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Future prospects towards attaining zero-emission of greenhouse gases from crude oil refinery plants

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ABSTRACT

The contribution of greenhouse gas emissions from crude oil refineries to the global climate change has been so problematic. The end results of this has been linked to global warming causing adverse effects on public health and making the environment unsafe for living. This review article examines the challenges and effects emanating from the release of greenhouse gases from crude oil refining operations. In-depth discussions and salient points, shedding light for prospective researchers on the critical areas that should be investigated and improved on to attain net-zero emissions in refinery, were presented. The effects of the increase in the global number of refineries on GHG emissions trend in top countries are discussed. Top 10 countries and refinery industries with the highest GHG emissions were referenced as case studies. Between 2000 and 2021, the cumulative GHG emissions from refineries attained 34.1 Gt due to increase in the number of refineries while the top 10 enterprises accounted for approximately 33.8–38.1 %. Accumulative reduction of 532 Mt and 928 Mt of CO_2 emissions are expected between 2020 and 2030 if the efficiencies of refineries in the top 10 countries and global refineries are respectively improved. Technologies such as hydrogen-based refining and carbon capture, utilization, and storage (CCUS); integration of circular economy principles; green financing and government-backed incentives; and government-based policies are some of the steps that can be taken to make reduction of GHG emissions from refineries a reality. In conclusion, the stated vital points regarding future prospects towards attaining net-zero emissions from crude oil refinery plants will be beneficial for prospective researchers and the entire globe.

1. Introduction

Crude oil refineries are vital sectors of the global energy industry which convert crude oil into valuable products such as gasoline, jet fuel, diesel and petrochemicals. However, the processes required in their production significantly contribute to greenhouse gas (GHG) emissions, posing substantial risks to the environment and human health (Wei et al., 2016). Refineries account for sulfur oxides (SO_2), nitrogen oxides (NO_x), volatile organic compounds (VOCs), particulate matter (PM) and carbon dioxide (CO_2) emissions which are linked to global warming, smog formation, acid rain and serious respiratory diseases (Popoola et al., 2013a). Owning by the rising global climate crisis, there is a growing urgency for the oil and gas industry, particularly refineries, to lower their carbon footprint. The shift toward net-zero emissions target is becoming a central pillar of environmental policy and corporate sustainability (Zhao et al., 2019). In the context of refineries, net-zero emissions means drastically reducing emissions from both refining operations and the energy required to power those operations, with any remaining emissions being either captured or offset through various methods. In this regard, it is essential for refineries to adopt strategies to alleviate their contribution to global warming while ensuring energy security and economic viability (Baltrenas et al., 2011).

The various sources of GHG in crude oil refineries are those originating majorly from (1) fossil fuels combustion purposely for power generation, heating and refining processes; (2) reforming and catalytic cracking processes which are employed in converting heavy

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hydrocarbons into more valuable lighter fractions releasing volatile organic compounds like benzene, toluene and xylene into the atmosphere; (3) unintentional leaks of gases coming from equipment such as valves, tanks, pipes and compressors; and (4) flaring which involves the burning of excess gases (Adebiyi et al., 2015). Though flaring lowers immediate safety risks, significant CO_2 and other pollutants particulate matter, CO and hydrocarbons are often generated. Fig. 1 shows the global CO_2 emissions from some countries around the world between 2000 and 2020.

The achievement of net-zero emissions is a vital objective in tackling climate change, and this objective extends to industries such as refineries, which are among the highest donors to global CO_2 emissions (Popoola and Yusuff, 2021a). The challenge of achieving net-zero emissions for refineries is particularly complex as a result of their huge dependence on fossil fuels. Crude oil is the primary raw material for refining, and refineries also depend on fossil fuels like natural gas and fuel oil, to power energy-intensive processes like distillation and cracking. These high-temperature processes are essential for separating and converting crude oil into usable products but also generate significant CO_2 emissions through fossil fuels combustion (Laturkar and Laturkar, 2023a). Based on this, achieving net-zero emissions for refineries necessitates a transformation in both the way refineries operate and the energy sources they rely upon.

To reach net-zero emissions, refineries must focus on two key strategies: emission reduction and carbon offsetting. Emission reduction effort is targeted at cutting down the direct emissions produced during refinery operations (Saleh and Hassan, 2024). This can be attained via improving energy efficiency, shifting to renewable energy sources, and adopting new technologies that minimize carbon emissions. For example, refineries could integrate sources of renewable energy such as solar, wind, or biomass into their operations to replace carbon-intensive fossil fuels. In addition, energy-efficient technologies and process optimization can assist in minimizing the total energy required to carry out refining operations, thus lowering emissions (Popoola et al., 2018).

On the other hand, carbon offsetting involves compensating for remaining emissions through activities that reduce or capture carbon elsewhere. One of the most promising technologies for carbon offsetting in refineries is carbon capture and storage (CCS) (Onakpohor et al., 2024). Though CCS is still at the initial stage of implementation and development, it offers significant potential for reducing the carbon footprint of industries like refining. Additionally, refineries could invest in projects that contribute to carbon sequestration, such as forest restoration or renewable energy initiatives; to offset their remaining emissions (Michael and Joepen, 2021). This review critically explores the available technologies to achieve net-zero emissions in refineries. It provides information on the cumulative GHG emissions generated from top 10 refineries and countries of location. Information on the potential techniques that could be adopted and the expected volume of GHG emissions that could be reduced is presented. This paper bridges the gap between the industry and prospective researchers on how zero-emission of greenhouse gases from crude oil refinery plants could be attained via comprehensive explanations of future prospects in this regard.

2. Techniques for attaining net-zero emissions in refineries

As previously mentioned, the two strategies via which net-zero emissions can be attained in refineries are emission reduction and carbon offsetting. These strategies are often interconnected and may necessitate significant initial investments, but they offer substantial long-term environmental and economic benefits. This is a complex mission that requires the adoption of technologies aimed at reducing emissions throughout both production and energy generation processes.

- **Emission Reduction**

  The effective technologies which may be applicable in achieving emission reduction include (1) improvements of energy efficiency, (2) integration of renewable energy and (3) hydrogen utilization in crude oil refinery plants. The improvement of energy efficiency is one of the greatest effective and immediate strategies for reducing emissions in refineries. By optimizing refinery processes, upgrading equipment, and implementing advanced energy management systems (EMS), refineries can considerably minimize energy consumption. For example, systems of heat recovery allow refineries to capture and reuse waste heat, minimizing the need for additional energy inputs (Kang et al., 2020). By implementing EMS, refineries can monitor and control energy usage, ensuring that energy is used efficiently across operations. These improvements can lead to reduced operating costs and a substantial decline in carbon emissions, contributing to both economic savings and environmental goals.

  Another essential strategy for attaining net-zero emissions in refineries is the integration of renewable energy sources. Refineries traditionally rely on fossil fuels like fuel oil and natural gas for energy-intensive processes. By shifting to different sources of

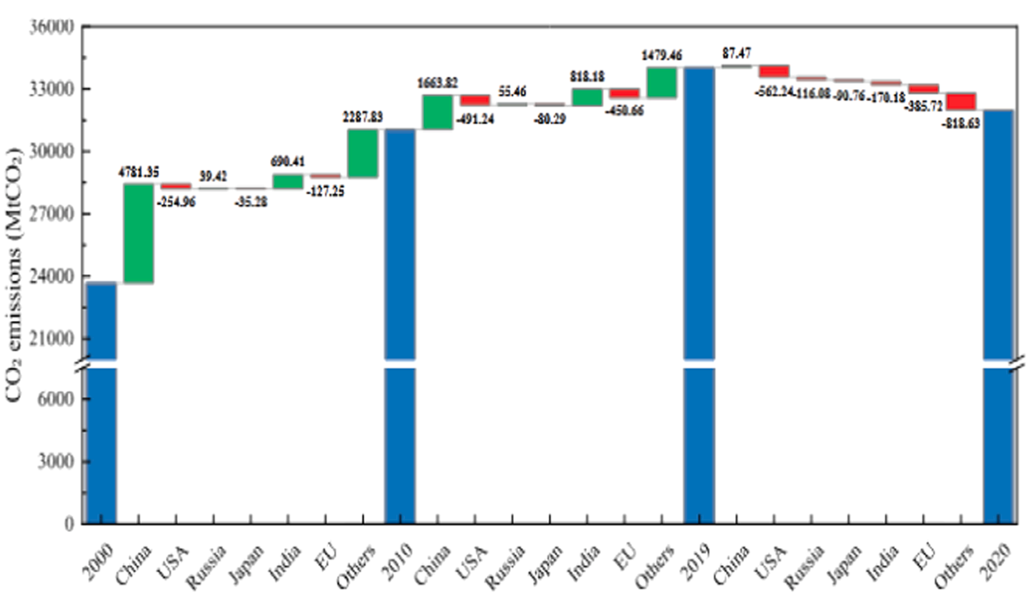

Fig. 1. Global CO_2 emissions from some countries around the world.

renewable energy such as wind, solar or biomass, refineries can significantly minimize their carbon footprint. These renewable sources can power operations such as distillation, cracking, and other high-temperature processes, which are typically fossil fuel-dependent. This does not only help in reducing CO_2 emissions but also contributes to the broader decarbonization efforts in the energy sector (Al-Rubaye et al., 2023).

Hydrogen, particularly green hydrogen manufactured via renewable electricity, is emerging as a promising clean energy source for the refining industry. Hydrogen can replace natural gas in energy-intensive refining processes such as hydrocracking and hydrogenation. These processes are essential for producing refined products, but they are typically carbon-intensive when powered by fossil fuels. Green hydrogen offers a cleaner alternative, enabling refineries to reduce their carbon emissions while maintaining production efficiency. Additionally, hydrogen can be used to produce hydrogenated products, such as clean fuels, further supporting the refinery's decarbonization goals. As hydrogen production technology continues to advance, its integration into the refining sector could be helpful in minimizing emissions (Zhao et al., 2021a).

- **Carbon offsetting**

Carbon capture and storage (CCS) is a vital technique of carbon offsetting from the atmosphere to attain net-zero emissions in refineries. This technology involves capturing CO_2 directly from the point of emission, such as from a refinery's smokestack, and transporting it to be deposited in underground geological formations (Ragothaman and Anderson, 2017). CCS has the ability to capture a significant portion of a refinery's CO_2 emissions, offering a feasible solution for industries that continue to produce high levels of carbon emissions. Although CCS technology is still in development and faces challenges in terms of scalability and cost, it is widely recognized as a key component of a broader strategy for reducing industrial emissions. By implementing CCS, refineries can effectively mitigate a large portion of their emissions, helping to meet net-zero targets.

2.1. Influence of increase in crude oil refinery numbers on GHG emissions trend in some countries around the globe

Between 2010 and 2018, approximately 24 % increase in GHG emissions was linked to the crude oil refining sector while a reduction by 9 % was noticed after these years due to the widespread COVID-19 pandemic (Lei et al., 2021). Crude oil refineries number increased from 739 to 839 between 2000 and 2021 from which the United States, China, United Kingdom and Europe took approximately 53 % of the global number making them to be among the regions with highest number of refineries. Though a decline in the number of refineries from 155 to 123 was recorded in the United States, the volume of crude oil being refined steadily and approximately remained constant at 17 million barrels per day (Mbd). In contrary, decrease in the crude oil volume refined (due to reduction in the average capacity of refinery) by 84.2 % and 39.1 % was recorded for the Caribbean and Sub-Saharan Africa respectively. In China, the increase in the refineries number from 127 to 179 before 2007 greatly influenced the level of crude oil demand resulting in average refinery capacity increase after 2007 (Dietz et al., 2021).

Consequently, the number of refineries greatly increased around the world causing the total GHG emissions from refineries globally to attain 34.1 Gt between 2000 and 2021. This record was based on an annual average increase at the rate of 0.7 % with the United States, China and EU27&UK contributing 24.1 %, 12.6 % and 15.6 % respectively of the total GHG emissions. Refineries located in China recorded approximately times three of the GHG emissions between 2000 and 2021 from 102.2 to 313.3 Mt. A similar case was reported in refineries located in India with rapid GHG emissions. However, a decline in the GHG emissions in refineries located in the Unites States from 25.9 % to 22.5 % between 2000 and 2021 did not deny them being ranked first around the globe. The order of GHG emissions from crude oil refining operations with reference to top ten countries around the world as at 2021 is United States > China > Russia > India > Japan > South Korea > Iran > Saudi Arabia > Italy > Brazil recording approximately 8.94 > 4.83 > 2.22 > 2.03 > 1.81 > 1.52 > 1.18 > 1.06 > 0.88 >- 0.71 (CO_2 equivalent Gt) (Ma et al., 2023) as shown in Fig. 2.

Global records have revealed the existence of 498 enterprises comprising 1095 refineries under their control. Out of these, only 4 % of the total enterprise (approximately 20 enterprises) dominated both the global GHG emissions and oil refining production between 2000 and 2021 (Zaman and Moemen, 2017). The United States, Russia, China and India took five, three, two and two respectively out of the top 20 enterprises while the United Kingdom, Brazil, Venezuela, Saudi Arabia, France, the Netherlands, Japan and Iran took one each (Zaman and Moemen, 2017). Between 2000 and 2021, the top 10 out of the 20 enterprises accounted for 33.8–38.1 % of the GHG emissions while 17.7–20.5 % was recorded for the remaining 10 enterprises. The respective average carbon emission intensity for the two groups were ranging 61.4–62.4 and 56.3–59.1 $kgCO_2eq/bbl$. The order of cumulative GHG emissions from the top ten enterprises engaging in crude oil refining is China Petrochemical Corp (China) > China National Petroleum Corp (China) > Exxon Mobil Corp (United States) > Valero Energy Corp (United States) > Saudi Arabian Oil Co (Saudi Arabia) > Royal Dutch Shell Plc (Netherlands) > Marathon Petroleum Corp (United States) > Rosneft Oil Co (Russia) > ENEOS Corp (Japan) > Chevron Corp (United States) emitting 1553.528 > 1445.516 > 1428.638 > 1418.899 > 1270.252 > 1164.017 > 1120.754 > 1051.236 > 924.141 > 869.692 Mt respectively as at 2021 (Ma et al., 2023). This information is presented in Fig. 3.

2.2. State-of-the-art on achieving net-zero emissions from crude oil refinery plants

Table 1 presents previous studies conducted and the state-of-the-art regarding how net-zero emissions could be attained from crude oil refinery plants. This comprises the title of the article consulted; scope of study and methodology; limitations; Observations and results obtained; strategies or technologies adopted for GHG emissions reduction; and conclusions. The table summarizes the role of refineries on the global economy and the adverse effects of GHG emissions during operations on the environment and human health. From the consulted literatures, it was made known that larger reduction of emissions could be attained while still aspiring betterment towards absolute transitioning to net-zero emissions. In summary, with reference to the articles consulted, studies have shown that appreciable cost will be needed by refinery in tackling GHG emissions and there is need to adopt cleaner technologies. The benefits of renewable energy incorporation into refinery operations; strengthening and enforcing of regulations for sustainable environmental safety; feasible outcome of positive and favorable policies from the government; the necessity for international collaborations among countries to tackle global warming; the need to fund research studies in the area of GHG emissions; the importance and significance of public and community awareness on global warming effects; and how the recommended strategies of GHG emissions reduction can be sustainable for future reference are the major suggestions, observations and conclusions.

2.3. Analysis of the potential outcomes of global GHG emissions reduction in crude oil refineries using technological approaches

Suggestions are made and some proactive steps have been taken by refineries around the globe to reduce GHG emissions. It has been projected that CO_2 emissions (which form part of GHG) could be reduced by 3–6 % between 2020 and 2030 if refineries' efficiencies are improved globally without the addition of new refineries (Marschinski et al.,

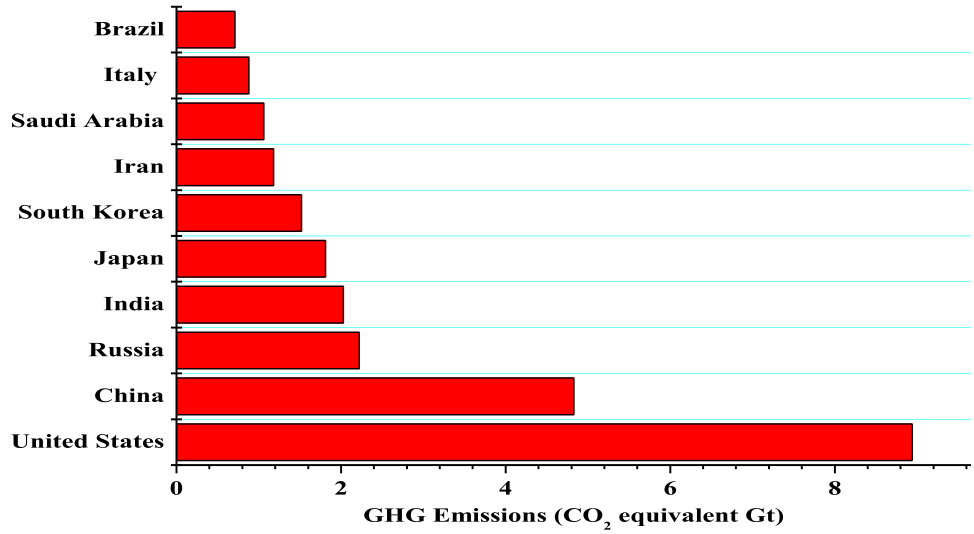

Fig. 2. Top 10 countries with highest GHG emissions from crude oil refineries located within them as at 2021.

2020). Within this period, an accumulative reduction of 532 Mt of CO_2 emissions is expected if the efficiencies of refineries in the top 10 countries (producing largest GHG emissions) are improved only while a reduction of 928 Mt is envisaged if all the efficiencies of all the refineries around the globe are improved. India and China have been specified to possess the most significant CO_2 emissions reduction in order of 105 Mt and 193 Mt respectively (Lei et al., 2021).

About 3 % of the GHG emissions from refineries could be reduced if catalytic cracking units could be upgraded to cleaner hydrocracking ones. The cumulative GHG emissions reduction from 446 Mt to 555 Mt between 2020 and 2030 is achievable with this technique. A situation where upgrading of all deep processing refineries to hydrocracking mode is executed in the United States has the potential of reducing cumulative CO_2 emissions to 196 Mt. In a scenario where scarcity of deep processing refineries is looming, such as Africa, the cumulative CO_2 emissions reduction is simply 3 Mt. In Asia, more than 50 % reduction of GHG emissions is feasible amounting to approximately 417 Mt if hydrocracking units are incorporated into all shallow processing refineries (Masnadi et al., 2018). Reductions of 63 Mt, 68 Mt and 74 Mt are feasible in Latin America, Middle East and Africa respectively if this same approach is adopted. Global reduction of cumulative CO_2 emissions by 4 % (731 Mt) to 9 % (1452 Mt) between 2020 and 2030 is attainable if the two previously mentioned measures are combined together. Significant reductions of GHG emissions in Europe and China attaining 219 Mt and 271 Mt could be achieved with this approach (Cai et al., 2019). Lastly, the elimination of coking units and backward catalytic cracking from crude oil refinery while the deep processing refineries is cleaned have been suggested to ensure GHG emissions in middle-aged refineries (Lei et al., 2021).

3. Future prospects of crude oil refineries towards attaining net-zero emissions

- **Technological innovations in clean refining**

  The future of crude oil refining will rely heavily on cleaner technologies that reduce carbon emissions. Hydrogen-based refining,

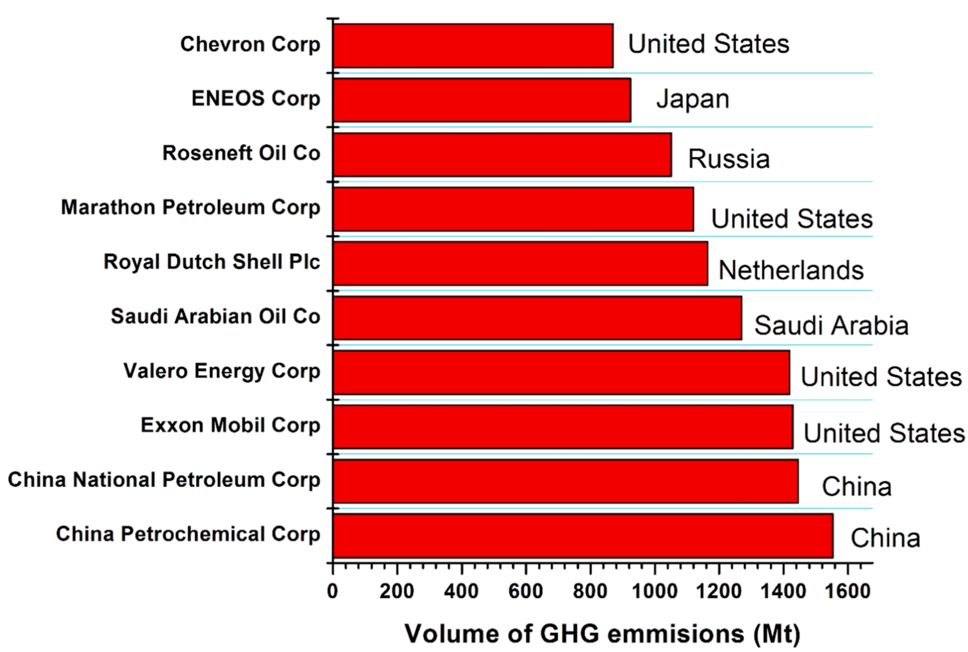

Fig. 3. Volume of GHG emissions in Mt from top ten enterprises engaging in crude oil refining and their respective countries of residence.

Table 1
Previous related studies on the state-of-the-art regarding how net-zero emissions could be attained from crude oil refinery plants.

Title	Scope of Study/ methodology	Limitation(s)	Observation(s)/ Results	Strategies/ Technologies	Adopted Technique	Conclusions	Ref.
IEA report on "The Oil and Gas Industry in Energy Transitions".	1. Focuses on the role of the oil and gas industry in energy transitions, including decarbonization strategies, reducing greenhouse gas emissions, and aligning with net-zero goals. 2. Emphasizes methane emission reductions, carbon capture utilization and storage (CCUS), and integration of low-carbon hydrogen. 3. The report analyzes data and scenarios such as the Stated Policies Scenario (STEPS) and the Net Zero Emissions (NZE) scenario by 2050. 4. It identifies pathways for emissions reductions, highlights technological advancements, and proposes strategic policy changes to transition the sector.	1. Key challenges include limited current investment in low-carbon technologies (less than 1 % of capital expenditure), scalability of new technologies, and the dependency on policy frameworks to drive systemic change. 2. Resistance from national oil companies adds complexity.	1. Methane emissions account for nearly half of operational emissions in the sector. 2. Electrifying operations and implementing CCUS can significantly reduce emissions. 3. Achieving net-zero requires a 75 % reduction in oil and gas demand by 2050 in the NZE scenario.	Reduction of methane emission Implementation of decarbonization Carbon capture utilization and storage	Emission reduction Carbon offsetting Carbon offsetting	1. Investment of $600 billion could halve the emissions intensity of oil and gas operations by 2030. 2. Demand for oil and gas peaks before 2030 in STEPS but requires steeper declines in NZE. 3. Cleaner technologies and policy-driven transitions can achieve substantial reductions in GHG emissions.	(International Energy Agency IEA, 2023)
The Role of Hydrogen in a global sustainable energy strategy	1. Investigates the use of hydrogen as a sustainable energy source for industrial operations, electricity generation, and transportation. focuses on how hydrogen is produced, its advantages for the environment, and how it fits into energy systems. 2. Examines production technologies such as developing biological techniques, renewable energy-powered water electrolysis, and steam methane reforming (SMR). 3. Examines case studies of hydrogen uses in developed nations such as Germany and Japan. 4. Includes environmental and techno-economic evaluations.	1. High production costs for green hydrogen. 2. Infrastructure challenges for hydrogen storage and distribution. 3. Scalability issues for biological hydrogen production and intermittent renewable energy supply.	1. Electrolysis efficiency improvements (e.g., advanced catalysts) reduce costs. 2. Fuel cell vehicles (FCVs) show promise but face infrastructure gaps. 3. Hydrogen in industrial applications enhances energy efficiency and reduces carbon intensity.	Hydrogen utilization	Emission reduction	1. Green hydrogen, when fueled by renewable energy sources, makes zero-carbon energy systems possible. 2. European pilot projects show how hydrogen can stabilize electricity networks and decarbonize industry. 3. The integration of renewable energy is supported by hydrogen storage.	(Andrews and Shabani, 2014)
Exploring the Barriers to Implementation of Carbon Capture Utilisation and	1. The study examines the technological, financial, and legal challenges preventing	1. High initial costs for CCUS technology implementation. 2. Lack of adequate infrastructure for	1. CCUS is technically feasible but needs substantial adaptation for local conditions in Nigeria.	Carbon capture utilization and storage	Carbon offsetting	1. Nigeria's energy sector, heavily dependent on fossil fuels, needs substantial	(Betiku and Bassey, 2022)

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Table 1 (*continued*)

Title	Scope of Study/ methodology	Limitation(s)	Observation(s)/ Results	Strategies/ Technologies	Adopted Technique	Conclusions	Ref.
Storage in Nigeria.	CCUS from being implemented in Nigeria. 2. It talks about CCUS's possibilities for Nigeria's energy industry and climate objectives. 3. The research makes use of case studies on CCUS deployment in other nations, technical evaluations, and a survey of the body of current literature. 4. The study pinpoints issues unique to Nigeria's energy and infrastructural environment.	CO_2 capture, transport, and storage. 3. Insufficient financial incentives and government policies to support large-scale projects.	2. The absence of carbon pricing and regulatory support hinders investment in CCUS technologies. 3. Public awareness of CCUS is limited.			investment to integrate CCUS technologies effectively. 2. Clear policy frameworks and international collaboration are key to overcoming barriers.	
The role of environmental policy in influencing governance and sustainability practices among Nigerian quoted companies a proposed framework.	1. Explains how governance and sustainability practices in Nigerian businesses are influenced by environmental legislation. 2. Focuses on governance frameworks, corporate environmental reporting, and incorporating sustainability activities into daily operations. 3. The methodology assesses how Nigerian listed firms report on environmental, social, and governance (ESG) issues. 4. Stakeholder and resource dependency theories are used to examine how outside forces affect business operations and sustainability reporting.	1. Variability in the quality of sustainability reports across companies. 2. Limited data availability for consistent measurement of sustainability practices. 3. Lack of regulatory enforcement and standardization for environmental disclosures.	1. Effective environmental policies improve transparency, corporate accountability, and community engagement. 2. Board size, independence, and expertise are significant factors influencing environmental reporting quality. 3. Economic incentives and policy alignment drive better ESG practices.	-	-	1. Strong environmental policies improve a company's performance in corporate governance measures and sustainability disclosures. 2. Adoption of global frameworks, such the Sustainable Development Goals (SDGs) of the UN, increases Nigerian companies' competitiveness internationally.	(Kumo et al., 2023)
Improving energy efficiency in electric systems in oil refineries: Economical and environmental evaluation.	1. The study evaluates the potential for improving energy efficiency in electric systems within oil refineries. 2. It focuses on strategies to enhance system performance, reduce energy waste, and lower environmental impacts through optimized technologies. 3. Reviews mathematical modeling techniques	1. The high expense of updating current infrastructure, technical difficulties integrating cutting-edge technology, and variations in energy performance indicators between facilities are some of the difficulties.	1. Major inefficiencies arise in energy generation, distribution, and conversion units. 2. Key improvements include reducing flaring, optimizing process conditions, and utilizing waste heat recovery systems. 3. Digital tools like real-time monitoring enhance efficiency.	Reduction of energy waste and enhancement of energy efficiency	Emission reduction	1. Effective energy management can lead to 30–50 % energy savings in key process areas like fired heaters, utilities, and compressors. 2. Optimization strategies reduce emissions and operational costs while increasing reliability	(Abdallah and El-Shennawy, 2019)

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Table 1 (*continued*)

Title	Scope of Study/ methodology	Limitation(s)	Observation(s)/ Results	Strategies/ Technologies	Adopted Technique	Conclusions	Ref.
	and energy management frameworks, including the use of energy performance indices (EPIs) for process areas. 4. Highlights methods like cogeneration, heat recovery, and system optimizations						
Challenges and opportunities in Nigeria's renewable energy policy and legislation	1. Investigates how to incorporate renewable energy sources such as biomass, wind, and solar into current energy systems. 2. Highlights possible possibilities to advance the adoption of sustainable energy while concentrating on technical, financial, and policy issues. 3. Evaluates the integration of renewable energy in different industries and areas by combining case studies with research reviews. 4. Evaluates energy storage technologies, grid stability, and cost-benefit scenarios for the deployment of renewable energy using analytical models.	1. Intermittency and variability of renewable energy sources complicate grid integration. 2. High initial costs of infrastructure upgrades and energy storage systems. 3. Regulatory and policy inconsistencies across regions hinder seamless adoption.	1. Smart grid technologies and distributed energy resource management systems offer solutions to integration challenges. 2. Energy storage systems like batteries and pumped hydro are crucial for managing variability. 3. Decentralized renewable energy systems improve grid reliability	Integration and incorporation of renewable energy	Emission reduction	1. Renewable energy integration enhances sustainability by reducing carbon emissions and dependence on fossil fuels. 2. Grid modernization, supported by policy incentives, is essential for successful implementation. 3. Economic benefits include lower energy costs and job creation in clean energy sectors.	(Onuh et al., 2024)
Carbon capture and storage (CCS): The way forward.	1. Explores Carbon Capture and Storage (CCS) as a critical technology for mitigating climate change. 2. Discusses its role in reducing CO_2 emissions from large point sources such as coal-fired power plants, cement factories, and oil refineries. 3. Reviews CCS technologies including pre-combustion, post-combustion, and oxy-fuel combustion methods. 4. Analyzes transport mechanisms (pipelines, shipping) and storage options (saline aquifers, depleted oil/gas fields). 5. Highlights international CCS projects such as Sleipner in Norway	1. High costs of capture, transport, and storage infrastructure. 2. Energy penalties associated with CO_2 capture and compression processes. 3. Public acceptance issues and regulatory uncertainties in many regions.	1. Saline aquifers and depleted oil fields offer promising storage options, with monitoring systems ensuring minimal leakage risks. 2. Integration with Enhanced Oil Recovery (EOR) adds economic incentives but raises questions about net carbon reductions.	Reduction of CO_2 emission Carbon capture via pre- and post-combustion	Emission reduction Carbon offsetting	1. CCS can reduce emissions by capturing up to 90 % of CO_2 from industrial sources. 2. Long-term projects like Sleipner and Quest demonstrate feasibility and scalability. 3. Successful implementation requires supportive policies and international cooperation.	(Bui et al., 2018)

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Table 1 (*continued*)

Title	Scope of Study/ methodology	Limitation(s)	Observation(s)/ Results	Strategies/ Technologies	Adopted Technique	Conclusions	Ref.
	and Boundary Dam in Canada.						
A review of trends and drivers of greenhouse gas emissions by sector from 1990 to 2018.	1. The study analyzes global GHG emissions trends from 1990 to 2018, focusing on key sectors: energy systems, transport, buildings, industry, and AFOLU (Agriculture, Forestry, and Other Land Use). 2. Decomposition analysis was combined using the Kaya framework to assess emissions drivers (e.g., population, energy intensity) with sectoral and regional trends analysis. Emissions are evaluated for direct and indirect sources	1. Uncertainties in non-OECD data and land-use emissions. 2. Excludes consumption-based emissions. 3. Challenges in integrating indirect emissions from global trade.	1. Energy systems dominate emissions globally; progress varies regionally. 2. Rapid emissions growth in Asia due to industrialization. 3. Improvements in energy efficiency in OECD regions are offset by rising material demands elsewhere.	Emission drivers estimations	Emission reduction	1. Total GHG emissions grew by 11 % (2010–2018), driven by fossil fuel use. 2. Decarbonization progress in Europe contrasts with sustained reliance on coal in some regions.	(Lamb et al., 2018)
Environmental sustainability measures in the oil and gas industry	1. This focuses on environmental sustainability measures in the oil and gas industry, addressing impacts across upstream, midstream, and downstream operations. 2. Discusses key sustainability practices, technological innovations, and challenges in implementation. 3. This uses analytical review based on industry practices, case studies, and sustainability frameworks. 4. Examines carbon capture technologies, water recycling, and emission reduction strategies within a lifecycle perspective of hydrocarbon reservoirs.	1. Highlights the high cost of implementing sustainability measures. 2. Limited adoption of innovative technologies, regulatory disparities, and data gaps in global operations. 3. Identifies challenges in transitioning to low-carbon solutions.	1. Identifies significant emissions from oil and gas operations, the growing importance of regulatory compliance, and increasing investments in renewable energy and eco-friendly technologies. 2. Notes positive trends in energy efficiency improvements.	Implementation of environmental sustainability measures	Emission reduction	1. Demonstrates that sustainability practices like carbon capture and wastewater recycling can significantly mitigate environmental impacts. 2. Stresses the need for a balanced approach to meet energy demands while reducing ecological footprints.	(Laturkar and Laturkar, 2023b)
Assessment of efficiency improvement and emission mitigation potentials in China's petroleum refining industry	1. The study assesses the efficiency improvement and emission reduction potential in China's petroleum refining industry using a specialized process-based MESSAGEix-petroleum refining model. 2. Focuses on energy consumption, emissions, and the impact of policy and technological interventions. 3. This involves	1. Limited database on energy efficiency measures and technologies. 2. Assumptions on crude oil production and imports, as well as data availability for specific technical parameters, introduce uncertainties. 3. Lacks feedback between oil consumption and downstream product demand.	1. Energy efficiency measures reduce total energy consumption by up to 9 % (EE) and 12 % (EE_CP) by 2050. 2. Significant CO_2 emissions (47 %) stem from process activities like atmospheric distillation and catalytic cracking, with limited reductions from energy efficiency interventions	Emission mitigation and controlling measures	Emission reduction	1. Maximum savings in softened water (80 %) and 27 % in electricity and coke usage under EE_CP. 2. CO_2 emissions reduced by 10 % under EE_CP. 3. GHG reductions minimal: 1 % $PM_{2.5}$, 2 % SO_2, and 4 % NO_x. 4. Suggests a combination of energy efficiency and pollutant-specific controls.	(Zhao et al., 2021b)

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Table 1 (*continued*)

Title	Scope of Study/ methodology	Limitation(s)	Observation(s)/ Results	Strategies/ Technologies	Adopted Technique	Conclusions	Ref.
	development of MESSAGEix-petroleum refining model, integrating detailed technical characteristics of refining processes. 4. Conducted simulations under three scenarios: Baseline (BL), Energy Efficiency (EE), and Energy Efficiency with Carbon Price (EE_CP) from 2010 to 2050.						
Adaptive CO_2 emissions mitigation strategies of global oil refineries in all age groups	1. This study assesses global oil refineries' CO_2 emission data from 2000 to 2018, including 1056 operating refineries. 2. The sources for this data correlation include databases like Industry. 3. The development of a time-series CO_2 emissions inventory (CEADs-GREI) using plant-level data. 4. Annual emissions estimated using refinery throughput and emission factors. 5. Analyzed emission patterns and reduction potentials by age, region, and technology.	1. Limited data on unit-level operating hours and energy consumption. 2. Larger uncertainties for refineries with unknown configurations or in developing regions due to incomplete data.	1. CO_2 emissions increased by 24 % from 2000 to 2018. 2. Asia, especially China and India, emerged as major contributors due to new refineries. 3. Deep processing refineries had significantly higher emissions compared to shallow ones.	Estimation of global CO_2 emission	Carbon offsetting and emission reduction	1. Without intervention, refineries will emit 16.5 Gt CO_2 from 2020 to 2030. 2. Efficiency improvements and technology upgrades could cut emissions by up to 10 % in the same period. 3. Mitigation strategies vary by region and refinery age.	(Lei et al., 2021)
Hydrogen for net zero	1. The study focuses on clean hydrogen, including renewable hydrogen (produced via electrolysis or biomass gasification with carbon sequestration) and low-carbon hydrogen (produced from non-renewable sources with CCS). 2. Hydrogen demand and abatement potentials are modelled under a 1.5–1.8°C global warming scenario, using economic and energy transition parameters. 3. The analysis spans 39 sub-sectors and considers regional and global dynamics	1. Lack of standardized global methodologies for defining and certifying hydrogen as "renewable" or "low-carbon". 2. High initial investment and infrastructure requirements.	1. Transitioning to clean hydrogen requires scaling production, infrastructure, and end-use technologies. 2. Regional dynamics influence adoption rates, with Europe and China leading in steel and industrial applications	Utilization of clean hydrogen gotten from electrolysis Low-carbon hydrogen adoption	Emission reduction Carbon offsetting	1. Clean hydrogen has the potential to abate 730 MT of CO2 annually by 2030, rising to 7 GT annually by 2050. 2. Significant reductions in emissions are expected in steel production, ammonia synthesis, and power.	(Hydrogen Council, 2021)
Hydrogen for decarbonization	1, The study focuses on hydrogen produced via water electrolysis and methane reforming with CCS, highlighting physical and chemical challenges of hydrogen's low	1. Limited scalability of electrolysis due to high electricity demand. 2. Significant energy loss during hydrogen storage and transport. 3. Low efficiency in power applications	1. Ammonia, methanol, and steel production are high-priority applications for low-carbon hydrogen. 2. Marine and aviation fuels are potential growth sectors.	Hydrogen production Methane reforming	Emission reduction Carbon offsetting	1. Decarbonization potential is sector-specific, with high impacts in industrial applications like ammonia and methanol production and limited feasibility in residential use.	(Clean Air Task Force, 2023)

(*continued on next page*)

Table 1 (*continued*)

Title	Scope of Study/ methodology	Limitation(s)	Observation(s)/ Results	Strategies/ Technologies	Adopted Technique	Conclusions	Ref.
	energy density and difficult storage/ transport. 2. The study considers analysis based on current hydrogen production statistics, supply chain challenges, and lifecycle emissions of clean hydrogen under policy-driven frameworks for decarbonization.	(24 % RTE for electrolytic hydrogen).	3. Residential and light-duty vehicle uses are less viable.				

electrification of processes and carbon capture are major innovative areas. Hydrogen-based refining involves using green hydrogen synthesized via renewable energy, replacing natural gas and cutting CO_2 emissions significantly. Similarly, electrification of refinery processes, such as distillation and heating, can decarbonize these energy-intensive operations (Jing et al., 2020). Additionally, refineries can begin their journey towards net-zero emissions by implementing incremental upgrades to existing equipment. Retrofitting furnaces, turbines, and heat exchangers to improve energy efficiency and reduce emissions is a cost-effective starting point. Additionally, adopting advanced process control systems to optimize operations can result in significant emissions reductions without requiring major capital investment (Talaei et al., 2020).

- **Circular economy and waste reduction**

  Refineries can adopt circular economy principles by reducing waste, recycling by-products, and reusing resources. Instead of discarding waste, refineries could adopt waste-to-energy technologies or use waste materials, such as plastics, to create fuels or chemicals (International Energy Agency IEA, 2021). This approach can reduce landfill waste and decrease the use of petroleum-based feedstocks. Moreover, improving resource efficiency through circular models can reduce operational costs and minimize emissions over time.

- **Green financing and investment opportunities**

  As global markets increasingly prioritize sustainability, green financing will be crucial to supporting refinery decarbonization. Green bonds, ESG funds, and government-backed incentives can provide the necessary capital to adopt low-carbon technologies. This shift can relieve the initial high costs of clean technologies and make the shifting to net-zero emissions to be more financially viable for refineries. Governments must enact policies that facilitate the transition to net-zero emissions (Wu et al., 2022; Popoola and Yusuff, 2021b). This includes implementing carbon pricing mechanisms, offering subsidies for clean technologies, and providing incentives for refineries to adopt renewable energy sources. Harmonized global regulations could reduce the complexity of compliance for multinational refineries and create a more stable market for green technologies.

- **Strengthening policy frameworks**

  Global cooperation and uniform regulatory standards will be vital for achieving net-zero refineries. Refineries around the world should come into terms focusing on global GHG emissions reduction to create more enabling and friendly environments. Governments should also establish clear long-term policies that incentivize investment in clean technologies, encouraging refineries to reduce their carbon footprints (Boersma and Kriesten, 2017).

- **Green hydrogen production and refining processes electrification**

  Green hydrogen synthesized via water electrolysis with the aide of renewable energy has a promising pathway potential for decarbonizing refinery processes. Hydrogen can replace natural gas in processes like hydrotreating and hydrogenation. Although currently expensive, green hydrogen cost is anticipated to reduce as renewable energy becomes more widespread. In the same way, electrification is a promising strategy for decarbonizing refineries, particularly when electricity comes from renewable sources (International Renewable Energy Agency IRENA, 2020). Electrifying refinery processes such as heating and separation could reduce fossil fuel dependency and help lower emissions. However, some challenges remain in generating the high-temperature heat required by some refinery processes.

- **Use of advanced biofuels and increased energy efficiency**

  Refineries could use advanced biofuels, derived from algae or waste, as an alternative to conventional biofuels and fossil fuels. These fuels are produced from non-food sources, minimizing competition with food production and providing more sustainable feedstocks. Advanced biofuels could be extremely active in decarbonizing sectors such as aviation and shipping. However, studies on the economic analysis of replacing fossil fuel with biofuels in refineries together with the sustainability are still rare. Future studies should critically look into quantifying the cost analysis of GHG emissions reduction using fossil fuels in refinery operations and the cost that may be incurred in generating biofuels from the suggested sources. Nonetheless, the quantity of biofuel energy that can be generated should be investigated in comparison with the conventional energy consumption with fossil fuels. To make this more viable and sustainable, it is recommended that refineries should apply energy generated from biofuels to power some small units within the refinery to ascertain the efficacy of this technology. Policies that will make this sustainable can then be fully incorporated.

  Also, advancing energy efficiency in refineries via technological upgrades and process optimization is one of the most efficient means of reducing emissions. Technologies like heat recovery systems and energy management software can help refineries optimize energy use, leading to lower emissions over time. Refineries should invest in energy-efficient techniques and process optimization to reduce energy usage. Refineries generate significant amounts of waste heat during operations. Recovering and repurposing this heat can increase total energy efficiency, lower energy consumption and reduce emissions. This can include upgrading to more efficient equipment, optimizing heating and cooling processes, and reducing flaring (Adebiyi, 2022; Popoola et al., 2022; Liu et al., 2021).

- **Integration with renewable energy and implementation of digital technologies**

Refineries can minimize their reliance on fossil fuels via using renewable energy (Fig. 4). This can be used to offset fossil fuel consumption, helping to lower emissions while providing a stable, long-term energy supply. Furthermore, the implementation of digital technologies like machine learning, artificial intelligence and big data analytics can assist refineries in optimizing their energy consumption and reducing emissions (Zhao et al., 2021b). These technologies can improve operational efficiency by identifying inefficiencies in real time, predicting equipment failures, and optimizing refining processes (Tao et al., 2021).

- **Transitioning to low-carbon petrochemicals and investment in carbon neutrality**
  Refineries can shift focus from producing high-carbon fuels to producing low-carbon petrochemicals that are essential in industries like plastics, fertilizers and non-toxic chemicals. Using sustainable feedstocks and cleaner processes for petrochemical production can significantly reduce refinery emissions. This reduces their carbon footprint while diversifying their product offerings. Refineries should adopt comprehensive carbon management plans that include not only emissions reductions but also carbon offsetting strategies. This could involve investing in reforestation projects or purchasing carbon credits from other sectors to neutralize any remaining emissions after reducing operational CO_2 output (Yu et al., 2008). Also, a growing number of refineries are committing to achieving carbon neutrality by investing in renewable energy or carbon offsets. Carbon-neutral refineries balance their emissions by funding reforestation projects or purchasing renewable energy credits, helping to contribute to broader decarbonization efforts.
- **Investment in research and development coupled with industrial collaboration**

Increased investment in R&D will lead to breakthroughs in refining technologies that significantly reduce emissions. This is crucial to enhance discovering new refining technologies that can drastically reduce emissions, such as next-generation catalysts, more efficient distillation methods, and alternative feedstocks. Collaborative research efforts between governments, industries, and academic institutions will be key to developing more energy-efficient refining processes (Mohanta et al., 2023). The refining industry will benefit from greater collaboration and knowledge sharing, which will accelerate the implementation of low-carbon technologies. By working together, refineries can overcome high capital costs and technological hurdles, scaling up solutions to achieve net-zero emissions. Nevertheless, future research should focus more on how refineries can be producing low-sulfur fuels which have a reduced environmental impact as compared with high-sulfur fuels, especially in terms of reducing greenhouse gas emissions (Fazakas et al., 2023).Nonetheless, joint collaborative research can be conducted between crude oil refineries and petrochemical industries on production of useful fine chemicals from captured CO_2 via chemical processes. Fig. 5 is the cyclic representation of various possible finished products that could be prepared from captured CO_2.

- **Use of biomass and waste feedstocks and their hydrogenation**
  Biomass and waste feedstocks such as residues from agricultural origin or municipal solid waste can be used in refineries to reduce reliance on fossil raw materials. These feedstocks are renewable and can help lower the carbon footprint of refined products. Also, refineries can use hydrogenation to convert bio-oils or waste products into high-quality fuels and chemicals, reducing the need for fossil feedstocks. This process enables a circular economy by turning waste into treasured resources (Veza et al., 2023).
- **Sustainable Aviation Fuel (SAF) production**
  Refineries can pivot toward the production of Sustainable Aviation Fuel (SAF), which has a reduced carbon footprint than conventional jet fuel. SAF, derived from biomass or waste oils, can significantly reduce lifecycle emissions in the aviation industry, a sector that is challenging to decarbonize (United Nations Framework Convention on Climate Change UNFCCC, 2022).
- **Decentralized refining and modular systems; and process intensification**
  Modular refining systems offer a more flexible and sustainable alternative to traditional large-scale refineries. These smaller, scalable units can be powered by renewable energy and biofuels, reducing emissions and improving efficiency (Lala et al., 2024; Popoola et al., 2013b). Process intensification involves redesigning refinery processes to make them more efficient, reducing energy consumption and emissions while enhancing the overall output. Innovations in reactors and separation technologies are central to this strategy.
- **Global carbon markets and low-carbon fuels for heavy industries**
  Participation in global carbon markets allows refineries to offset emissions through carbon credits, which can be traded to finance low-carbon technologies. By participating in these markets, refineries can gain financial incentives for reducing emissions (Wei et al., 2022). Equally, low-carbon fuels such as low-sulfur diesel or ammonia can help reduce emissions from heavy industries like steel and cement production, as well as from the shipping sector.

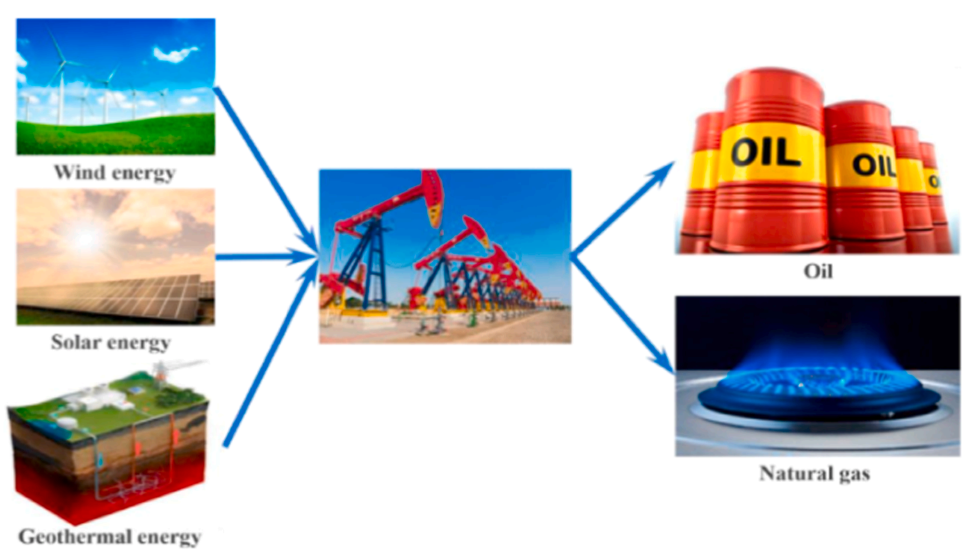

Fig. 4. Integrating sources of renewable energy for crude oil processing.

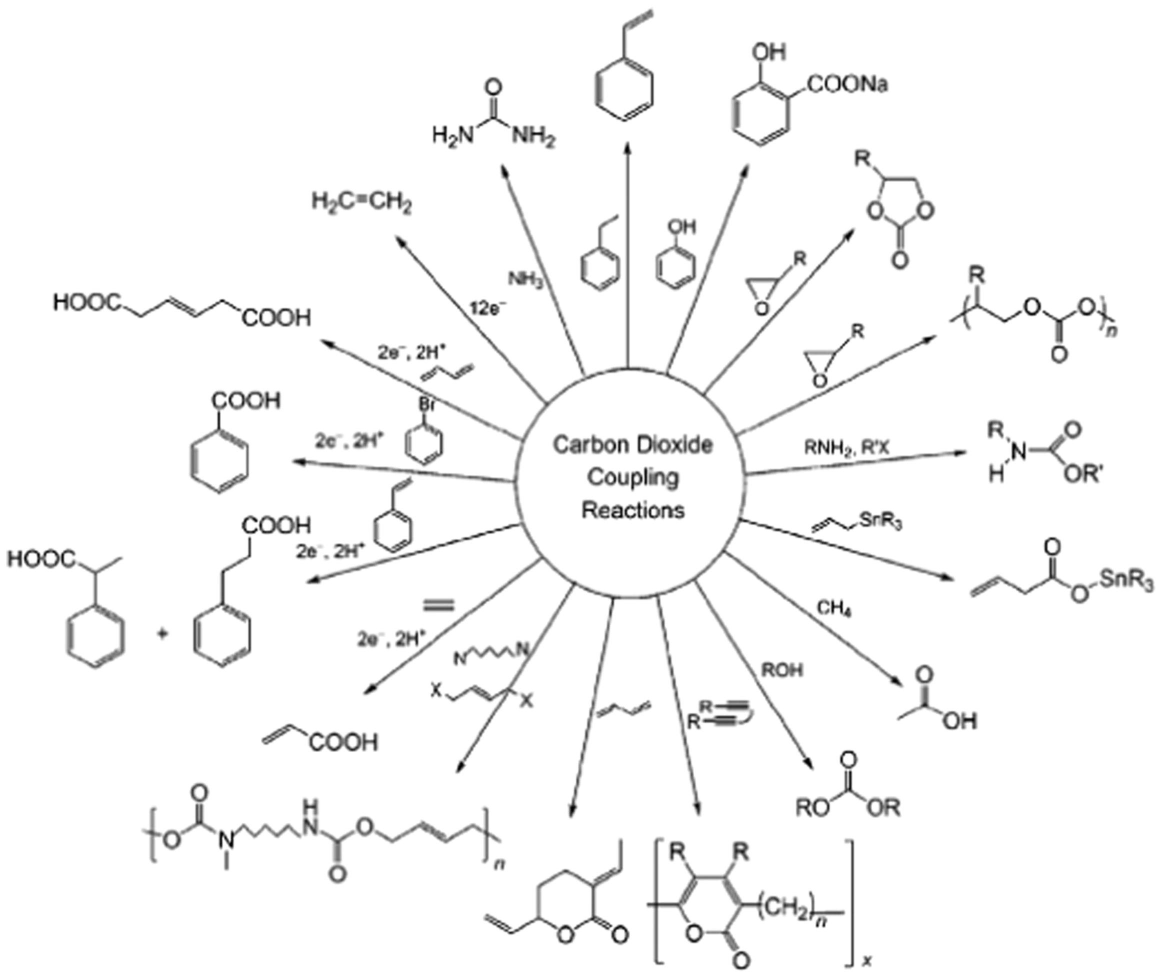

Fig. 5. Various finished chemicals that could be produced from captured CO_2 (Yu et al., 2008).

Refineries could produce these fuels to decarbonize difficult-to-electrify industries (Intergovernmental Panel on Climate Change IPCC, 2021).

- **Smart grid integration together with carbon-intensive sectors for synergies**

By integrating with smart grids, refineries can effectively manage their energy demand and optimize consumption based on renewable energy availability, reducing fossil fuel reliance and cutting emissions. This also allows for more efficient energy distribution and consumption, optimizing when and how electricity is used based on availability from renewable sources. Also, refineries can collaborate with other carbon-intensive sectors, such as cement and steel industries, to create synergies in decarbonization efforts (World Health Organization WHO, 2020). By sharing carbon capture infrastructure or hydrogen production facilities, refineries can reduce costs and speed up emissions reductions.

4. Conclusions

Despite the inestimable influence of refining industry on the global economy, it stands out as one of the highest contributors of GHG emissions resulting from the high energy demand of the operations involved. There is global need to transit to net-zero emissions to safe our environment from climate change and other hazardous health risks being posed. Achieving net-zero emissions in crude oil refineries requires collaboration from multiple stakeholders, including governments, industry players, environmental organizations, and technology providers. A unified global policy framework is critical to ensure consistent and fair regulations, which can facilitate the global adoption of clean technologies. Cross-sector collaboration and investments in research and development will also play pivotal roles in overcoming the existing barriers to sustainable refining practices. In conclusion, while the challenges in attaining net-zero emissions in crude oil refineries are substantial, they are not in surmountable. Through technological innovation, policy support, financial incentives, and industry collaboration, refineries can minimize their carbon footprint and influence the efforts in tackling global climate change. The transition to net-zero is not environmentally essential but also presents a business opportunity, allowing refineries to future-proof their operations in a decarbonized world. The journey toward a sustainable refining industry is complex, yet crucial for the planet well-being and future generations.

CRediT authorship contribution statement

Lekan Taofeek Popoola: Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Formal analysis, Conceptualization. **Yuli Panca Asmara:** Visualization, Validation, Resources. **Lois Onyejere Nwobodo:** Resources, Methodology. **Celestine Chidi Nwogbu:** Methodology, Formal analysis. **Usman Taura:** Validation, Resources, Investigation. **Alfred Ogbodo Agbo:** Project administration, Conceptualization.

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The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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