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Review

An Overview of the Hydrocarbon Sector in India for Carbon Capture Scope

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Abstract

The hydrocarbon sector in India plays a pivotal role in the country's energy landscape, encompassing exploration, production, refining, and distribution activities. This abstract provides a concise overview of the sector's current status, challenges, and prospects. India's hydrocarbon reserves range from conventional to unconventional sources, with significant potential yet to be tapped. However, the sector faces challenges such as declining production from mature fields, technological limitations in exploration and production, and regulatory hurdles in land acquisition and environmental clearances. Strategic partnerships with international oil companies and technological advancements have enhanced the efficiency and sustainability of hydrocarbon operations in India. The refining segment of the hydrocarbon sector is a significant contributor to India's economy. These refineries cater to both domestic demand and export markets, employing advanced processes to produce high-quality petroleum products. Regarding distribution, India has a vast network of pipelines, storage facilities, and retail outlets to ensure the efficient supply of hydrocarbon products to consumers. The sector is also transitioning towards cleaner fuels and renewable energy sources, driven by environmental concerns and global commitments to reduce carbon emissions. By leveraging technology, fostering innovation, and adopting sustainable practices, India can strengthen its position as a key player in the global hydrocarbon market. Vipin et al. 2024 concluded in their study that carbon dioxide emissions from the mining and mineral processing industries can be used for beneficial purposes. This opens the door for further research in other sectors also i.e. hydrocarbon, which has ample opportunity and scope to cater to similar situations. Experimental work has been discussed in this technical paper, which was conducted for the carbonation of process liquor for converting CO_2 into Na_2CO_3 and its further usage for leaching reagents in the industry.

Keywords

Hydrocarbon; carbon capture; innovation; refining; distribution; India; flue gas

1. Indian Hydrocarbon Sector Overview

The hydrocarbon sector stands as a cornerstone of India's energy framework, serving as a vital engine of economic growth and development. Comprising a complex network of exploration, production, refining, and distribution activities, this sector is fundamental in meeting the nation's burgeoning energy demands. India's hydrocarbon reserves, ranging from conventional to unconventional sources, offer immense potential for sustained development and expansion. Improved Petroleum Extraction is one of the principal industrial benefits of Carbon Capture, Utilization, and Storage (CCUS) [1]. The contrast in aqueous and gaseous densities will engender a sweeping mechanism wherein aqueous content tends to sweep hydrocarbons downward while gas tends to displace the hydrocarbons upward [2]. Aladasani et al., 2012 [3] developed methodologies for screening miscible Carbon Dioxide (CO_2) for Enhanced Petroleum Recovery (EPR) applications by furnishing intricate distributions and correlations of reservoir properties documented in miscible CO_2 projects, alongside a prognostication model for miscible CO_2 recovery. Andrei et al., 2010 [4] assessed EPR-CO_2 extension to alternative petroleum fields and its impact on petroleum extraction and project economics. Petroleum extracted via CO_2-EPR boasts an emissions factor of 438 kg CO_2 e/bbl, lower than traditional petroleum (500 kg CO_2 e/bbl) [5]. Findings demonstrate that petroleum extracted from CO_2 EPR is a low-carbon energy source, with an emissions factor lower than prevailing U.S. domestic crude oil or any alternative petroleum origin [6]. Based on approximations, 7.59 kg CO_2 can be converted into 1 kg acetate, which can be utilized to cultivate heterotrophically 1.11 kg dry algae; an overall yield of 0.03 kg bio-oil produced per kg CO_2 captured was evaluated [7]. The investigation underscored pivotal facets of CO_2 assimilation and represents a progressive stride toward utilizing nanofluid with the substantial potential for augmented CO_2 miscible petroleum recovery [8]. Administering H_2 (in limited quantity) facilitated CO_2 retention in hydrates under Indian offshore conditions [9]. A response-surface-centric economic model has been formulated to compute the profitability of CO_2-EPR for the FWU site with prevailing petroleum prices, indicating that roughly 31% of the 1000 realizations can yield profit [10]. Electrochemical synthesis must achieve at least 60% efficiency in electrical-to-chemical conversion and renewable electricity costs must plummet below 4 cents per kilowatt-hour to rival feedstocks derived from fossil fuels [11]. CO_2 enhances petroleum recovery by dissolving in, swelling, and reducing petroleum viscosity.

Hydrocarbon gases (e.g., natural and flue gas) are employed for miscible petroleum displacement in select large reservoirs [12]. Research scrutinizes asphaltene destabilization in crude petroleum during CO_2 infusion across varying pore dimensions, and aligns the findings with the tenets of the Yen–Mullins model for asphaltene behavior [13]. Farajzadeh et al., 2022 [14] deduced that polymer injection into reservoirs with elevated water content can present a resolution to two significant challenges of the transitional phase: (1) satisfying global energy requisites via amplified petroleum recovery and (2) mitigating the CO_2 footprint of petroleum extraction (increased and cleaner petroleum). CO_2-EPR currently stands under scrutiny as an ultimate long-term geologic storage solution for CO_2 due to its economic viability from incremental petroleum production counterbalancing the expense of carbon sequestration [15]. These selected studies offer a comprehensive overview of the petroleum sector in India, covering various dimensions such as policy, technology, sustainability, investment, and pricing. They contribute valuable insights to the existing body of literature and serve as essential references for researchers, policymakers, and industry practitioners seeking to understand and address the challenges and opportunities in India's hydrocarbon sector. Figure 1 provides an overview of the hydrocarbon sector in India [16]. It represents India's refining capacity as 249 MMTPA (million metric tons per annum).

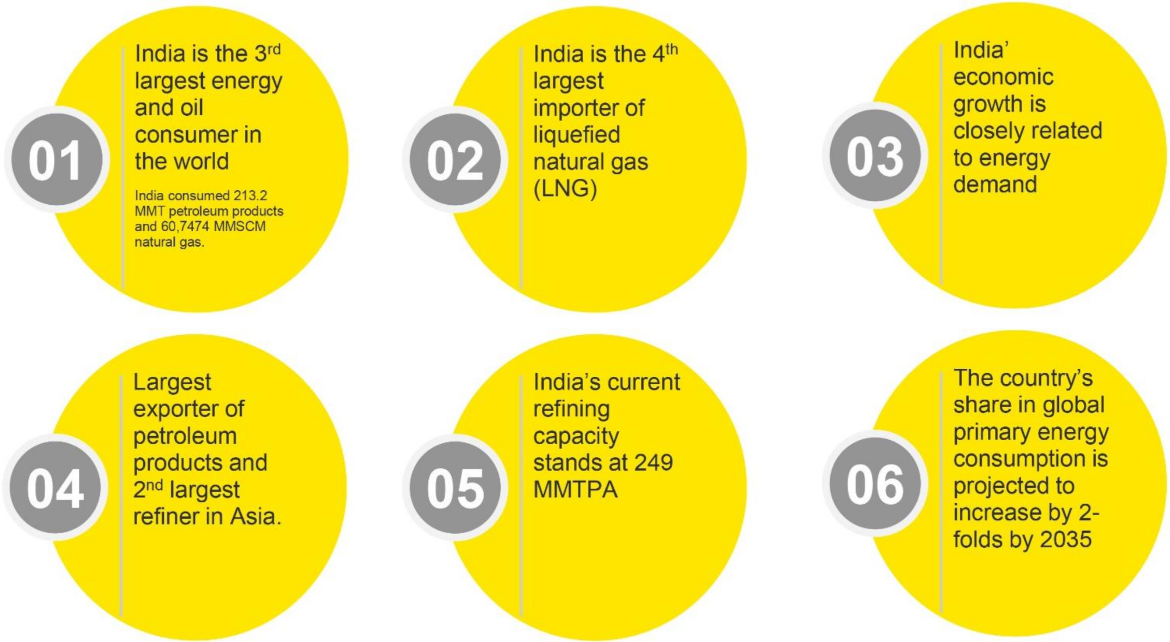

Figure 1 Hydrocarbon sector overview in India.

2. Introduction

India's hydrocarbon sector is a major contributor to CO_2 emissions, with oil and gas operations emitting over 250 million tonnes of CO_2 annually. As India aims for net zero by 2070, carbon capture is critical to decarbonizing hard-to-abate sectors. The country's energy demand is projected to rise by 35% by 2030, increasing fossil fuel reliance despite renewable growth. Moreover, with enhanced oil recovery (EOR) potential exceeding 400 million barrels, carbon capture can boost domestic production while mitigating emissions. Scaling CCUS (Carbon Capture, Utilization, and Storage) now aligns with India's climate commitments, energy security goals, and industrial competitiveness in a carbon-conscious global economy. The primary objective of crude oil processing on a scale is to transform raw crude oil into a diverse range of valuable petroleum products that meet the demands of various industries and consumers worldwide. Crude oil processing aims to refine crude oil into marketable products such as gasoline, diesel, jet fuel, heating oil, lubricants, and petrochemical feedstocks. These products serve as vital energy sources for transportation, heating, and electricity generation, as well as essential components in manufacturing processes for countless goods and materials. Additionally, crude oil processing seeks to optimize the efficiency of refining operations, enhance product quality, ensure compliance with environmental regulations, and maximize profitability for refineries and associated industries. Furthermore, in the context of sustainable development and environmental stewardship, the objective of crude oil processing includes minimizing the environmental impact of refining operations, reducing greenhouse gas emissions, and promoting the adoption of cleaner technologies and renewable energy sources in the refining sector. Overall, the objective of crude oil processing is to meet global energy needs efficiently, sustainably, and responsibly, while supporting economic growth and development around the world. Refineries are a significant part of the hydrocarbon sector in India, which deal with crude oil processing for the production of several components, mainly via the distillation process. It also generates a good amount of carbon content in the atmosphere. India has begun implementing Carbon Capture, Utilization, and Storage (CCUS) technologies through several pilot and industrial-scale initiatives, particularly in the hydrocarbon and cement sectors. One of the pioneering examples is the Tuticorin Alkali Chemicals and Fertilizers Ltd. (TACFL) plant in Tamil Nadu, which has been operational since 2016. In collaboration with UK-based Carbon Clean Solutions, the facility captures approximately 60,000 tons of CO_2 annually from a coal-fired boiler. It reuses it for soda ash production, showcasing a successful industrial symbiosis model. Another notable project is by the Oil and Natural Gas Corporation (ONGC), which evaluates CCUS as part of its enhanced oil recovery (EOR) operations in aging oil fields, such as the Gandhar field in Gujarat. These initiatives reflect a growing domestic capacity for integrating CCUS into industrial processes. A 2023 study [17] highlights that such localized, small-scale applications in India have achieved costs as low as $40 per ton of CO_2, making them relatively affordable and scalable under targeted policy and infrastructure support. These examples underline the strategic potential of CCUS in India's decarbonization roadmap while emphasizing the need for broader regulatory and financial enablers [18]. Table 1 provides details about several refineries in India that have a scope of a sufficient amount of carbon capture and research [19].

Table 1 List of petroleum refineries in India.

Sl. No.	Refinery	Oil company	Sector	State	Location	Capacity (10^6 tonnes/y)
1	Jamnagar Refinery (for exports)	Reliance Industries Limited	Private	Gujarat	Jamnagar (SEZ)	35.4
2	Jamnagar Refinery (for domestic market)	Reliance Industries Limited	Private	Gujarat	Jamnagar	33
3	Vadinar Refinery	Nayara Energy Limited	Private	Gujarat	Vadinar	20
4	Kochi Refinery	Bharat Petroleum Corporation Limited	Public	Kerala	Kochi	15.5
5	Mangalore Refinery	Oil and Natural Gas Corporation	Public	Karnataka	Mangalore	15
6	Paradip Refinery	Indian Oil Corporation Limited	Public	Odisha	Paradip	15
7	Panipat Refinery	Indian Oil Corporation Limited	Public	Haryana	Panipat	15 (capacity expanding to 25)
8	Gujarat Refinery	Indian Oil Corporation Limited	Public	Gujarat	Vadodara	13.7 (capacity expanding to 18)
9	Mumbai Refinery	Bharat Petroleum Corporation Limited	Public	Maharashtra	Mumbai	12
10	Guru Gobind Singh Refinery	HPCL-Mittal Energy Limited	Joint venture	Punjab	Bathinda	11.3
11	Manali Refinery	Chennai Petroleum Corporation Limited	Public	Tamil Nadu	Chennai	10.5
12	Visakhapatnam Refinery	Hindustan Petroleum Corporation Limited	Public	Andhra Pradesh	Visakhapatnam	8.3 (capacity expanding to 15)
13	Mathura Refinery	Indian Oil Corporation Limited	Public	Uttar Pradesh	Mathura	8
14	Haldia Refinery	Indian Oil Corporation Limited	Public	West Bengal	Haldia	8

15	Bina Refinery	Bharat Petroleum Corporation Limited (earlier a JV of BPCL & Oman Oil Company. [17])	Public	Madhya Pradesh	Bina	7.8
16	Mumbai Refinery	Hindustan Petroleum Corporation Limited	Public	Maharashtra	Mumbai	9.5
17	Barauni Refinery	Indian Oil Corporation Limited	Public	Bihar	Barauni	6 (capacity expanding to 9)
18	Numaligarh Refinery	Oil India Government of Assam	Public	Assam	Numaligarh	3 (capacity expanding to 9)
19	Bongaigaon Refinery	Indian Oil Corporation Limited	Public	Assam	Bongaigaon	2.35
20	Guwahati Refinery	Indian Oil Corporation Limited	Public	Assam	Guwahati	1
21	Nagapattnam Refinery	Chennai Petroleum Corporation Limited	Public	Tamil Nadu	Nagapattinam	1 (capacity expanding to 9)
22	Digboi Refinery	Indian Oil Corporation Limited	Public	Assam	Digboi	0.65 (capacity expanding to 1)
23	Tatipaka Refinery	Oil and Natural Gas Corporation	Public	Andhra Pradesh	Tatipaka	0.07

3. Typical Refinery Process

The crude oil refinery process in India involves several key steps to transform crude oil into valuable petroleum products. Here are the primary steps typically employed in a refinery [20-22].

3.1 Desalting

The crude oil entering the refinery often contains salt, water, and other impurities. Desalting is the initial step where these impurities are removed using water to wash the crude oil, ensuring smoother downstream processing.

3.2 Distillation (Fractionation)

The crude oil is heated in a distillation tower, and the various components with different boiling points are separated into fractions. These fractions include gases (such as methane and propane), naphtha, gasoline, kerosene, diesel, and heavier products like lubricating oils and asphalt.

3.3 Conversion

Conversion processes such as cracking and reforming alter the molecular structure of specific fractions to produce higher-value products. Cracking breaks down heavy hydrocarbons into lighter ones while reforming and rearranging molecules to produce gasoline blending components and other high-octane fuels.

3.4 Treatment

Various treatment processes are employed to improve the quality of refined products. These include hydrotreating, which removes sulfur, nitrogen, and other impurities to meet environmental regulations and enhance product quality.

3.5 Blending

Refined products may undergo blending to achieve desired specifications and properties. This involves mixing different fractions and additives to produce gasoline, diesel, jet fuel, and other products with specific performance characteristics.

3.6 Final Product Storage

The finished petroleum products are stored in tanks before distribution. Storage facilities ensure a steady supply of products to meet market demands and provide flexibility in refining operations.

3.7 Distribution

The final step involves distributing the refined products to consumers through pipelines, tanker trucks, railcars, or ships. Distribution networks transport products to retail outlets, industrial consumers, and other end-users nationwide.

These steps may vary slightly depending on the configuration and complexity of the refinery, as well as the specific requirements of the market. However, they represent the fundamental processes involved in crude oil refining in India and other refining centers globally [23-25]. Please refer to Figure 2 for an idea about the processing of crude oil in hydrocarbon sectors [26].

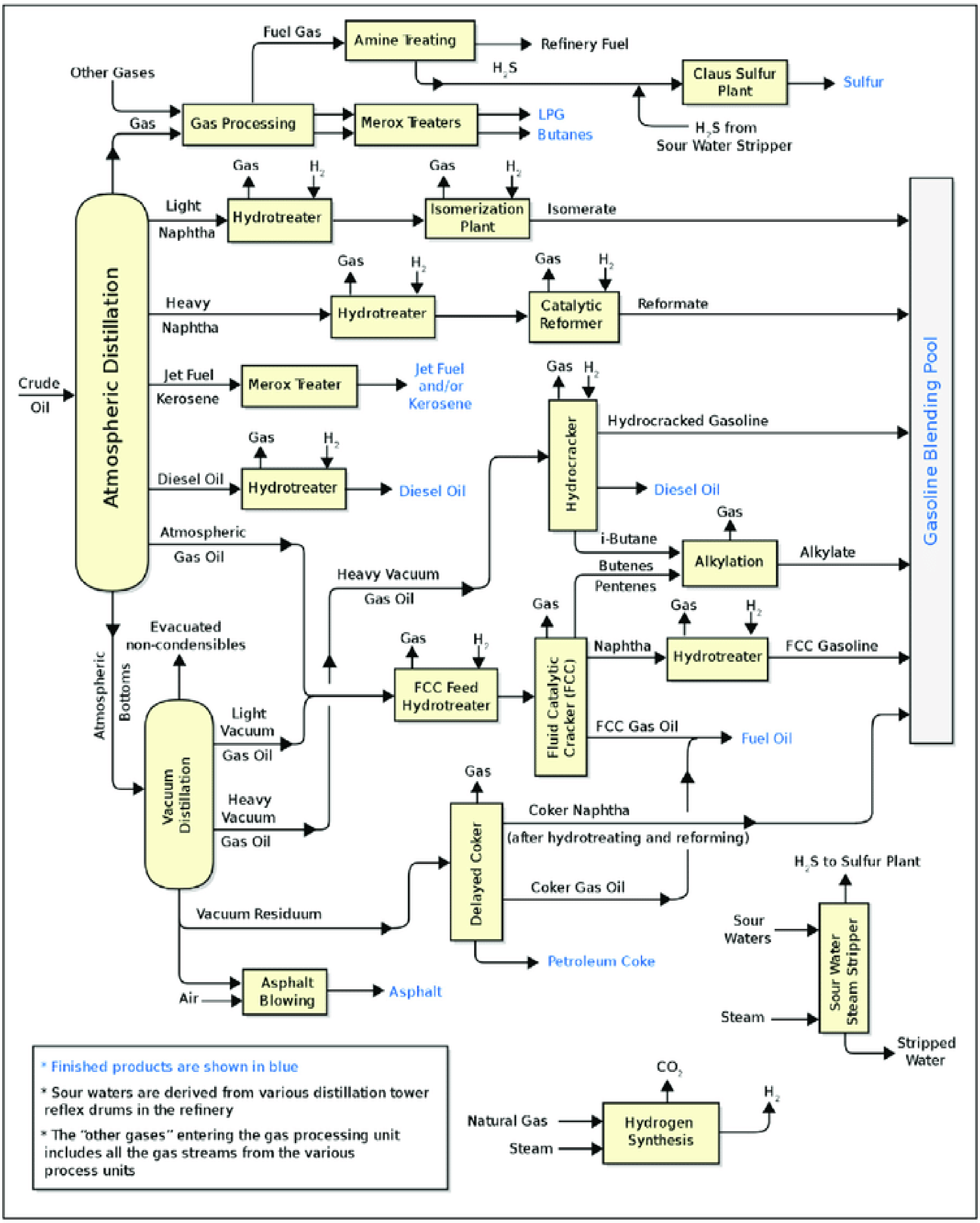

Figure 2 Process flow diagram of a typical refinery.

4. Main Chemical Reactions

Here are the main chemical reactions represented by equations in the crude oil refinery process:

4.1 Distillation

No specific chemical reactions occur during distillation. It's a physical process based on the different boiling points of hydrocarbon fractions.

4.2 Cracking

4.2.1 Thermal Cracking

$C_{10}H_{22} \rightarrow C_5H_{12} + C_5H_{10}$ (Decane splits into pentane and pentene).

4.2.2 Catalytic Cracking

$C_{12}H_{26} \rightarrow C_8H_{18} + C_4H_8$ (Dodecane is converted into octane and butene with the help of a catalyst).

4.3 Reforming

$C_6H_{14} \rightarrow C_6H_6 + 3H_2$ (Cyclohexane is converted into benzene and hydrogen).

4.4 Isomerization

n-$C_6H_{14} \rightarrow$ iso-C_6H_{14} (Normal hexane is converted into isohexane).

4.5 Alkylation

$C_4H_{10} + C_2H_4 \rightarrow C_6H_{14}$ (Isobutane reacts with ethylene to form hexane).

4.6 Hydrotreating

Desulfurization reaction: $R\text{-}S\text{-}R + 2H_2 \rightarrow 2RH + H_2S$ (Organic sulfur compound reacts with hydrogen to form hydrogen sulfide and desulfurized hydrocarbon). Denitrification reaction: $R\text{-}NH_2 + 3H_2 \rightarrow RH + 2NH_3$ (Organic nitrogen compound reacts with hydrogen to form ammonia and denitrified hydrocarbon).

4.7 Hydrocracking

$C_{12}H_{26} + H_2 \rightarrow C_6H_{14} + 6CH_4$ (Dodecane reacts with hydrogen to form hexane and methane).

These equations represent simplified versions of the chemical reactions occurring in the crude oil refinery process. Actual refining involves a combination of these reactions and additional complexities based on the specific methods and technologies employed.

5. Scope of Research in the Hydrocarbon Sector in India

The hydrocarbon sector in India offers a broad scope for research across various dimensions, reflecting the complexity and importance of this industry within the country's economy and global energy landscape [27-29]. Some potential areas for research in the hydrocarbon sector in India include:

5.1 Exploration and Production (E&P) Technology

Research into innovative exploration and production technologies can help optimize hydrocarbon recovery from existing fields and explore new reserves more efficiently. This includes advancements in seismic imaging, reservoir characterization, drilling techniques, and enhanced oil recovery (EOR) methods tailored to India's geological formations.

5.2 Unconventional Resources

With the growing interest in unconventional resources such as shale gas, coalbed methane (CBM), and gas hydrates, there is scope for research to assess the potential of these resources in India, develop extraction techniques, and evaluate their economic and environmental viability.

5.3 Policy and Regulatory Frameworks

Research focusing on analyzing policy and regulatory frameworks governing the hydrocarbon sector can provide insights into their effectiveness in promoting investment, fostering innovation, ensuring environmental sustainability, and balancing stakeholders' interests.

5.4 Energy Security and Geopolitics

Studies examining India's energy security challenges, geopolitical dynamics, and international energy partnerships can contribute to a better understanding of the country's strategic priorities, vulnerabilities, and opportunities in the global hydrocarbon market.

5.5 Environmental Impact and Sustainability

Overcoming regulatory and technological challenges in carbon capture within India's hydrocarbon sector requires a multifaceted approach. Firstly, establishing a clear and supportive regulatory framework is essential. Technologically, India must focus on adapting cost-effective and modular carbon capture solutions suitable for retrofitting existing hydrocarbon infrastructure. Additionally, mandating carbon capture readiness in new refinery and petrochemical projects can make future-proof investments. Finally, capacity building and international collaboration are key to bridging technological gaps, ensuring India meets its decarbonization goals without compromising energy security or industrial growth.

5.6 Downstream Sector Development

Research focusing on the downstream sector, including refining, petrochemicals, and marketing, can explore opportunities for capacity expansion, technology upgrades, product diversification, and market expansion to meet evolving consumer demands and regulatory requirements.

5.7 Infrastructure and Logistics

Studies on infrastructure development, including pipelines, storage facilities, terminals, and transportation networks, can identify bottlenecks, assess investment needs, and optimize logistics to ensure the efficient supply and distribution of hydrocarbon products across India.

5.8 Human Capital Development

Research on human capital development in the hydrocarbon sector, including workforce skills, training programs, and knowledge transfer, can address the industry's talent requirements and support the development of a skilled workforce capable of driving innovation and competitiveness.

5.9 Climate Change and Energy Transition

Research exploring the implications of climate change, energy transition policies, and decarbonization efforts in the hydrocarbon sector can help stakeholders anticipate future trends, assess risks and opportunities, and develop strategies for adaptation and diversification.

Overall, research in the hydrocarbon sector in India spans a wide range of disciplines and topics, offering opportunities to address critical challenges, drive technological innovation, and shape the future of energy development in the country [30-32].

6. Importance of Carbon Capture from Refineries with Results and Discussions

Carbon capture from crude oil refineries is necessary for several reasons:

6.1 Reducing Greenhouse Gas Emissions

Crude oil refining processes emit significant amounts of carbon dioxide (CO_2), a greenhouse gas contributing to global warming and climate change [33]. Carbon capture helps mitigate these emissions by capturing CO_2 before it is released into the atmosphere.

6.2 Regulatory Compliance

Many countries and regions have implemented regulations and targets to reduce greenhouse gas emissions. Refineries must comply with these regulations to avoid penalties and maintain operating licenses. Carbon capture technology enables refineries to reduce their carbon footprint and meet regulatory requirements.

6.3 Corporate Social Responsibility

Refineries often have corporate social responsibility (CSR) goals to reduce environmental impact and contribute to sustainability efforts [34]. Implementing carbon capture demonstrates a commitment to environmental stewardship and can enhance the reputation of the refinery within the community.

6.4 Resource Efficiency

Carbon capture technology can also capture other pollutants and impurities along with CO_2, improving air quality and reducing environmental pollution. This contributes to resource efficiency and promotes a cleaner and healthier environment for surrounding communities.

6.5 Future-Proofing Operations

As the global focus on environmental sustainability increases, there is a growing trend toward carbon-neutral and low-carbon technologies. Refineries that invest in carbon capture and other emission reduction measures position themselves for long-term viability in a changing regulatory and market landscape.

6.6 Results and Discussions

International collaborations have significantly advanced the deployment of Carbon Capture, Utilization, and Storage (CCUS) technologies within India's hydrocarbon sector. A notable example is the partnership between the U.S. Department of Energy (US-DoE) and India's Department of Science and Technology (DST), focusing on supercritical carbon dioxide (CO_2) and CCUS technologies [35]. This collaboration facilitates knowledge exchange and joint research initiatives, accelerating CCUS adoption in India. Additionally, India's engagement in the multilateral platform for Accelerating CCUS Technologies has opened avenues for collaboration with countries like the USA and Norway, promoting the development of CCUS projects tailored to India's energy landscape. Furthermore, the establishment of the National Center of Excellence in Carbon Capture and Utilization at IIT Bombay, supported by international partnerships, underscores the role of global cooperation in building domestic CCUS capabilities [36]. These collaborations enhance technological expertise and contribute to policy frameworks and financial mechanisms essential for scaling CCUS solutions in India's hydrocarbon industry. Overall, carbon capture from crude oil refineries is necessary for mitigating climate change, complying with regulations, fulfilling corporate responsibilities, improving resource efficiency, and ensuring the long-term sustainability of refinery operations [37-39]. To effectively convey the importance of carbon capture from crude oil refineries, several key aspects are as follows:

6.6.1 Greenhouse Gas Emissions Reduction

Carbon capture technologies offer considerable promise for lowering greenhouse gas emissions across multiple sectors. According to the Intergovernmental Panel on Climate Change (IPCC), meeting the targets set by the Paris Agreement requires the integration of carbon capture and storage (CCS), particularly to address emissions from sectors where reduction is especially challenging [40]. Within heavy industry, CCS remains one of the few viable pathways for achieving deep emission cuts, especially for processes with unavoidable CO_2 output. Recent innovations highlight the real-world potential of CCS. A notable example is a $32 million investment by a consortium of tech firms in a Norwegian initiative aimed at capturing carbon from waste-to-energy facilities, targeting the removal of 100,000 metric tons of CO_2 between 2029 and 2030. This project illustrates both the scalability and effectiveness of the approach. The International Energy Agency (IEA) also notes that modern CCS systems can eliminate up to 90% of CO_2 emissions from industrial flue gases, confirming the technology's critical role in climate mitigation [41]. A graph illustrating the significant CO_2 emissions through conventional refining processes is mentioned in Figure 3. This graph represents the emissions from several sections of hydrocarbon refineries, highlighting the environmental impact.

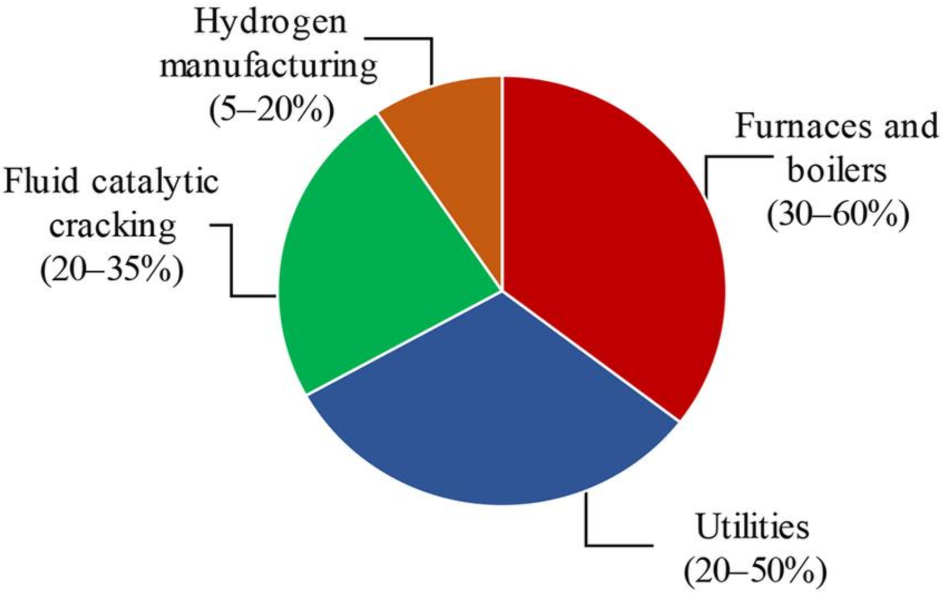

Figure 3 Overview of primary CO_2 emissions sources from refineries [42].

6.6.2 Regulatory Compliance and Penalties

Chhattisgarh leads India's power sector emissions with 132 million metric tons of CO_2 equivalent ($MtCO_2e$) in 2023, followed by Uttar Pradesh at 126.3 $MtCO_2e$. Collectively, the top ten emitting states produced over 840 $MtCO_2e$ in 2023. Implementing carbon capture, utilization, and storage (CCUS) technologies is vital for these high-emission regions to meet environmental regulations and avoid potential financial penalties. The Indian government estimates that an investment of ₹30,000 to ₹50,000 crore in CCUS by 2030 is necessary to achieve net-zero targets by 2070. Failure to adopt such measures could result in non-compliance with future emission standards, leading to substantial fines and increased operational costs. A suitable Figure 4 illustrating state-wise CO_2 emissions is as follows.

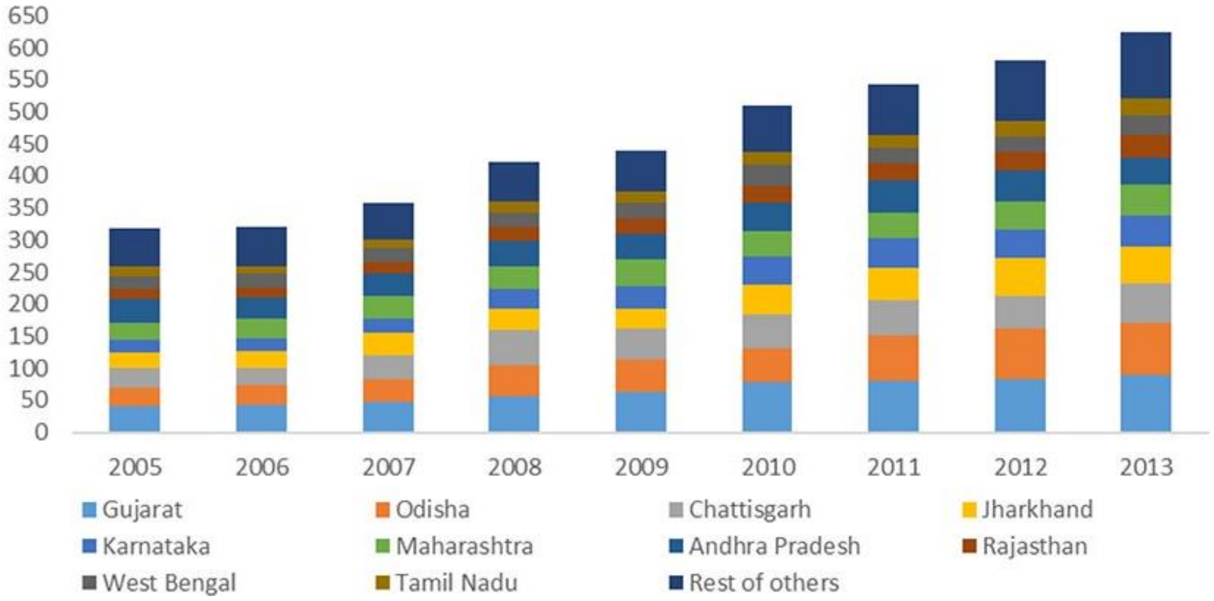

Figure 4 State-wise CO_2 emissions in the Statista report for India [43].

6.6.3 Cost-Benefit Analysis

The adoption of Carbon Capture and Storage (CCS) in India's hydrocarbon sector presents both economic and environmental considerations [44]. A feasibility study conducted at the Indian Oil Corporation Limited's (IOCL) Koyali refinery demonstrated the potential to capture approximately 0.7 million tons per annum (mtpa) of CO_2 from Hydrogen Generation Units, with plans to utilize the captured carbon for Enhanced Oil Recovery (EOR) in ONGC's Gandhar oilfields [45]. Additionally, studies suggest that CCS could help mitigate nearly 740 million tons of CO_2 at costs below $60 per ton, underscoring its viability for large-scale emissions reduction. However, barriers such as significant capital investment, high energy consumption, and the need for a well-defined policy framework must be addressed to maximize the benefits of CCS in India's hydrocarbon industry [46]. The global carbon capture and storage market from 2022 to 2032 (USD Billion) is mentioned for reference in Figure 5.

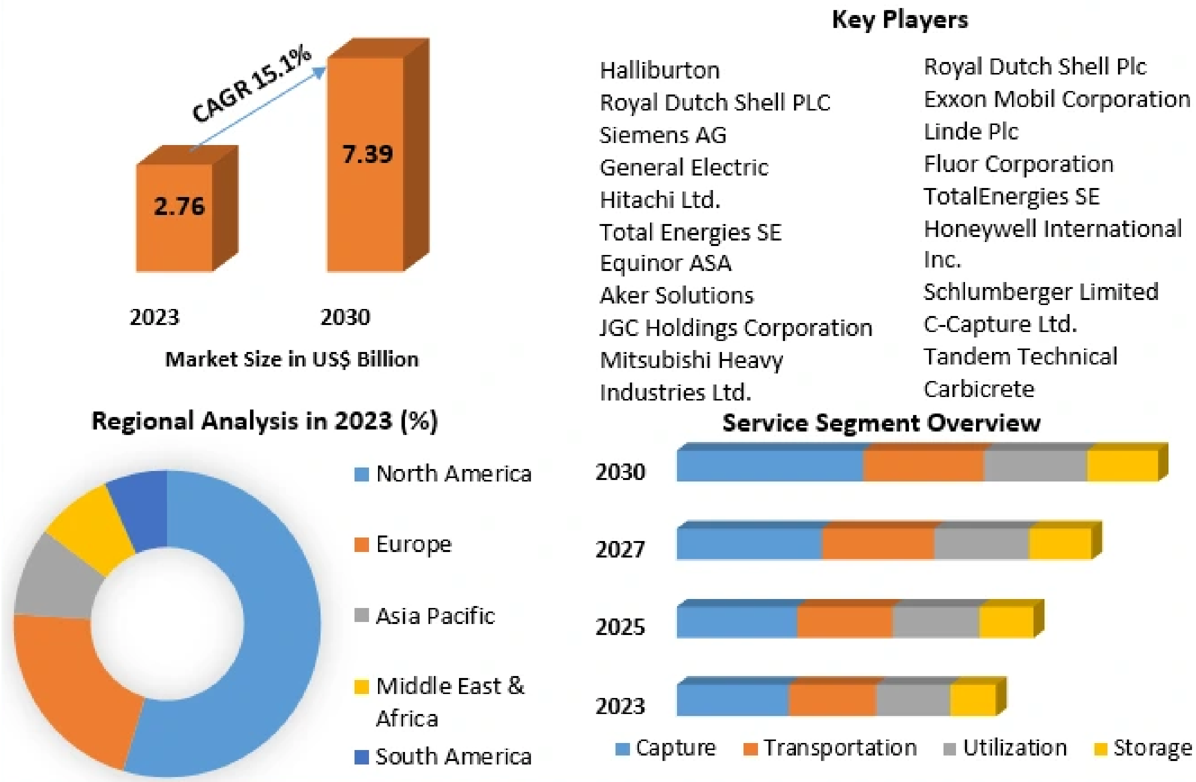

Figure 5 Carbon capture, utilization, and storage market [46].

6.6.4 Environmental Impact

The deployment of Carbon Capture and Storage (CCS) technologies in India offers significant environmental benefits beyond CO_2 reduction, including lowering air pollutants like sulfur dioxide (SO_2) and nitrogen oxides (NO_x) [47]. A study analyzed twelve coal-fired thermal power plants within a 300-kilometer radius of Delhi and found that flue-gas desulfurization (FGD) technology could reduce SO_2 emissions by 67%, cutting annual emissions from 281 kilotons to 93 kilotonnes [48]. While CCS primarily targets CO_2, integrating it with technologies like FGD can simultaneously capture other harmful pollutants, improving air quality and public health. However, challenges such as high capital investment, energy consumption, and clear policy frameworks must be addressed to fully leverage CCS in India's hydrocarbon sector [49]. The CREA study provides a detailed analysis of the potential reduction in SO_2 emissions with FGD deployment. Overall, the adoption of CCS and complementary technologies in India's hydrocarbon industry could significantly curb CO_2, SO_2, and NO_x emissions, contributing to environmental sustainability and public health improvements [50]. Figure 6 represents the trends of anthropogenic emissions, annual PM2.5 concentration, energy consumption, and GDP in China between 2013 and 2020.

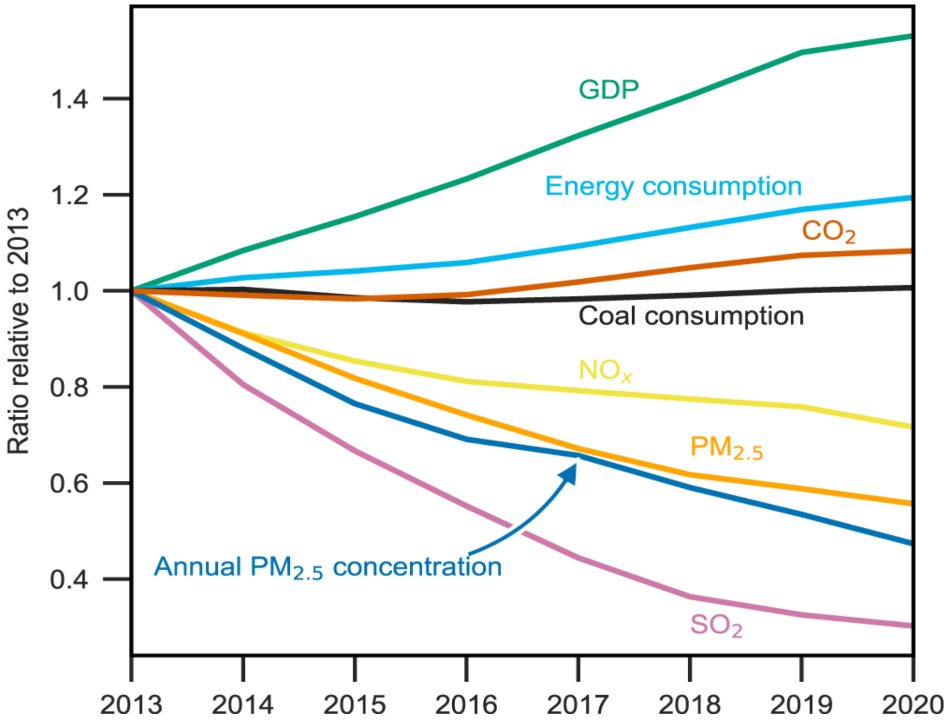

Figure 6 Trends of anthropogenic emissions, annual PM2.5 concentration, energy consumption, and GDP in China between 2013 and 2020 [51].

6.6.5 Future Trends and Market Demand

Figure 7 illustrates the growing trend of carbon pricing and the increasing demand for low-carbon products in global markets. This demonstrates the strategic importance of investing in carbon capture technology to remain competitive and meet evolving consumer preferences. As per 6Wresearch, the India Voluntary Carbon Credit sector is anticipated to expand at a Compound Annual Growth Rate (CAGR) of 16.62% from 2021 to 2027. The supply from India has experienced a manifold increase in recent years and is projected to sustain its growth trajectory. Nonetheless, the absence of governmental initiatives to cultivate carbon credit markets and regulatory foresight has resulted in conservative growth projections for the forecasted period.

Figure 7 Indian carbon credit market overview, 2017-2027F ($ Million) [52].

From Figure 3 to Figure 7, anyone can visualize the importance of carbon capture from crude oil refineries regarding environmental, regulatory, economic, and market considerations. This visual representation enhances understanding and facilitates informed decision-making regarding adopting carbon capture technology.

6.7 Scope of Carbon Capture in the Hydrocarbon Sector

Carbon capture in the hydrocarbon sector involves capturing carbon dioxide (CO_2) emissions generated during the production, processing, and combustion of hydrocarbon fuels. Several methods can be employed for carbon capture in the hydrocarbon sector:

6.7.1 Pre-Combustion Capture

In pre-combustion capture, carbon dioxide is captured before hydrocarbon fuels are burned. This process involves converting hydrocarbons into synthesis gas (syngas), primarily hydrogen and carbon monoxide. CO_2 is then separated from the syngas using pressure swing adsorption (PSA) or physical solvent absorption.

6.7.2 Post-Combustion Capture

Post-combustion capture involves capturing CO_2 from the exhaust gases produced by the combustion of hydrocarbon fuels. This method typically utilizes chemical solvents or solid adsorbents to capture CO_2 from the flue gas stream selectively. The captured CO_2 is then purified and compressed for storage or utilization [53].

6.7.3 Oxy-Fuel Combustion

Oxy-fuel combustion involves burning hydrocarbon fuels in a mixture of oxygen and recycled flue gases, resulting in a flue gas stream consisting primarily of CO_2 and water vapor. The CO_2 can be easily captured from this concentrated stream using absorption or adsorption processes.

6.7.4 Chemical Looping Combustion

Chemical looping combustion is when hydrocarbon fuels are cyclically reacted with metal oxides. This results in the production of CO_2 and water vapor in one reactor, while the metal oxide is reduced to its metallic form. The CO_2 can then be easily captured from the flue gas stream, and the metal oxide can be regenerated for reuse.

6.7.5 Membrane Separation

Membrane separation involves using selective membranes to separate CO_2 from other gases in the flue gas stream. Membrane separation is typically used with other capture methods to enhance efficiency.

6.7.6 Cryogenic Separation

Cryogenic separation involves cooling the flue gas stream to very low temperatures, causing CO_2 to condense into a liquid while other gases remain in a gaseous state. The liquid CO_2 can then be separated and stored for further use or disposal.

Assessing the applicability of Carbon Capture, Utilization, and Storage (CCUS) methods like pre-combustion, post-combustion, and oxy-fuel combustion to India's refinery sector necessitates consideration of existing infrastructure and operational constraints. Post-combustion capture, which involves extracting CO_2 from flue gases after fuel combustion, is particularly suitable for retrofitting existing refineries due to its compatibility with current setups and lower initial investment requirements. This approach allows for incremental implementation without significant overhauls. In contrast, pre-combustion capture requires substantial modifications, as it involves gasifying fuel to separate CO_2 before combustion, a process not typically integrated into India's refinery designs. Oxy-fuel combustion, which burns fuel in pure oxygen to produce a CO_2-rich flue gas, faces challenges related to the high costs and energy demands of oxygen production, making it less viable given current technological and economic conditions. Therefore, for large-scale deployment in India, post-combustion capture emerges as the most practical and cost-effective method, aligning with the country's goal of reducing emissions while leveraging existing refinery infrastructure.

Experiments were conducted for the carbonation of process liquor generated from the mining and mineral processing industry, as mentioned in Figure 8, using flue gas. The results of the experimental work are mentioned in Table 2. It represents the complete carbonation of NaOH into desired reagents Na_2CO_3 and $NaHCO_3$, which can be recycled again in plants for leaching operations.

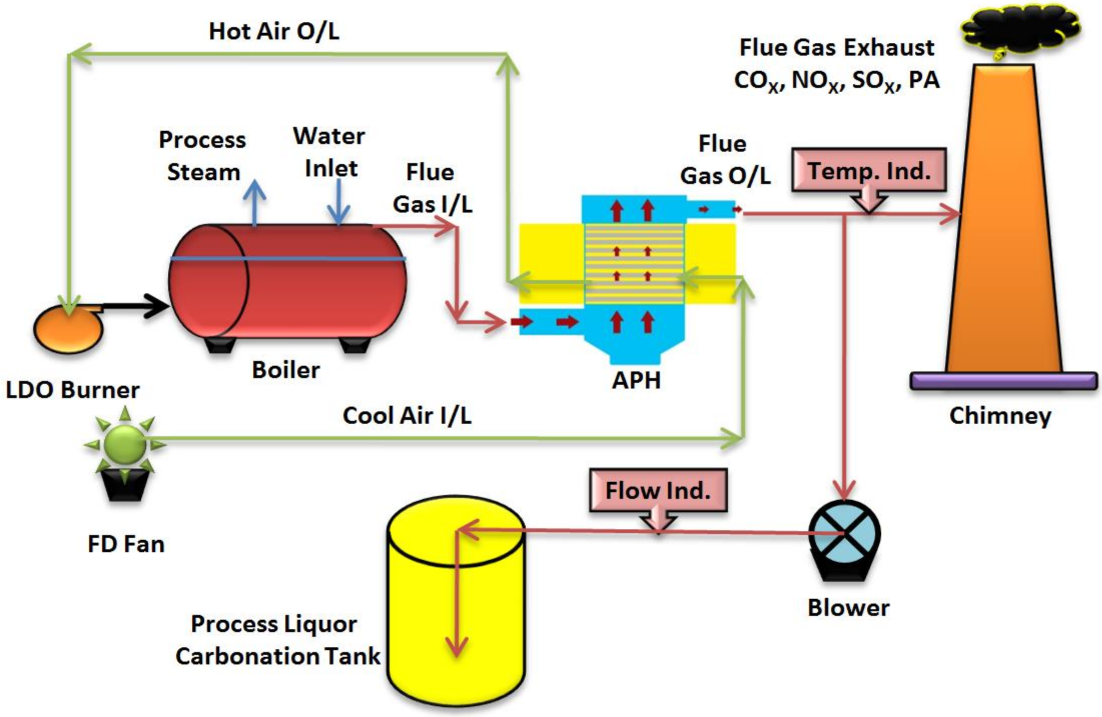

Figure 8 Carbon capture research in the mineral processing industry.

Table 2 Chemical composition of process liquor in carbonation trials by using flue gas.

Sl. No.	Carbonation time (minutes)	Liquor sample volume (ml)	HCl titration volume (V_1) (ml)	HCl titration volume (V_2) (ml)	NaOH (GPL)	$NaHCO_3$ (GPL)	Na_2CO_3 (GPL)
1	0	5	4.8	7.0	17.49	0	39.21
2	30	5	4.0	6.6	9.42	0	46.34
3	60	5	3.2	6.5	0	1.41	57.04
4	90	5	2.9	6.5	0	9.89	51.69

The carbonation trial results demonstrate a progressive chemical transformation during CO_2 absorption from flue gas into a sodium-based solution, with significant implications for industrial applications. Initially, NaOH (17.49 gpl) is rapidly consumed within 60 minutes, indicating strong CO_2 absorption capacity, while Na_2CO_3 concentration increases from 39.21 to 57.04 gpl, confirming the formation of carbonate [54]. Beyond 60 minutes, Na_2CO_3 partially converts to $NaHCO_3$, which increases to 9.89 gpl at 90 minutes, signifying the onset of bicarbonate formation. This sequential conversion—from NaOH to Na_2CO_3 to $NaHCO_3$—not only illustrates the efficiency of CO_2 capture but also provides a tunable pathway for producing valuable carbonate and bicarbonate compounds. These findings are critical for optimizing flue gas treatment systems, determining residence time, and enhancing the economic viability of carbon capture through integrated chemical utilization. Once captured, the CO_2 can be transported via pipelines or ships to suitable storage sites such as depleted oil and gas reservoirs, saline aquifers, or geological formations for long-term storage. Alternatively, captured CO_2 can be utilized in enhanced oil recovery (EOR) operations, the production of chemicals and fuels, or mineral carbonation processes.

Recent quantitative projections indicate that carbon capture, utilization, and storage (CCUS) can significantly reduce CO_2 emissions from India's refinery sector, one of the most significant industrial sources of greenhouse gases. According to a study published [55], Indian refineries emitted approximately 60–70 million tons of CO_2 annually. Modeling scenarios that integrate post-combustion CCUS systems projects that up to 45–55% of these emissions could be captured using current technologies, equating to a potential reduction of 30–38 million tons of CO_2 per year. The study also suggests that when integrated with enhanced oil recovery (EOR), captured CO_2 can provide an additional revenue stream, improving economic feasibility [56]. Furthermore, India’s National CCUS roadmap anticipates that the refinery sector could contribute around 15% of the total national CO_2 capture potential by 2040, assuming progressive policy support and international technology transfer. These projections emphasize the critical role of CCUS in meeting industrial decarbonization targets and align with India's commitment to net-zero emissions by 2070 [57]. Figure 9 is a generated chart illustrating the projected CO_2 emissions reduction in Indian refineries through CCUS. Residual emissions represent the portion of CO_2 that remains uncaptured due to technical limitations (e.g., low concentration CO_2 streams), economic infeasibility for specific emission points, and operational or integration constraints in refinery systems.

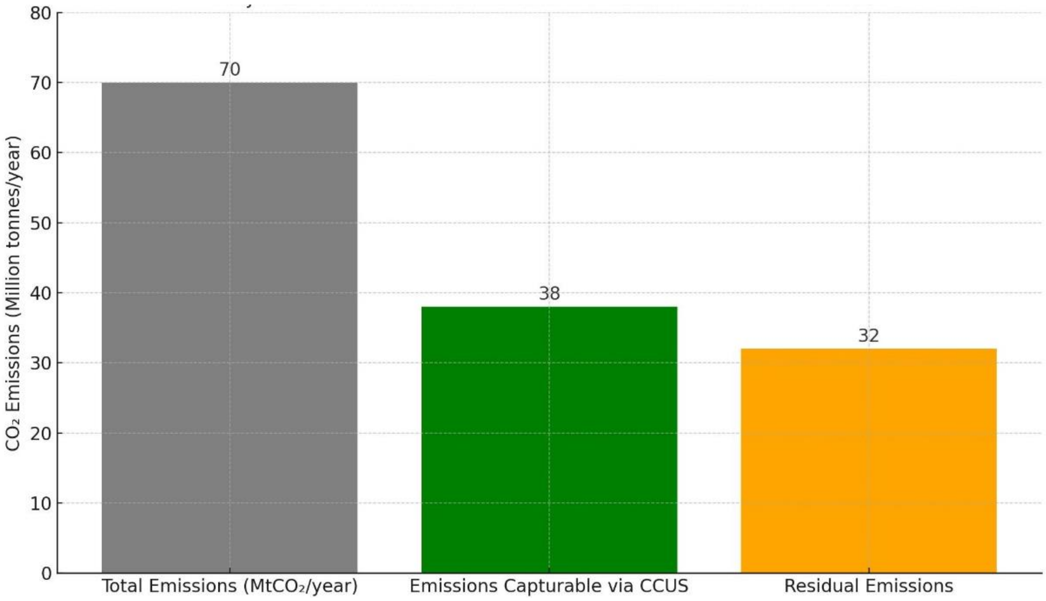

Figure 9 Projected CO_2 emissions reduction in Indian refineries via CCUS.

Table 3 provides a comparative analysis of the hydrocarbon sector with coal-fired power plants and steel production in India, based on CO_2 emissions intensity, total contribution, CCUS potential, and implementation challenges.

Table 3 Comparative analysis of the hydrocarbon sector with other sectors in India.

Parameter	**Coal-Fired Power Plants**	**Steel Industry**	**Hydrocarbon Sector (Refineries & Gas)**
Estimated CO_2 Emissions	~1,100 million tonnes/year	~250 million tonnes/year	~70 million tonnes/year
Share in India's Total Emissions	~50%	~12%	~3–4%
CO_2 Emissions Intensity	High	Very High	Moderate
CCUS Potential	Very High – significant, concentrated point sources	High – particularly in blast furnaces and DRI units	Moderate – mostly flue gases; some high-purity CO_2 sources
Current CCUS Projects	Pilot projects (e.g., NTPC) are underway	Limited pilot projects	Few pilots (e.g., IOCL Koyali)
Infrastructure Readiness	Moderate – centralized plants ease implementation	Low to moderate – requires significant retrofitting	Moderate – compatible with post-combustion technologies
Implementation Challenges	High cost, retrofitting old plants	High capital cost, dispersed sources	Cost, CO_2 transport infrastructure, regulatory gaps
Policy Support	Strong (e.g., NTPC's net-zero targets, CCUS roadmap)	Growing interest, yet underdeveloped	Increasing (e.g., NITI Aayog CCUS report)

7. Conclusion

In conclusion, the crude oil refinery process in India is a multifaceted operation that plays a crucial role in meeting the nation's energy demands and driving economic growth. Through intricate steps, including desalting, distillation, conversion, treatment, blending, and distribution, crude oil is transformed into a wide range of valuable petroleum products essential for various industries and daily life activities. Despite the challenges posed by fluctuating crude oil prices, environmental regulations, and evolving market dynamics, the Indian refining industry has demonstrated resilience and adaptability. With advancements in technology, process optimization, and strategic investments, Indian refineries have been able to enhance efficiency, improve product quality, and meet stringent environmental standards. Looking ahead, the Indian crude oil refining sector faces opportunities and challenges alike. The growing demand for cleaner fuels, the emergence of renewable energy sources, and shifting consumer preferences necessitate continuous innovation and adaptation within the industry. Furthermore, ensuring energy security, promoting sustainable development, and embracing digitalization is imperative for the long-term viability and competitiveness of the Indian refining sector. In conclusion, by leveraging technological advancements, fostering innovation, and adopting sustainable practices, the crude oil refinery process in India can continue to evolve and thrive in the dynamic global energy landscape. With strategic planning, investments, and collaborative efforts among stakeholders, the Indian refining industry is well-positioned to navigate challenges and seize opportunities for growth and development in the years to come [58]. Carbon capture technology presents a pivotal solution for mitigating greenhouse gas emissions from crude oil refineries. By implementing advanced capture systems, refineries can significantly reduce their carbon footprint while simultaneously addressing regulatory requirements and corporate sustainability goals. The adoption of carbon capture not only enhances environmental stewardship but also fosters resource efficiency and community well-being by mitigating air pollutants and promoting a cleaner future. As global efforts intensify to combat climate change, investing in carbon capture from crude oil refineries emerges as a strategic imperative, ensuring both environmental responsibility and the long-term viability of refining operations in a rapidly evolving energy landscape. Recent findings also support the usage of carbon emitted from industries in the process itself [59]. Carbonation is an essential process in several chemical industries. Specific boilers are used in industries for steam generation. Several types of fuels are used for boilers, i.e., light diesel oil, coal, natural gas, liquefied petroleum gas, biomass, etc. [60]. After the burning of these fuels, flue gas is generated. This flue gas contains a combination of SO_x, NO_x, CO_x, etc. Experiments concluded that CO_2 in flue gas can be used to carbonate process liquor in chemical industries.

The economic feasibility of Carbon Capture, Utilization, and Storage (CCUS) in India's hydrocarbon sector is increasingly favorable, especially when considering long-term environmental and financial benefits. Capture costs vary by process, with high-purity CO_2 sources such as ammonia and hydrogen plants estimated at $15–25 per tonne. Meanwhile, diluted streams in refineries and cement plants range between $40 and $ 120 per tonne [61]. Specifically, studies on India's Koyali refinery report capture costs around $55–60 per tonne [62]. Despite these upfront costs, CCUS offers significant value through enhanced oil recovery (EOR), which can generate revenue and offset investment. Additionally, CCUS supports emission reductions vital for meeting India's climate goals and offers potential earnings from emerging carbon markets and credits [63]. According to the

International Energy Agency, these benefits, coupled with declining technology costs and policy support, make CCUS a viable and scalable solution for industrial decarbonization in India.

India's hydrocarbon sector is actively transitioning toward cleaner technologies through policy-level commitments and strategic investments. The government has implemented the Hydrocarbon Exploration and Licensing Policy (HELP), which introduces a uniform licensing system for the exploration and production of all hydrocarbons, aiming to simplify operations and encourage investment in cleaner technologies. Additionally, the government permits up to 100% Foreign Direct Investment (FDI) under the automatic route for renewable energy projects, facilitating increased capital flow into clean energy initiatives. To further support the transition, the government has established Ultra Mega Renewable Energy Parks, providing land and transmission infrastructure to renewable energy developers on a plug-and-play basis, thereby reducing entry barriers and promoting large-scale clean energy projects. Moreover, the NITI Aayog's report on 'Carbon Capture, Utilisation, and Storage (CCUS)' outlines strategies for integrating CCUS technologies into the energy sector, emphasizing their potential to mitigate carbon emissions and support sustainable development. These initiatives collectively reflect India's commitment to fostering a cleaner, more sustainable hydrocarbon industry through comprehensive policy reforms and targeted investment strategies.

Evaluating the readiness of Indian refineries for Carbon Capture, Utilization, and Storage (CCUS) implementation reveals that facilities with high-purity CO_2 emission sources and proximity to potential storage sites are better positioned for adoption. The Koyali refinery in Gujarat, operated by Indian Oil Corporation Limited (IOCL), exemplifies this potential, with the capability to capture over 5,000 tons of CO_2 per day for Enhanced Oil Recovery (EOR) operations at nearby oilfields [64]. Similarly, refineries in eastern India benefit from clustering opportunities with active coalbed methane extraction sites, facilitating integrated CCUS networks. However, these refineries face technical challenges, including the need for substantial infrastructure development for CO_2 transportation and storage, high capital investment requirements, and the establishment of regulatory frameworks to support CCUS deployment [65]. Addressing these challenges through targeted policies and investments is crucial for advancing CCUS in India's refining sector [66].

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Author Contributions

The authors confirm their contribution to the paper as follows: study conception and design: Vipin Kumar Sharma, Sunil Kumar Thamida, Raja Sinha; data collection: Vipin Kumar Sharma, Raja Sinha; analysis and interpretation of results: Vipin Kumar Sharma, Sunil Kumar Thamida, B. Naveen

Kumar Reddy; draft manuscript preparation: Vipin Kumar Sharma, Sunil Kumar Thamida, Raja Sinha. Editing and conception: Vipin Kumar Sharma, Sunil Kumar Thamida, B. Naveen Kumar Reddy, Raja Sinha; review and execution: Sunil Kumar Thamida, B. Naveen Kumar Reddy; guidance and approval: Sunil Kumar Thamida, B. Naveen Kumar Reddy. All authors reviewed the results and approved the final version of the manuscript.

Competing Interests

The authors have no conflicts of interest to declare that are relevant to the content of this article.

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