthetic liquid hydrocarbons that mimic the properties of conventional jet fuel.



However, the key bottleneck in making PtL SAF commercially viable lies in the cost and scalability of green hydrogen. The cost of production of SAF using PtL is far higher than other technologies based on HEFA and ATJ. To be precise, PtL led SAF is roughly 6 times the cost of conventional fuel whereas HEFA and AtJ based SAF is 3 to 5 times more expensive but PtL presents most potential for reduction in SAF costs with scale in production. Reducing the cost per kilogram of green hydrogen is essential to make SAF competitive and accessible to airlines and fuel suppliers using PtL. According to an estimate by Mckinsey, the fuel synthesis process using this route accounts for only 12.5% of total cost of production whereas the renewable electricity accounts for about 25%, green hydrogen production plant's capital costs about 30% and carbon capture about 15-30%.



The Emerging SAF Landscape in India

India, as one of the fastest-growing aviation markets, faces a dual imperative: support industry expansion while meeting its climate commitments. While the SAF ecosystem in India is still in its nascent stage, momentum is building due to growing international pressure (e.g., CORSIA compliance), rising jet fuel imports, and an increasing domestic push for decarbonization.

The Indian government, through the Ministry of Civil Aviation and MoPNG, has begun drafting a Sustainable Aviation Fuel Roadmap, with industry stakeholders like Indian Oil, Hindustan Petroleum, and Air India participating in feasibility pilots. Early test flights using SAF blends (typically up to 10%) have already been conducted by airlines like SpiceJet and IndiGo in collaboration with oil marketing companies. In addition, the Government of India has set the following indicative targets for SAF blending (initially only for international flights)::

- **1% SAF blending by 2027**
- **2% SAF blending by 2028**

However, the country faces significant challenges like:

- **Feedstock constraints (especially for HEFA pathways)**
- **High production costs due to lack of scale**
- **Absence of a definitive SAF blending mandate or pricing incentives, unlike in the US or EU**

To overcome these barriers, India will need to explore alternative pathways such as Power-to-Liquids (PtL) and Alcohol-to-Jet (ATJ), which leverage India's abundant renewable energy potential and growing ethanol production base. This shift opens a critical window of opportunity for green hydrogen players to enable a domestic SAF market that is both scalable and cost-competitive.

As India explores advanced SAF pathways like Power-to-Liquids (PtL) and Alcohol-to-Jet (ATJ) to circumvent feedstock bottlenecks and meet long-term decarbonization targets, green hydrogen becomes a foundational input. This is where Hygenco brings a distinctive advantage.

Hygenco, India's leading green hydrogen innovator, is already at the forefront of building commercially viable and industrial-scale hydrogen projects. Our edge lies in two core competencies:

1. **Cutting-edge R&D in process optimization & proprietary AI/ML Platform** – focused on lowering the levelized cost of green hydrogen through high-efficiency electrolyzer operations, renewable energy integration, and smart O&M strategies.

2. **Innovation-led technology development** – aimed at designing next-generation, hydrogen-enabled solutions that can be tailored for downstream applications, including SAF production pathways such as PtL and ATJ.

We at Hygenco are fully committed to decarbonising the world and are uniquely equipped–both technologically and commercially – to produce e-SAF using our green hydrogen, partnering across the value chain to build a sustainable aviation future.

By aligning with India's emerging SAF roadmap and leveraging our strengths in renewable hydrogen deployment, Hygenco is well-positioned to become a key enabler in making sustainable aviation a commercial reality, not just a policy aspiration.

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15. Noise control of Plant and effect on neighbourhood community – Approach & Discussion

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HISTORY

The present author working in present field from last 18 years with holding role in pipe, machinery noise and vibrations for Toyo Engineering India Pvt.Ltd.(hereinafter will be referred as Toyo).

Toyo is a worldwide leader in Oil & Gas along with offshore field.

ABSTRACT

In plant, due to large machinery noise is generally generated which sometimes affect the work area as well nearby community also.

Noise is generated due to rotary machinery, safety valves etc. in normal and emergency mode of operations. The plant noise control is a significant activity which regulates overall noise in plant work area as well on the plant fence.

Present paper illustrates approach for the noise control in running plant as well as designing, erecting new plant.

1. INTRODUCTION

Noise control for refinery involves creating overall noise control which includes machinery noise, work area and at the plant boundary connecting the neighbourhood community.

Present paper focuses on the overall noise control from initial planning phase till commissioning of the plant. This process is essential in understanding the impact of noise on the environment and surrounding communities in order to get safe environment and comply with regulatory standards.

Effective noise management can involve Engineering controls, such as installation of noise barriers or sound insulation, as well as operational changes like optimizing equipment usage to reduce noise levels. Regular monitoring and updating of noise maps are also crucial to access the effectiveness of mitigation measures and ensure ongoing compliance with noise regulations, ultimately aiming to minimize impacts on nearby communities.

2. ABBREVIATIONS

The standard abbreviations which will be commonly used in present paper is illustrated.

SPL Sound Pressure Level

PWL Sound Power Level

dB/dB(A) Noise level in decibels in linear or A weighted scale

Leq Equivalent continuous noise levels. The continuous sound level that over a specified time period has same energy as fluctuating sound levels that occur during that period

ISO International Standard organization which publishes international standards including those related to noise

ANSI American National Standard Institute: An organization that oversees the development of voluntary consensus standards for various sectors, including noise control

OEM Original equipment manufacturer

The understanding these abbreviations helps in interpreting noise maps and reports effectively facilitating better noise management and compliance in refinery operations.

3. CODES & STANDARDS

While conducting noise control for refineries or any type of plant, several codes and standards are commonly referenced to guide the process and ensure compliance with regulatory requirements.

Some common key standards and guidelines which are useful for noise control:

ISO 9613 provides the guideline on the calculation of outdoor noise levels from industrial areas. It includes methods for assessing sound propagation over distance and accounting for various environmental factors.

OSHA Standards The Occupational Safety and Health Administration (OSHA) has regulations regarding noise exposure limits in the workplace, which can inform mapping efforts to ensure worker safety within refinery operations.

Local regulations The individual country and state is having own regulations the specific noise requirements that dictates permissible noise levels for industrial activities including refineries.

The codes and standards have vast variety and for individual country, standard and regulation changes.

4. NOISE SOURCES AT PLANT

Refineries are complex industrial facilities that generate significant noise from various operations. Key noise sources include compressors and turbines which produce high-pitched continuous noise due to high-speed rotations and aerodynamic processes.

Pumps and motors are common contributors emitting noise from vibrations, cavitation and mechanical operations.

Heat exchangers and cooling towers generate noise from the flow of fluids and air, while boilers and furnace contribute through combustion processes and steam movement.

High pressure valves and piping systems create noise due to turbulent flow, especially during venting and blowdown.

Fans and Blowers used for ventilation or process cooling produce steady and broadband noise. The flare stack used for burning off excess gases produce loud roaring noises during flaring events.

The cumulative noise from all such sources can pose risk to worker health and affect nearby communities.

Effective noise control measures such as acoustic insulation, silencers and regular equipment maintenance are essential to mitigate these impacts.

5. NOISE OPERATION SCENARIOS

Noise in refinery operations arises from various scenarios depending on processes and equipment in use.

Routine operation such as turbine and compressor operation generate continuous noise due to high-speed rotation and aerodynamic flow. Similarly pumps and motors contribute steady noise from vibrations, cavitation and mechanical fluctuations.

Fluid flow through piping systems and valves particularly during high pressure releases create turbulent noise while scenarios like venting or blowdown can cause sudden high intensity noise.

Non-routine events such as emergency shutdowns can significantly elevate noise levels which in turn to high noise levels for shorter duration of time. These temporary scenarios often result in higher noise due to valve adjustments and process instabilities. In extreme cases, malfunctions or leaks in piping and valves can create unexpected loud noise posing risk to personal nearby communities.

Addressing these noise scenarios requires action from initial planning / engineering phase and careful noise estimation is required. This will be helpful to implement operational practices to ensure worker safety and compliance with noise regulations.

6. NOISE CONYTROL ACTIVITIES IN PLANT

Noise control in refineries is essential to protect workers, meet regulatory requirements and minimize impact on nearby communities.

Effective noise control activities focus on identifying sources, mitigating emissions and managing exposure.

Engineering control of noise starts from basic engineering phase and supports till performance guarantee test during final commissioning phase.

Generally, in refinery type of big engineering projects, lot of OEM's are involved for the manufacturing of big and small type of machineries so establishment of common noise guideline is important and implementation of the same is also necessary.

The noise guideline shall include clear ideology for equipment noise, work area and noise for the plant boundary.

The exposure time along with permissible limit at the plant boundary is also essential.

The acoustic insulation for equipment and piping is essential and proper calculation basis shall be established for the same.

Generally during engineering phase, noise data shall be requested to OEM in order to form clear idea for the noise propagation.

Machinery noise of 85dB(A) is generally established value but in some countries work area is expected to be maintained at 81dB(A) so in such situation the machinery noise (irrespective of sizes) shall also be maintained near to 80 dB(A) or below in terms of SPL level.

The Silencers along with enclosures, barriers are necessary to restrict the noise propagation if it is exceeding permissible limits. Process modifications also plays a role to reduce the turbulence in pipes and in situation inside machinery also.

Administrative controls help manage worker exposure.

Refer Table 1 showing OSHA standard exposure limits for worker is exposing to noise.

Table 1: OSHA Standard Noise exposure limits

Maximum Allowable Duration per Day (Hours)	Noise Level (Slow Response) in dBA
8	90
6	92
4	95
3	97
2	100
1	105
0.5	110
0.25 or Less	115

Scheduling noisy activities for non-peak hours and creating designated quiet zones within the refinery are very effective strategies.

Monitoring noise levels through regular sound surveys ensure compliance with norms established by local regulatory authorities.

All the measures of noise control inside the plant creates safe working environment while reducing the overall noise impact of refinery operations.

a. Acoustic insulation and noise reduction

Acoustic insulation in plants is critical to mitigate noise exceeding permissible limits and comply with regulatory standards.

Effective acoustic insulation reduces noise transmission, minimizes its impact on personnel and enhances operational safety.

Key applications of acoustic insulation in refinery or any other type of plant includes:

a) Piping Systems: insulating pipes carrying fluids or steam for which noise is transmitted outside pipe.

The noise inside the pipe is caused by flow turbulence, vibration so in such situation noise radiated outside the pipe shall be controlled. **Refer Fig.1** for general composition of Acoustic insulation

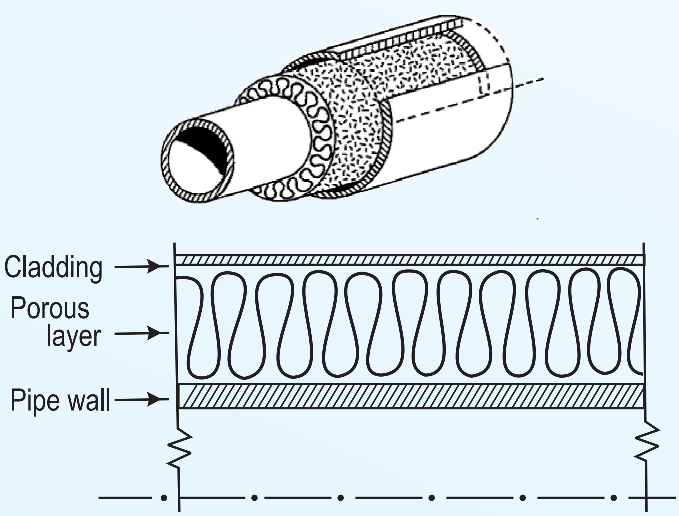


Fig.1. Acoustic insulation – general arrangement

(Fig.courtsey NWG5. Refer Section 11 References)

The porous layer along with cladding is useful for absorption of noise.

b) Equipment casings: Compressor, pump and turbines can be enclosed in acoustic enclosure or lagged with sound dampening materials.

For enclosed casing, heat load calculation plays an important role which avoid further tripping of machine.

The different acoustic insulation materials are available in market which can reduce the noise up to expected level like some customized material can reduce noise till 20dB or more in some applications.

The acoustic wall useful in some cases where noise machinery is near the plant boundary and in such situation acoustic barrier shall be used to avoid noise propagation outside the fence.

The benefit of acoustic insulation mainly lies with health, safety, operational efficiency of worker and meeting the compliance with noise regulations.

In some situation, community is very nearby to working plants so in such situation, community health is also taken care due to noise barrier.

7. FAILURE DUE TO HIGH ACOUSTIC ENERGIES

The high acoustic energies can lead to failure which is termed as Acoustic induced vibration (AIV) which is a critical issue. This occurs when high energy acoustic eaves, generated by the rapid release of pressurized gases or fluids through control valves, relief systems or piping excite and amplify vibrations in nearby structures.

These vibrations can lead to material fatigue, cracking and catastrophic failure of piping and equipment if not adequately addressed.

In refinery operations, high acoustic energy or waves are common produced in system handling high pressure gases such as steam, hydrogen or natural gas. Point to be noted that acoustic energies are in PWL form only while machinery noise is in SPL form.

When these gases expand rapidly through

relief or control valves, they generate intense sound waves at frequencies that can resonate with natural frequencies of surrounding piping or equipment. This resonance amplifies in vibrations creating significant dynamic amplification.

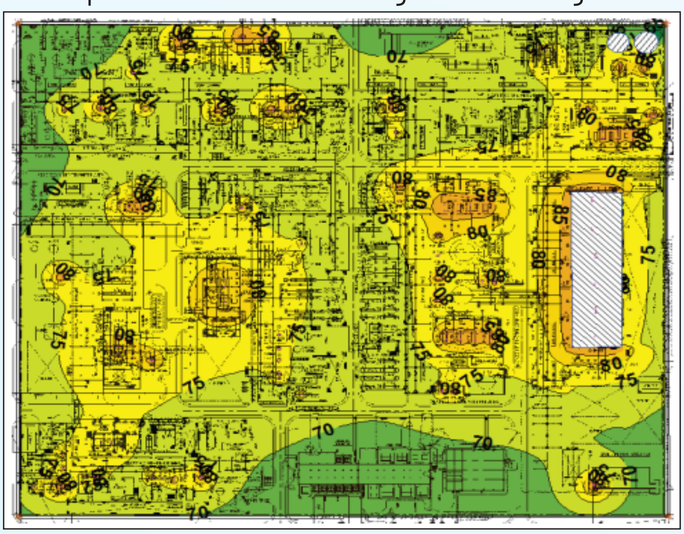
8. NOISE MAPPING

Noise mapping in refineries is a critical process used to assess, visualize and manage noise levels within the facility.

Refineries often operate large equipment's like compressor, pumps, turbines, flares etc. which can generate significant noise. Prolonged exposure to high levels can pose risks to worker's health, impact equipment performance and even lead to regulatory violations. Refer Fig.2 providing sample noise map of complete plant indicating sound propagation.

Fig.2 Sample Noise mapping plot

Noise mapping helps to identify high noise areas assess compliance with standards and implement effective mitigation strategies.



During planning phases, noise data can be predicted using some standard calculations and based on experience of make, type of machinery, driver details, kw rating of machine etc. noise can be predicted. Generally, every big machine shall be maintained with driver and auxiliary shall not exceed 85dB(A) at 1 meter distance.

In running plants, we need to measure noise levels using sound level meter shall be used. The noise data shall be collected at several locations. The recorded noise frequency spectrum, duration and peak noise levels are useful to identify machinery issue.

The acoustic simulation software shall be used to model noise sources, propagation paths and attenuation effects. This mapping identifies zones exceeding permissible noise limits (e.g., 85dB for 8 hours exposure as per OSHA guidelines).

The worker safety is a crucial aspect which can be saved by noise mapping studies. The hazardous zones shall be marked where hearing protection is essential.

The adherence to environmental noise and work area noise can also be maintained.

By integrating noise mapping into plant operations, facilities can reduce noise related risk and foster a safer and more compliant work environment.

9. COMPARISON OF NOISE MAPPING AND ACTUAL PLANT

The noise mapping study implies the predicted noise levels or the levels at the actual plant in propagating phase in nearby area (from source) while at actual plant operation, the noise level vary with respect to many variable parameters.

At actual plant operation, background noise plays a crucial role while estimating noise level from any source. It is continuous and ambient noise generated by various operational equipment and processes in the facility. Background noise is an important factor to consider for worker safety, communication and equipment performance.

The various sources contribute in background noise is rotating equipment, fluid flow, steam systems and other maintenance activities in the plant.

Background noise is usually steady with periodic peaks during specific operations such as venting or start-up / shut down activities.

When a noise propagates outdoors, the sound pressure level is seriously affected by meteorological, topographical and ground-surface conditions. As the influential conditions in the field measurement, therefore, such meteorological conditions as direction and speed of wind, temperature and relative humidity, topographical and ground surface conditions etc. shall be recorded as precisely as possible along with the weather condition.

10. CONCLUSION

The present paper describes the approach and importance of noise control in any type of plant.

Noise control is very critical aspect of operational safety and efficiency.

The noise control of individual machine, work area and at the plant fence is main concern while implementing noise control.

The health, safety and reduction in noise pollution will be helpful to monitor a safe and compliant refinery environment.

11. REFERENCES

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DISCLAIMER AND NOTES

1) **Fig 1** Sample noise mapping plot is Toyo’s technical property and no further copy for any use is allowed.
2) Present paper is based on experience and only approach for noise control is mentioned.

So present paper shall be considered as experience sharing of Author.

16. Most optimal pathways for SAF production

Mr. Raju Chopra currently working as Head-Technical Sales & Services in TOPSOE, His area of Interest is Advancing technology & catalyst solutions and services for the refinery and chemical industries, Driving innovation in decarbonization & sustainable energy solutions and Developing and implementing green fuels production technologies. He Led and contributed to major national and international projects, delivering significant technical and commercial value. He Held diverse leadership roles across technical, sales, business development, and managerial domains in the refinery and chemical sectors.

Abstract

Choosing the right technology is essential for unlocking value and decreasing the cost of production while offering high flexibility and reliability. Topsoe spends 8-9% of their revenue annually in R&D which enables us to offer most innovative processes, catalysts and high-performance proprietary hardware to our customers. Topsoe is in a unique position to provide highly energy efficient solutions to produce SAF with minimal carbon intensity.

HydroFlex™

Process feedstock such as virgin oils, waste oils and fats to produce HEFA-based Sustainable Aviation Fuel. The market-leading HydroFlex™ technology is designed to produce SAF with minimal Carbon Intensity (CI) compared to traditional fossil aviation fuel. Innovations in grading, HDO, dewaxing and hydrocracking catalysts allows to maximize the SAF yields and offer high flexibility during the entire cycle length. Special gradings allows to run feeds with high contaminants, HDO catalysts reduces the production of heavy ends during end of run, noble metal based highly selective dewax and hydrocracking catalyst offers low gas and naphtha production. Topsoe's HydroFlex™ solutions for renewable fuel production have been in operation for several years in 22+ units globally.

G2L™ Biofuels

This pathway allows the production of sustainable aviation fuels using commercially proven technology with natural and synthetic gas-based feedstocks. Utilizing synthesis gas (CO+H2) produced through biomass gasification or Topsoe reforming combined with Topsoe hydroprocessing technologies and Sasol's LTFT™ (low temperature Fischer-Tropsch) technology to produce ASTM approved Fischer-Tropsch synthetic paraffinic kerosene (FT-SPK). Highly selective cobalt based FT catalyst along with noble metal based dewaxing and hydrocracking catalyst allow to achieve as high as 80 wt% SAF yield from Fischer Tropsch wax.

G2L™ eFuels

Create eFuels from renewable energy via green hydrogen, and from CO_2 via carbon capture. By combining synthesis gas, Fischer-Tropsch and hydroprocessing technologies, the G2L™ eFuels solution efficiently produces FT-SPK/eJet and green naphtha. The process is built around our already proven solutions, integrating Topsoe's newly developed technologies like fully electrified eREACTTM.

One of the major advantages of FT with eREACTTM lies in its flexibility to recycle unused hydrocarbons. In a once through system, lighter products such as naphtha are typically removed and sold separately – reducing overall kerosene yield and potentially complicating offtake strategies. The recycle loop not only increases kerosene yield to 100% of product output, while maintaining a higher than 95% CO_2 efficiency but also significantly reduces hydrogen and electricity demand. Topsoe continues to assist their customers worldwide in solving their sustainability challenges through their innovative solutions using their versatile process design, in-depth knowledge on catalysis and high numbers of commercial references.

1. Introduction

Currently, aviation contributes approximately 1 billion tons of CO_2 annually, accounting for over 2% of global emissions1. Achieving net-zero emissions while meeting the growing demand for air travel necessitates a multifaceted approach, with Sustainable Aviation Fuels (SAF) playing a pivotal role. According to IATA, to achieve net zero by 2050 in the aviation sector, SAF will contribute 65% share towards reduction in emissions needed by aviation to reach net-zero in 20502 (Refer Figure-1).

SAF production increased to 600 million liters (~0.47 million tons) in 2023 and is estimated to reach 1,900 million liters (~1.5 million tons) in 2024 globally. Most of the existing facilities today are based on the HEFA technology pathway. India's aviation industry has experienced significant growth in the past 10 years.

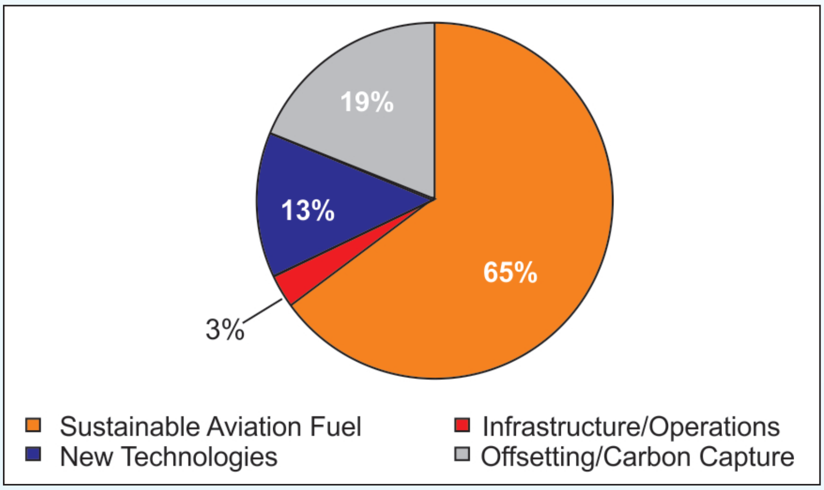

Fig. -1: Various contributors to achieve net zero by 2050 in the aviation sector

2. Background and Context

The global aviation sector has seen a steady increase in fuel demand, driven by rising passenger numbers and expanding air cargo operations. The projections indicate a strong continued growth. SAF Market has undergone significant changes over last 4-5 years and several notable capacity SAF capacity additions have taken place, now more than 20 companies are capable to produce SAF either via standalone or standalone facilities. The domestic air passengers in India have more than doubled in the past decade, with Indian airlines significantly expanding their fleets. On the other hand, the number of operational airports in the country has doubled from 74 in 2014 to 157 in 2024 and the aim is to increase this number to 350-400 by 2047.

Indian Government has made strong commitments to reduce the total projected carbon emissions by one billion tons from now onwards till 2030 and reducing the carbon intensity of its economy by less than 45% by 2030. The end goal of this policy is to achieve a Net Zero target by 2070. India aspires to achieve 1% SAF by 2027 and 5% SAF by 2030.

3. Overview of SAF Technologies

SAF encompasses a range of technologies designed to produce aviation fuel from renewable sources. Key types include:

- HEFA : Hydrotreated esters and fatty acids derived from oils and/or fats.

- FT-SPK : Produced via Fischer-Tropsch synthesis, using gasified biomass or CO_2 and H_2.

- ATJ : Converts alcohols like ethanol into jet fuel or methanol to jet

Each technology has unique advantages and offers varying degrees of GHG emission savings as illustrated in the Figure-2 below (typical GHG emission savings are shown in parenthesis, bottom part). The green boxes illustrate processes offered by Topsoe and/or partners of Topsoe.

Whereas the e-Fuel based solutions to the right offer the largest GHG emission reduction potential, these technologies are relatively high capex due to inclusion of electrolyzer and its associated facilities.

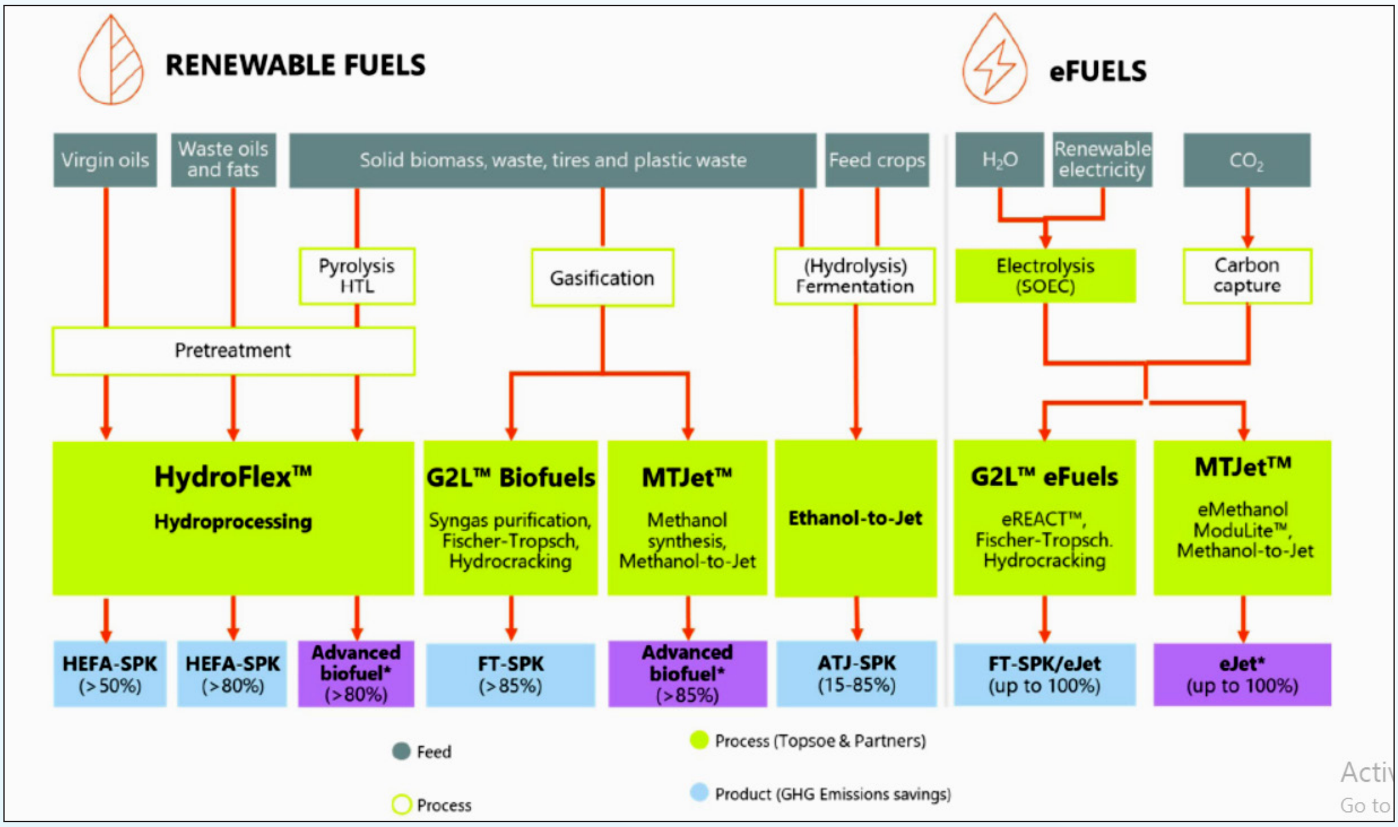

Fig. -2: Overview of Topsoe SAF solutions (*: not approved SAF pathways yet)

4. Technology solutions by Topsoe and Partners

Topsoe has developed several cutting-edge technologies to produce SAF efficiently and sustainably, either alone or together with partners, such as Sasol:

HydroFlex™: This process converts a wide range of feedstocks, including virgin oils, waste oils, and fats into HEFA-based SAF. HydroFlex™ is designed to minimize carbon intensity, making it a market leader in sustainable fuel production. Innovations in grading, HDO, dewaxing and hydrocracking catalysts allows to maximize the SAF yields and offer high flexibility during the entire cycle length. HEFA pathway is the cheapest to produce SAF.

Co-processing is a low hanging fruit where even small amounts of fossil feedstock, such as crude oil, can be replaced with renewable feedstock, such as vegetable oil, animal fat, and used cooking oil (UCO). These are processed together in the hydrotreater (Refer Figure-3). Kerosene hydrotreater emerges as the most preferred choice. With the right catalysts, this unit can maximize the conversion of biogenic carbon into the jet fuel fraction, thereby optimizing SAF production. Low-pressure reactor operation makes co-processing in the kerosene hydrotreater option unique with respect to the high recovery of biogenic carbon. Co-processing is a fast track to SAF production that can function as a short-term solution to comply with the upcoming SAF mandates in the next few years. To meet the cold flow properties requirements of Jet A and Jet A1 fuels, deep dewaxing of these biogenic paraffins is essential. This process is made possible by Topsoe's highly selective dewaxing catalyst, TK-930 D-wax, which effectively facilitates the necessary deep dewaxing and, at the same time, retains the biogenic carbon in the jet fuel product. TK-930 D-wax catalyst allows to achieve more than 80% recovery of biogenic carbon in jet fuel product.

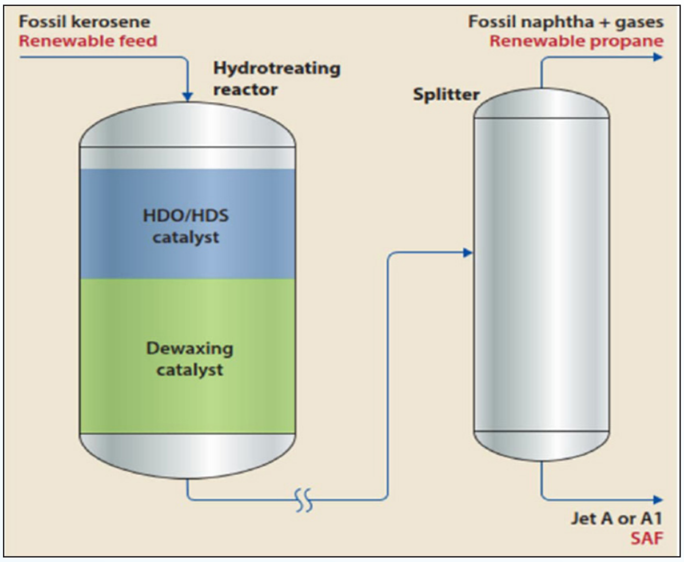

Fig. -3: Simplified loading to produce SAF by co-processing

G2L™: Fischer-Tropsch with Combustion RWGS (Reverse Water-Gas Shift)

Process convert CO_2 and hydrogen into synthetic hydrocarbons. Fischer-Tropsch (FT) processes first create syngas, a mixture of CO and H_2, which is then converted into hydrocarbons. In the FT-Combustion pathway a traditional tubular reformer or autothermal reformer is required to convert H_2 and CO_2 to synthesis gas ($CO + H_2$) for the Fischer-Tropsch reaction. The heat of reaction must be supplied through combustion of methane (converted from CO_2 and H_2) or by burning pure H2 (directly or indirectly) – a high energy and cost penalty solution.

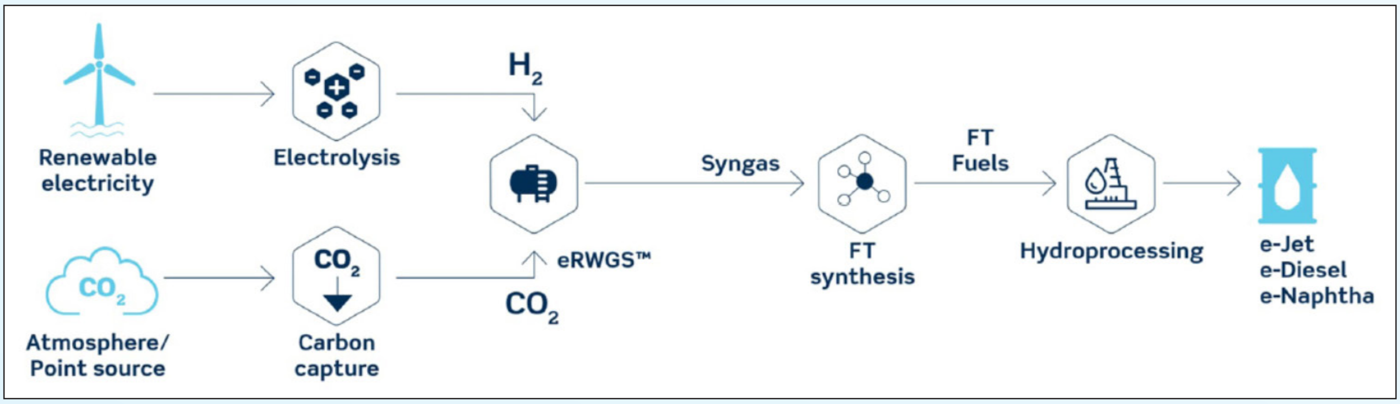

Fig. -4: Simplified flowsheet to produce FT-SPK with eREACT™ technology

G2L™ eFuels: Fischer-Tropsch with eREACT™ (electrified RWGS)

Combining renewable energy, green hydrogen, and CO2, this technology produces FT-SPK/eJet and green naphtha. The integration of Topsoe synthesis gas and hydroprocessing technologies with Sasol's LTFT™ technology ensures high efficiency and a low carbon footprint (Refer Figure-4). By contrast, eREACT™ replaces combustion with electric heating, improving hydrogen and electricity efficiency.

Unlocking efficiency with recycle and integration

One of the major advantages of FT with eREACT™ lies in its flexibility to recycle unused hydrocarbons. In a once-through system, lighter products such as naphtha are typically removed and sold separately – reducing overall kerosene yield and potentially complicating offtake strategies. With the G2L™ e-fuels approach - a fully integrated process where the Topsoe technologies are fully integrated with Sasol LTFT® technology - these light ends can be redirected into the front of the process, converted again alongside fresh CO_2 and hydrogen (Refer Figure-5). This recycling loop not only increases kerosene yield to 100% of product output, while maintaining a higher than 95% CO_2 efficiency but also significantly reduces hydrogen and electricity demand

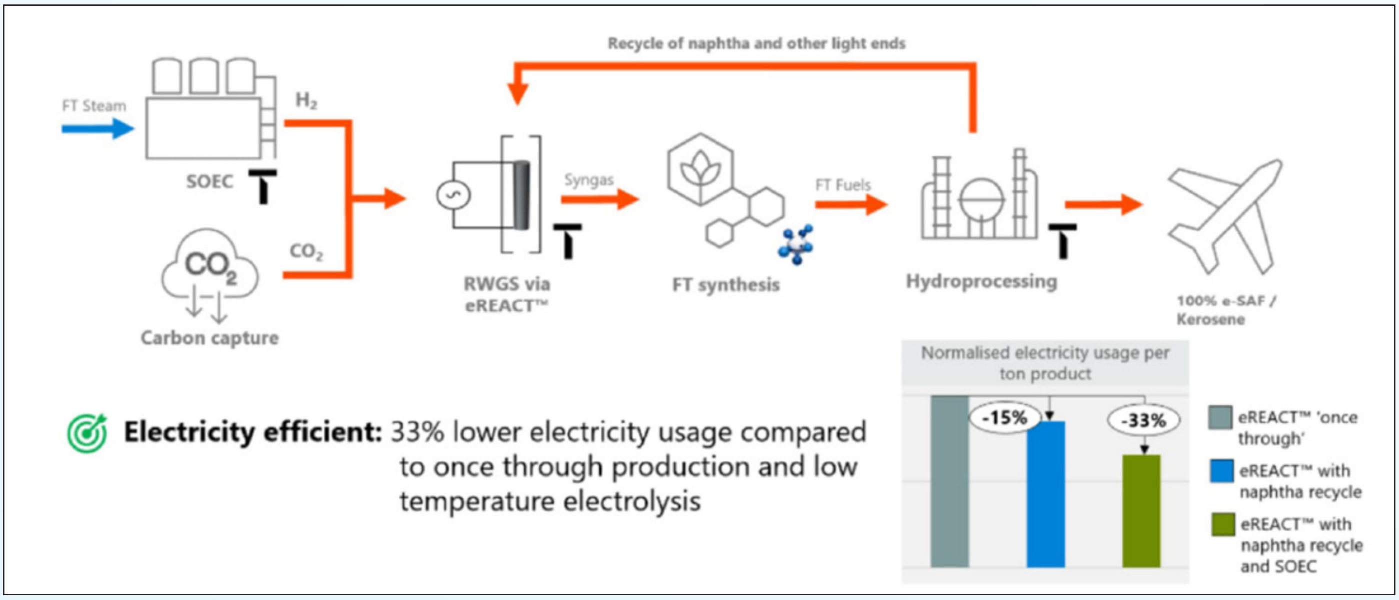

Fig. -5: Simplified flowsheet to produce FT-SPK with eREACT™ technology with recycle streams

For today's eSAF projects, the most cost-effective and efficient route is a fully integrated G2L™ eFuels solution including Fischer-Tropsch system with eREACT™, naphtha recycle and Solid Oxide Electrolysis Cell (SOEC) based hydrogen production. It not only addresses the thermodynamic and economic challenges of reverse combustion but sets a benchmark for how thoughtful technology choice can unlock real project value. SOEC is high temperature electrolyzer developed by Topsoe which is 30-35% more efficient as compared to conventional Alkaline or PEM electrolyzer.

ATJetTM Pathway: Topsoe is developing an ATJ pathway using ethanol as a feedstock for SAF production, expanding the range of renewable sources for aviation fuel.

The process involves Dehydration, oligomerization and hydrogenation steps and target to achieve maximum SAF yield at lower capex (Refer Figure-6). Integration with eREACTTM allows to recycle low value light hydrocarbons for H_2 production minimizing carbon intensity and maximizing credit generation. Presently this technology is under advanced stage of development and expected to be available soon for commercial use.

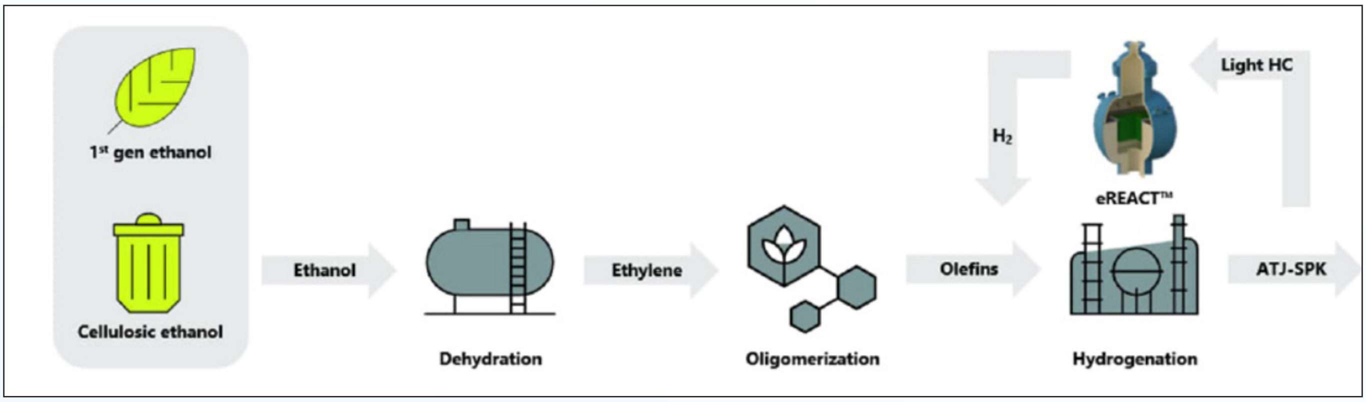

Fig. -6: Simplified flowsheet of ATJetTM to produce SAF from ethanol

5. Actual projects and references

Topsoe's **HydroFlex™** solutions provide full feedstock flexibility, and it is now possible for our customers to produce clean fuels from a wide range of feeds, such as plant and vegetable oils, waste from the paper industry, "black liquor", animal fat, pyrolysis oils, and extracts derived from wood chips, plastics, and coal. These feedstocks can be converted to transportation fuels, either in stand-alone plants or by co-processing with fossil refinery feedstocks.

Topsoe's HydroFlex™ solutions for renewable fuel production have been in operation for several years in 22+ units, primarily in Europe and North America. The first licensed unit treating renewable feed was started up in 2011 and has been operating successfully for more than a decade, showcasing the scalability and reliability of Topsoe's solutions.

Topsoe's and Sasol's **Gas-to-liquid (G2LTM)** technologies have been successfully implemented in various projects worldwide. Sasol is pioneer in synthetic fuels production using gas to liquid, coal to liquid and related technologies with over 70 years' experience.

Following plants are in commercial operation and running satisfactorily since past many years:

- 2 x 17,000 BPSD Escravos, Nigeria
- 2 x 18,500 BPSD Uzbekneftegas, Uzbekistan
- 2 x 2,500 BPSD Sasolburg Eq., South Africa
- 2 x 17,000 BPSD Oryx GTL, Qatar

e-SAF project is the Arcadia e-SAF project in Denmark, for which Topsoe and SASOL were selected as technology providers for an eFuel plant, which will be the world's first power-to-X plant on a large scale to produce jet fuel. The plant is intended to produce approx. 100 million litres of eJet annually and once operational, the plant will deliver eFuel for the Danish and European aviation markets to help meet the European Union mandate of 1.2% RFNBO (Renewable Fuels of non-Biological Origin) or eFuels in 2030.

Currently project is final investment decision (FID) stage.

Topsoe and Sasol have been selected to deliver technologies for German Aerospace Centre's (DLR) SAF production demonstration plant of 2,500 Tons per annum capacity in Q4 2024. Sasol and Topsoe will deliver their G2L™ eFuels technology, integrating Topsoe's innovative eREACTTM technology and hydroprocessing technology with Sasol's low-temperature Fischer Tropsch (LTFT™) technology.

Topsoe and Sasol have been selected by UK based company to deliver technologies for BioSAF production from syngas derived from biomass. Sasol and Topsoe will deliver their G2L™ technology, integrating Topsoe's hydroprocessing technology with Sasol's low-temperature Fischer Tropsch (LTFT™) technology. Plant capacity is 4,000 BPSD and project is expected to obtain FID by end of 2026.

6. Challenges

Presently, the main challenges for the aviation sector are to produce SAF and especially eJet at an industrial scale and competitive production cost. Achieving this goal takes solving several challenges: from certifications, to establishing consistent access to captured CO_2 and green hydrogen from renewable power. Equally important, it requires investment in and integration of new technologies.

When looking at the Levelized cost of producing SAF (LCOSAF), it can be seen from below graph (Refer Figure-7) that all pathways have a LCOSAF well above fossil jet, with the HEFA route being the least expensive and the synthetic fuel-based options being the most expensive, having a LCOSAF at least 3-4 times higher than that of fossil jet.

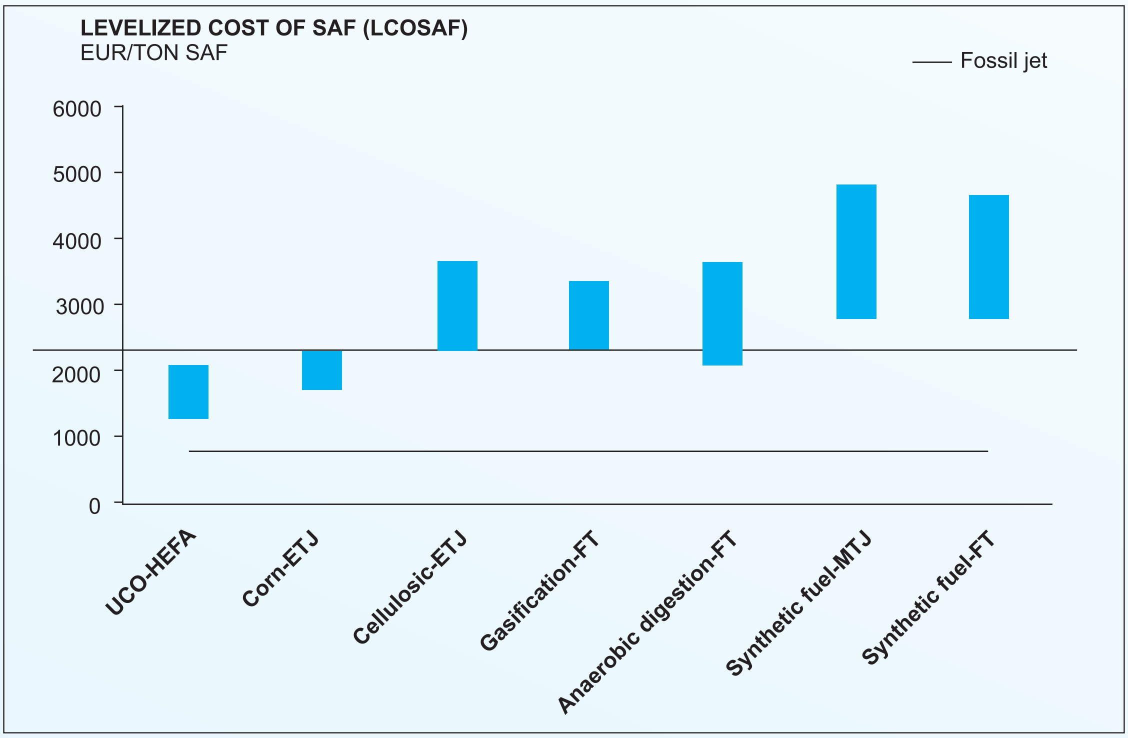

Fig. -7: Levelized cost of producing SAF (LCOSAF) for various pathways

Despite the economic benefits of the HEFA route compared to the alternatives, there are also some challenges, among others feedstock availability. Fatty acid-based feedstocks such as virgin oils, animal fats, and used cooking oils (UCO) are currently used. These are excellent feedstocks from a technical point of view, but they have limited availability. Virgin oils are preferably used for food and feed purposes (currently 15 to 20% of their production is used for biofuels)3 and while edible oils can be used for SAF production, ReFuelEU Aviation, encourages the use of waste and residue feedstocks, such as used cooking oil, to avoid competition with food crops and reduce the environmental impact. However, the most common alternatives, UCO and animal fats have limited amounts (around 40 million metric tons of waste and residue lipids)4. Therefore, the use of solid waste such as agricultural residue, forestry residue, organic fraction of municipal solid waste, or sewage sludge is a natural next step choice, which is currently being explored. In an Indian perspective it is worth mentioning that several programs for developing cultivation of alternative crops such as pongamia are ongoing, but presently the potential remains unclear.

Topsoe addresses the feedstock challenges through continuous innovation, strategic partnerships, and a commitment to excellence in process design and catalysis, positioning Topsoe as a leader in the transition to a decarbonized aviation industry.

7. Conclusion

Topsoe's HydroFlex™, G2L™ are commercially proven technologies and offer significant advantages in the decarbonization of the energy industry. By providing versatile, efficient, and high-performance solutions, Topsoe enables the production of renewable fuels and sustainable aviation fuels with a low carbon footprint.

HEFA route is the cheapest route to produce SAF and SAF production through co-processing is the most economical and fast-track pathway. Most of the SAF produced globally is through HEFA pathway utilizing feedstock such as virgin oils, waste oils and fats.

ATJetTM technology is under advanced stage of development and shall be available for commercialization soon.

ATJetTM is integrated end to end solution and is powered by HydroFlexTM technology.

For today's eSAF projects, the most cost-effective and efficient route is a fully integrated G2L™ eFuels solution including Fischer-Tropsch system with eREACT™, naphtha recycle and SOEC-based hydrogen production. It not only addresses the thermodynamic and economic challenges of reverse combustion but sets a benchmark forhow thoughtful technology choice can unlock real project value.

Despite the challenges encountered in the green transition, including feedstock availability and a reduction of the production costs of SAF and eJet, Topsoe is in a unique position to address these challenges and will through continuous innovation, technical expertise, and comprehensive support, help the energy industry achieve its decarbonization goals and contribute to transition into a more sustainable future.

References

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पेट्रोलियम एवं प्राकृतिक गैस मंत्रालय
Ministry of Petroleum and Natural Gas
Government of India