NEXT-GEN PETROCHEMICAL PROCESSES: DEVELOPING LOWER-CARBON PATHWAYS TO PRODUCE ESSENTIAL PETROCHEMICALS

1. Abstract

The global petrochemical industry is projected to exceed 1.25 trillion USD by 2035, sustaining a compound annual growth rate (CAGR) of 6.03% between the years of 2026 to 2035. The petrochemical industry's growth is propelled by increased demand for synthetic fibers and plastics, accelerated urbanization, and heightened use of "lightweight" materials across industries[1]. However, with society growing more concerned with climate change alongside CO_2 emissions and its implications on the environment, meeting this growth and demand for petrochemical products requires that more environmentally friendly, lower-carbon pathways be developed and further implemented. This review examines recent advancements in lower-carbon technologies, including catalysts, alternative feedstocks, and renewable energy integration in naphtha cracking, and proposes coordinated policy frameworks to advance a more sustainable and carbon-conscious industry. There have been many significant improvements in alternative feedstocks; with recycling, bio-based production, newly engineered microbes and "non-crop" biomass resources can be used to create a multitude of petrochemical products, minimizing carbon emissions[7]. Waste biomass utilization and CO_2 capture utilization and storage (CCUS) technologies have been enhanced but remain somewhat limited in widespread adaptation[3]. To decarbonize the high energy demands of naphtha cracking, electrification and ammonia-based fuel technologies have emerged as leading renewable alternatives[4]. Ultimately, furthering the future of lower-carbon pathways to produce necessary petrochemicals in the petrochemical industry cannot be standalone without coordinated, extensive policy measures that emphasize ecological awareness across all sectors, encourage diversity in petrochemical production, and regard the carbon life cycle with utter seriousness[7, 11].

2. Introduction

The global petrochemical industry is expected to reach new market heights; notably, the ethylene segment held the largest share at 40.6% of market revenue in 2025, and the methanol segment is projected to grow at a CAGR of 7.9% from 2026 to 2035[10]. However, sustaining this growth comes at a significant environmental cost. The petrochemical industry is the largest energy-consuming industrial sector, accounting for more than 30% of total industrial energy consumption and is on course to become the leading end-use of fossil fuels within the next three decades[4]. According to the International Energy Agency's (IEA) Global Energy Review (2025), overall energy-related CO_2 emissions reached a record high of 37.8 Gt CO_2, coinciding with unprecedented atmospheric CO_2 concentrations of 422.5 ppm in 2024[5]. Increased natural gas and coal consumption were the primary drivers of this rise[10]. Notable disparities exist between developing and advanced economies; developing economies saw a 1.5% increase in energy-related CO_2 emissions, while advanced economies achieved a 1.1% decrease, attributed to greater adoption of low-emissions energy sources[10]. These trends underscore the extent to which technological progress shapes both environmental outcomes and economic trajectories. Critically, naphtha cracking furnaces alone account for approximately 40% of the petrochemical industry's energy-related CO_2 emissions, making their decarbonization a central priority. Given that petrochemical production is highly energy-intensive and that 90% of plastic products are still derived from fossil feedstocks, continued advancement in lower-carbon pathways is essential to reducing global CO_2 emissions and decreasing fossil fuel dependency[3, 4]. This review examines the petrochemical industry's progress toward environmentally sustainable production through advancements in catalysts, alternative feedstocks, and renewable energy integration in naphtha cracking, addressing key challenges related to energy efficiency and scalability. It further acknowledges that the industry's transformation depends on coordinated efforts among policymakers, industry actors, and consumers to sustain lower emissions and uphold environmental responsibility[11].

3. Catalysts

In recent years, the petrochemical industry has agreed that lowering emissions and promoting sustainability is at the forefront of priorities[8]. Optimizing catalysts is one of the many ways the industry looks to achieve these goals, while also upgrading process efficiency in production[8].

3.1 Advancements in Nano catalysts

Nano catalysts have gradually emerged in petroleum refining; these catalysts possess a high surface area-to-volume ratio and nanoscale properties[2]. Nano catalysts' high surface area-to-volume ratio allows for more active sites present for reactions, inducing boosted conversion rates and strengthened selectivity required for jet fuel and diesel products[2]. Furthermore, nanoscale properties found in nano catalysts permit for honed control regarding shape and size of each particle, improving the stability and distribution of active sites, resulting in lowered byproduct formation and lengthened longevity under hydrocracking conditions[2].

Specifically, when metal nano catalysts, either gold or platinum, are scattered on carbon nanotubes where CO_2 hydrogenation is optimized, a conversion efficiency of 85% and selectivity of ~70% are possible due to smaller particle sizes. Nano catalysts, unlike traditional catalysts, can operate at lower temperatures, improving reaction rates, as illustrated in Figure 1 below. In summary, nano catalysts are opening doors for achieving lower carbon emissions in the petrochemical industry by permitting more efficient, selective, lower-temperature chemical processes, such as hydrocracking and catalytic reforming[2].

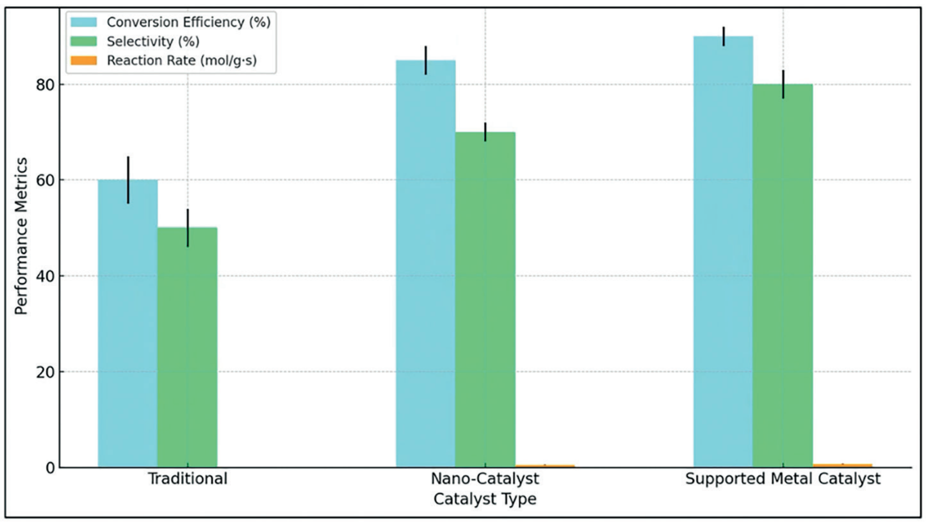

Figure 1: Catalysts and their Performance Metrics

Source: Akhtar, M. S.; Ali, S.; Zaman, W. Recent Advancements in Catalysts for Petroleum Refining. Catalysts 2024, 14, 841. https://doi.org/10.3390/catal14120841.

3.2 Advancements in Hierarchically Structured Catalysts

Hierarchically structured catalysts resemble porous structures present in biological and geological materials and can be further categorized as a blend of micro-, meso-, and macropores; these catalysts face improved mass transport within due to their hierarchical porosity, benefitting access to active sites[2]. Accordingly, hierarchically structured catalysts exhibit upgraded catalytic performance in processes, such as FCC, since the pores induce a beneficial environment for handling large hydrocarbon molecules[2]. Like nano catalysts, these benefits can be further amplified when intentional pore sizes and compositions are imposed, resulting in higher yields and evolved product dispersion[2]. With these aspects, hierarchically structured catalysts are the next step in lowering carbon emissions in processes, for hastened mass transfer and increased active sites give way to reductions in energy consumption and deactivation[2].

3.3 Advancements in Supported Metal Catalysts

Improving the long-term performance of catalysts relies upon advancements in dispersion and stability of metal particles within supported metal catalysts. As a result, hydrogenation and dehydrogenation reactions in hydrotreating and catalytic reforming can be elevated in their production of clean fuels and high-octane gasoline components[2].

Furthermore, the synthesis and characterization of these catalysts have grown, creating more productive, substantial systems that meet the demanding conditions of refineries[2]. In fact, the utilization of atomic layer deposition (ALD) as a synthesis process has produced highly uniform supported metal catalysts as this technique permits exact control involving thickness and composition of active layers, demonstrated in Figure 2 below[2]. Through this highly precise synthesis process, catalysts can be created with individualized features ranging from increased resistance to sintering and operating conditions of petroleum refining[2].

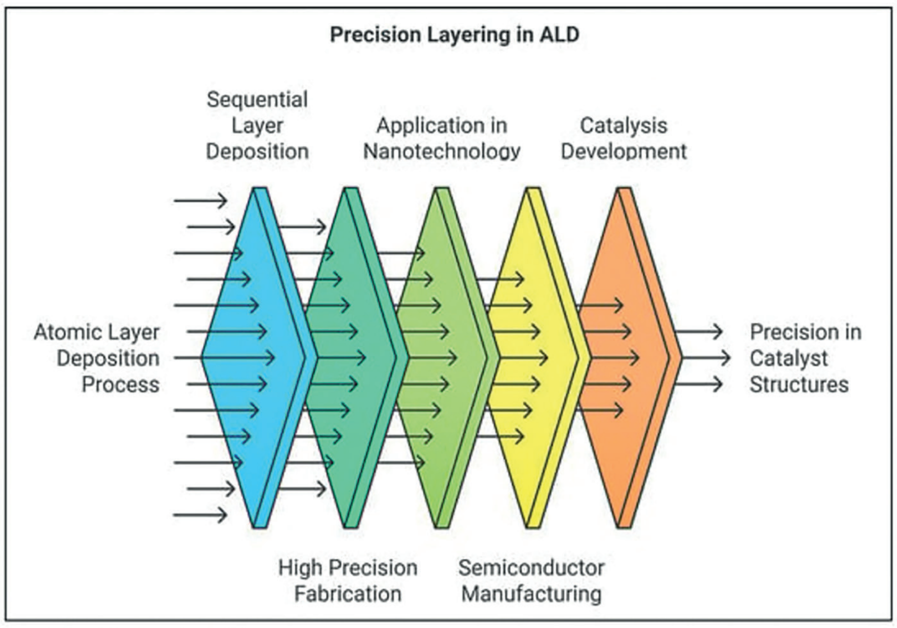

Figure 2: Precision Layering in ALD

Source: Akhtar, M. S.; Ali, S.; Zaman, W. Recent Advancements in Catalysts for Petroleum Refining. Catalysts 2024, 14, 841. https://doi.org/10.3390/catal14120841.

Strong metal-support interactions (SMSIs) alongside the minimization of particle sizes may achieve the full potential of conversion efficiency, selectivity, and reaction rate in supported metal catalysts[2]. With the addition of SMSIs, supported metal catalysts (metals, palladium or rhodium, on reducible oxide supports, like TiO_2 and CeO_2) may achieve a conversion efficiency of ~90%, selectivity of ~80%, and higher reaction rates have found to be possible even at lower energy and temperature levels under these conditions[2].

The refined ability to tweak the selectivity and yield of supported metal catalysts has furthered the growth of lower-carbon pathways in processes, such as hydrotreating and catalytic reforming, that often-faced challenges in managing waste and byproducts[2].

3.4 Green Catalysis

In response to growing environmental concerns, the petroleum refining industry has increasingly focused on advancing green catalysis where the primary focus is developing and applying catalysts that reduce the environmental implications of usual refining operations through sustainable material use, waste reduction, and extended catalyst longevity[2]. One key aspect of green catalysis is employing bio-based materials in catalyst synthesis since they provide an environmentally friendly alternative to traditional catalysts[2].

Bio-based catalysts have the versatility to be produced from natural polymers, plant-derived substances, or waste biomass[2]. Specifically, lignin-generated catalysts pose a more favorable possibility in refining processes since they are more sustainable, efficient, and reusable than standard catalysts[2,15]. Lignin-based catalysts possess high stability and exceptional performance provided by their aromatic units and three-dimensional interpenetrating polymer network arrangement[15]. Since lignin is a renewable biomass resource, lignin-derived catalysts reduce dependence on petroleum-based catalysts materials and contribute to reducing the overall carbon-footprint of catalytic processes[15].

More research has been conducted into lignin-derived solid acids and lignin-derived noble metal catalysts, with few branching into lignin-derived solid bases[15]. However, despite how promising lignin-based catalysts present themselves to be, more research into commercializing them and deriving their true capacity needs to be undergone if lower carbon pathways are to be achieved and mainstream in the future[15]. So, for future commercial applications, lignin-based catalysts should be further developed in scale-up reaction, and their use in biodiesel and hydrocarbons production should also be further investigated[15].

3.5 Catalysts and Carbon Intensity Reduction in Refining

Catalysts are a critical tool for reducing the carbon intensity of petroleum refining processes, including hydrotreating, catalytic cracking, and reforming[7, 8, 15]. Advanced synthesis techniques, such as atomic layer deposition (ALD) and microwave-assisted synthesis, have produced more precisely engineered catalysts that lower reaction energy barriers, reduce pollutant emissions, and decrease the energy input required per unit of refined output in conventional refining operations[2]. In microwave-assisted synthesis, reactants are rapidly heated through microwave radiation, yielding shorter reaction times, more consistent particle production, and finer control over heating at the molecular level — resulting in catalysts with higher surface area, crystallinity, and active site dispersion that drive more efficient reactions with less energy expenditure[2].

Novel catalytic materials, including nano- and hierarchically structured catalysts, have further enabled higher conversion rates and improved selectivity; by modifying pore structure and surface area, these catalysts enhance the diffusion of reactants and products, suppress unwanted byproduct formation, and reduce coke deposition on active sites- a key driver of energy waste and emissions in refining[2,8].

Together, these advances improve hydrogen utilization efficiency, reduce the frequency of energy-intensive catalyst regeneration cycles, and lower overall energy consumption per unit of output, all of which directly reduce the carbon intensity of refining operations[2,8]. As catalyst technology continues to mature, its contribution to achieving long-term net-zero targets in the petrochemical industry is increasingly supported by both laboratory and industrial-scale evidence[2 ,8, 9, 15].

4. Alternative Feedstocks

As demand for environmentally sustainable production grows, the petrochemical industry has increasingly turned to alternative feedstocks to reduce fossil fuel dependency and lower carbon emissions[4, 7] Key approaches include the recycling of plastic waste through material and chemical pathways, bio-based production from renewable biomass resources, and CO_2 capture and conversion technologies, each representing a distinct but complementary pathway toward a more carbon-conscious petrochemical industry[4, 7, 10].

4.1 Recycling of Plastic Waste

4.1.1 Chemical Recycling

Improved chemical recycling methods have looked to refine waste input, in turn, using them for chemical production of essential petrochemicals[4]. Chemical recycling may decrease carbon emissions when compared to incineration and landfilling since waste plastics could be converted back to pristine quality feedstocks[4, 7].

Chemical recycling is regarded as a high-energy process; thus, adding catalysts can hasten lengthy chemical processes and lower activation energy along with temperatures[4,7].To mitigate this energy barrier, the use of electricity as opposed to fuel to power systems have been looked into, namely microwave pyrolysis[7]. Also, researchers have been evolving plasma pyrolysis because it can handle a vast range of contaminants, while having more basic sorting and processing standards[7].

Implementing other resources, such as catalysts, enzymes, and solvents, have posed as solutions to endure heterogenous waste inputs; these in combination can be used for depolymerization, permitting restoration as new plastic[7].

Besides this, employing biological systems to execute chemical recycling have been studied; in fact, researchers have found microorganisms may be able to degrade most plastics. Furthering this would require the use of synthetic biology, machine learning, and other tools to construct cutting-edge frameworks[7].

Even though chemical recycling may be becoming more comprehensible and progressive as a method to repurpose contaminants, chemical recycling requires improvements in collecting waste plastics, lowering production costs, and containing CO_2 emissions[7]. However, chemical recycling challenges could be diverted by building more sorting centres that separate waste plastics more thoroughly and exercising CCUS technologies to reduce the emitted CO_2 that cannot be avoided in this process[4]. As a whole, these advancements in chemical recycling can fortify the path towards lower-carbon emissions in the production of petrochemicals[4,7].

4.2 Biomass-Derived Feedstocks

4.2.1 Bio-based Production

Bio-based production involves converting plant-derived materials into essential petrochemical products, offering a renewable alternative when conventional fossil fuel-based methods are insufficient to meet growing demand sustainably[7].

Even though bio-based production reduces carbon to a certain extent, researchers have been developing advancements in the biomass feedstocks used, processing technology, and end products since crops, such as corn, threaten food supply in the long term[4,7].

In replacement, lignocellulose may be a viable biomass-based feedstock since microorganisms, such as bacteria and fungi, have been manipulating the cellulose, hemicellulose, and lignin present to sustain their systems[7]. Thus, there have been attempts to replicate this natural process found in microorganisms in artificial systems to produce petrochemical products[7].

For instance, using chemical or biological tools with the aid of engineered microorganisms that would function as a converter for the product sugars, lignocellulose is separated into product sugars that act as building blocks in manufacturing various petrochemical products[7]. Besides separation, lignocellulose could be heated, producing hydrogen, carbon dioxide, and other molecules, and with available technology, these molecules can be assembled as complex petrochemicals[7]. Even though researchers have been exploring lignocellulose in bio-mass production, this strategy has not been widely applied and remains in the early phases of development[7].

In countries where affordable gas reserves are scarce, utilizing bio-based alternatives, such as bioethanol, bio ethylene, and bio-aromatics, may be a better strategy to meet decarbonization goals[6]. Bioethanol produces ethanol from sugar or starch-derived feedstocks, but even with its bio-based origins, CO_2 is still produced as a byproduct from the fermentation of sugars[13]. However, these emissions from bioethanol production can be diminished when paired with carbon-capture and storage techniques that work closely with ethanol biorefinery sites, which Archer Daniels Midland and the University of Illinois have achieved through the Illinois Basin-Decatur Project in 2021[13].

These plants, as raw materials, possess the ability to absorb CO_2 from the atmosphere as they grow, counterbalancing the CO_2 emitted from incinerated or landfill petrochemical products and allowing that CO_2 to return as biogenic carbon[3]. This relationship fostered by bio-based alternatives creates a cycle where CO_2 follows a loop as opposed to the non-biogenic CO_2 sequence fossil fuels release into the atmosphere[3].

On balance, bio-based production may minimize CO_2 emissions when equipped with advanced techniques and carbon-capturing and storage technologies[3,7,13]. Although strategies utilizing lignocellulose and bioethanol still have much room for improvement, shifting away from fossil fuels and lowering carbon emissions gradually ensures an improved path for the petrochemical industry in the direction of decarbonization[3,7,13].

4.2.2 Waste Biomass Utilization

As mentioned prior, sugars and other edible crops are used to produce present biomass plastics; however, certain economies cannot meet sufficient demand with biomass feedstock alone as a result of competition with food supplies; in accordance with this, utilizing waste biomass and second generation biomass can reduce this margin[4, 7].

A novel method that has been furthered is the use of wastepaper as a feedstock to produce ethanol[4]. In this methodology, wastepaper then undergoes saccharification and fermentation since wastepaper is rid of any lignin because of the pulp manufacturing process, making it an available carbon resource[4]. Once saccharification and fermentation are complete, ethylene can be acquired from ethanol[4]. Taking advantage of waste biomass, such as wastepaper, provides economies with a lower-carbon alternative when fossil fuels and bio-derived feedstocks cannot suffice, while strategically reducing waste and controlling carbon circulation within the industry[4].

Researchers from Sekisui Chemical+ Sumitomo Chemical have been developing a mixture composed of waste biomass and waste plastic as a feedstock to produce ethanol[4]. Essentially, this mixture of waste is pyrolyzed, creating syngas, then the syngas, through the implementation of biotechnology, produces ethanol[4]. At this last stage, ethanol can finally be converted to ethylene, with the intention of being repurposed as a feedstock for chemicals[4].

Waste biomass as a feedstock opens many opportunities for efficiently handling waste generated in the environment[4]. Whether it be wastepaper or waste plastic, developing these technologies may ease the process of becoming emissions free in the petrochemical industry because these efforts remove landfill waste along with their corresponding methane emissions, lowering the environmental footprint[11, 4]. Additionally, renewable energy, such as biodiesel, can be produced, shunning fossil fuel production[1, 4].

4.3 Carbon Dioxide as Feedstock

Researchers have been developing technology where CO_2 could be recovered from exhaust gas and utilized as a feedstock in manufacturing plastics[4]. Methanol synthesis is a technique on the rise demonstrating recovered CO_2 as a feedstock that synthesizes methanol alongside green hydrogen to produce ethylene and propylene by MTO and MTP[4]. This method still faces some challenges as a large volume of green hydrogen would need to be produced to provide enough ethylene or propylene, making it rather expensive[4]. Moreover, more waste facilities responsible for capturing and storing the CO_2 would need to be constructed as well as improved means in CO_2 transportation to petrochemical complexes[4]. However, projects, such as the Qilu-Shengli Oilfield Project in 2023, have created innovative technologies that revolutionize CCUS[12]. Differences in fossil fuel-derived CO_2 and CO_2 derived from chemical processes as feedstocks are demonstrated in Figures 3 and 4[4].

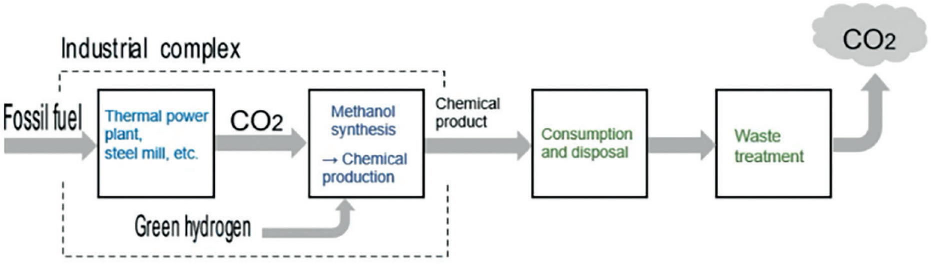

Figure 3: Using fossil fuel-derived CO_2 as a feedstock

Source: Furusawa, Y. Decarbonization of the Petrochemical Industry and Petrochemical Products; Renewable Energy Institute: 2023.

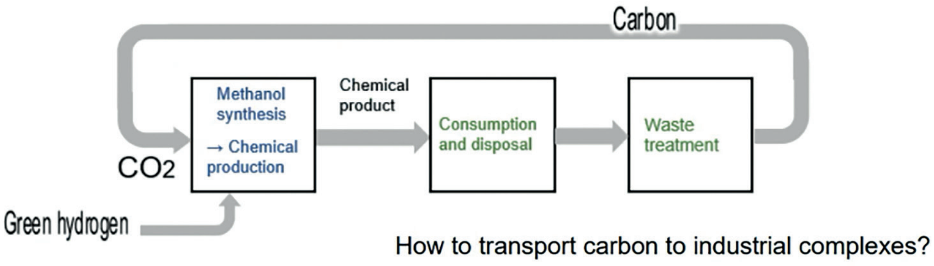

Figure 4: Using CO_2 derived from used chemical processes

Source: Furusawa, Y. Decarbonization of the Petrochemical Industry and Petrochemical Products; Renewable Energy Institute: 2023.

4.3.1 CO_2 Capture Utilization and Storage (CCUS)

CCUS technologies, as seen in figure 5 below, are developed with the purpose to reduce or remove CO_2 emissions in the atmosphere[13]. Enhancements in CCUS could benefit the environmental footprint of industries, such as the petrochemical industry, that often release CO_2 emissions to produce necessary products, such as plastics[13].

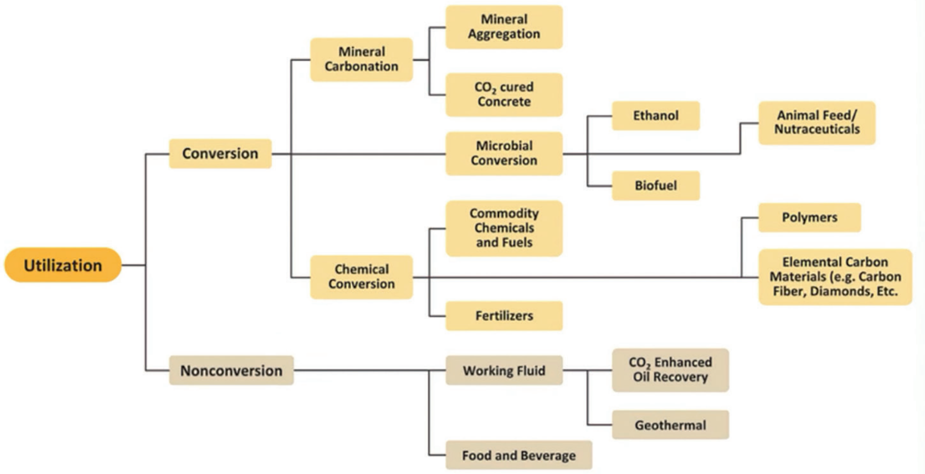

Figure 5: CO_2 Utilization Pathways and Products

Source: Bank of Ayudhya (Krungsri Research). Net Zero Pathways for Petrochemical Industry; 2024. https://www.krungsri.com/en/research/research-intelligence/net-zero-petrochemicals.

With respect to bioethanol production, direct air capture has commonly been used, specifically in the United States[13]. To improve this process, researchers have been looking to identify materials that can be reused throughout thousands of cycles of air capture, to improve processes, and to strengthen conditions that maintain material durability[13]. The availability of CCUS technology has improved to a certain extent, particularly in the United States, where the Illinois Basin - Decatur Project and Summit Agricultural Group and Navigator CO_2 Ventures have created substantial carbon capture and storage projects that effectively capture and store CO_2 from ethanol biorefineries[13]. Yet, these projects still recognize more ethanol biorefineries need more CO_2 storage sites near them[13].

Like the United States, China, in 2023, has enacted a CCUS project, the Qilu-Shengli Oilfield Project where CO_2 capture, pipeline transportation, injection, flooding and storage, and monitoring technologies have been substantially furthered[12].

CO_2 capture technologies have been improved through effective packing in extraction towers and efficient waste heat/residual pressure utilization technology, resulting in lower temperatures for distillation, a 10% decrease in energy consumption, and a 40% drop in capture cost[12]. Regarding CO_2 transportation along pipelines, the CO_2 density was stabilized around 9 MPa at lower temperatures, effectively preventing the production of hydrate[12]. Several adjustments have been made in CO_2 injection technology. Within the storage tank, constant pressure and low temperature are held; the injection pump following permits highly productive injective and separation gas-liquid[12]. Lastly, the measurement unit possesses heightened metering accuracy and can inject many wells simultaneously[12]. To upgrade miscibility, a high-pressure flooding system has been produced to grow sweep efficiency above 30% and increase recovery above 8%[12]. As part of CO_2 flooding and storage technology, the project has looked to optimize injection by furthering swept volume by 14% and tweaking dynamic gas-water ratios with the objective to maintain high resistance across the entire process[12]. Moreover, the monitoring system has been built to consider reservoir, wellbore, surface, and atmosphere environments to indicate real-time warning and monitoring[12].

These projects have resulted in significant advancements in CCUS technologies, which are especially of importance to rid the atmosphere and industrial sectors of CO_2 emissions when other methods may seem insufficient, preventing its release later on[12,13].

5. Renewables in Naphtha Cracking Furnaces

Naphtha cracking is the petrochemical process responsible for releasing the highest amount of energy-based CO_2 emissions since methane, a fuel, is utilized to heat the naphtha present in cracking furnaces[4]. Therefore, finding alternative methods to provide the heat necessary for naphtha cracking have been of interest, resulting in technologies that implement renewables, such as electrification and ammonia as fuel[4]. With these technologies, decarbonizing petrochemical processes could become more attainable[4].

5.1 Electrification

As opposed to utilizing methane as a fuel in heating naphtha cracking furnaces, e-furnaces are electrically heated, eliminating the dependence on fossil fuels and permitting lower temperature boundaries[4]. The renewable aspect of e-furnaces is how the electricity could be provided, preferably through renewable energy; factoring in this adjustment, CO_2 emissions may be minimized to zero[4].

Observing such potential, BASF, SABIC, and Linde, have embarked on building a demonstration plant in Ludwigshafen, Germany[4]. In their demonstration plant, they employ two methods where electric current is either dispensed to a tube or a heating element around the tube to administer heat4. Similarly, Coolbrook, ABB, and Braskem have planned a pilot plant located in the Netherlands designating the RotoDynamic Reactor where friction and shock waves are exercised in heating the furnace internally contrary to externally[4]. With the goal of commercialization, Toyo Engineering has planned on a demonstration study based in Thailand focusing on the advancement of electrification technology for ethylene cracking furnaces, resembling the Figure 6[4].

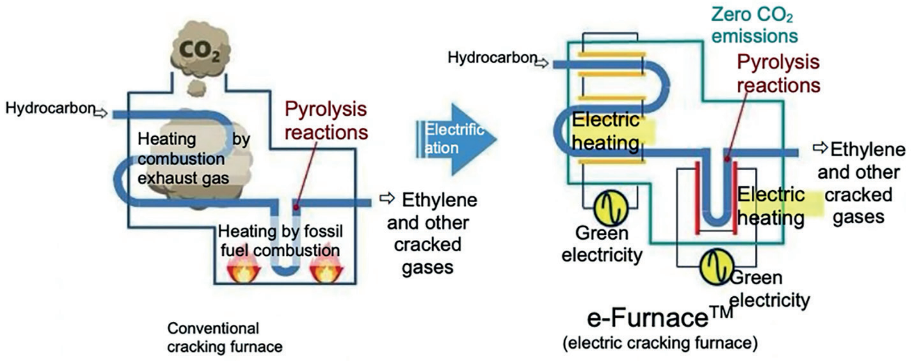

Figure 6: Electrification of naphtha cracking furnace

Source: Furusawa, Y. Decarbonization of the Petrochemical Industry and Petrochemical Products; Renewable Energy Institute: 2023.

The evident rise in research and implementation of electrification initiates a transition towards renewable energy[4]. When critical petrochemical processes, such as naphtha cracking, can take place with renewable energy and lower temperatures, then more efficient reactions, lower waste byproducts, and low to zero CO_2 emissions can take place, which all fundamentally push the industry away from fossil fuels and towards environmental sustainability[4].

The New Energy and Industrial Technology Development Organization (NEDO) in Japan has delved into fabricating a method where ammonia acts as a fuel for cracking furnaces as part of their NEDO Green Innovation Fund Project[4]. One segment of this project works towards creating burners for naphtha cracking furnaces adjusted to the unique combustion qualities of ammonia; in addition to this, the other segment emphasizes developing technology aiding in the synthesis of ammonia at room temperature and pressure through the inclusion of Mo catalyst4. NEDO could see the possibility of implementing green ammonia in these technologies; however, NEDO acknowledges how current management and supply challenges may withhold such an idea[4].

Utilizing renewable ammonia as a fuel for cracking furnaces marks a shift from fossil fuel dependency to renewable energy in the petrochemical industry, reducing CO_2 emissions in what were originally high energy and temperature processes; the potential may be further recognized once these projects are completed[4].

6. Policy

To ensure advancements in lower-carbon pathways are effectively scaled, coordinated policy intervention is essential, spanning carbon accounting reform, circular economy adoption, and cross-sector collaboration among producers, policymakers, and industry actors[2, 4, 6, 7].

6.1 Adopting Cyclical Carbon Use in the Petrochemical Industry

Although carbon recycling, the recovery and reuse of captured CO_2, is a widely accepted decarbonization principle, cyclical carbon use represents a more rigorous framework for minimizing net CO_2 emissions across petrochemical processes, as seen in Figure 7[4].

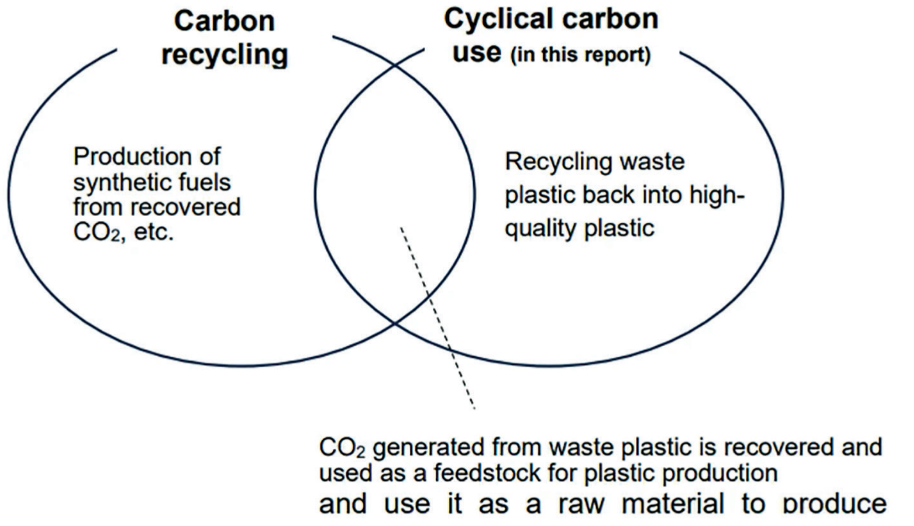

Figure 7: Cyclical carbon use vs. carbon recycling

Source: Furusawa, Y. Decarbonization of the Petrochemical Industry and Petrochemical Products; Renewable Energy Institute: 2023.

Unlike carbon recycling, which does not account for emissions released after a fuel is consumed, cyclical carbon use focuses on keeping carbon continuously circulating within a closed-loop system, preventing its re-entry into the atmosphere[4]. This distinction has direct policy implications, illustrated in Figure 8 below.

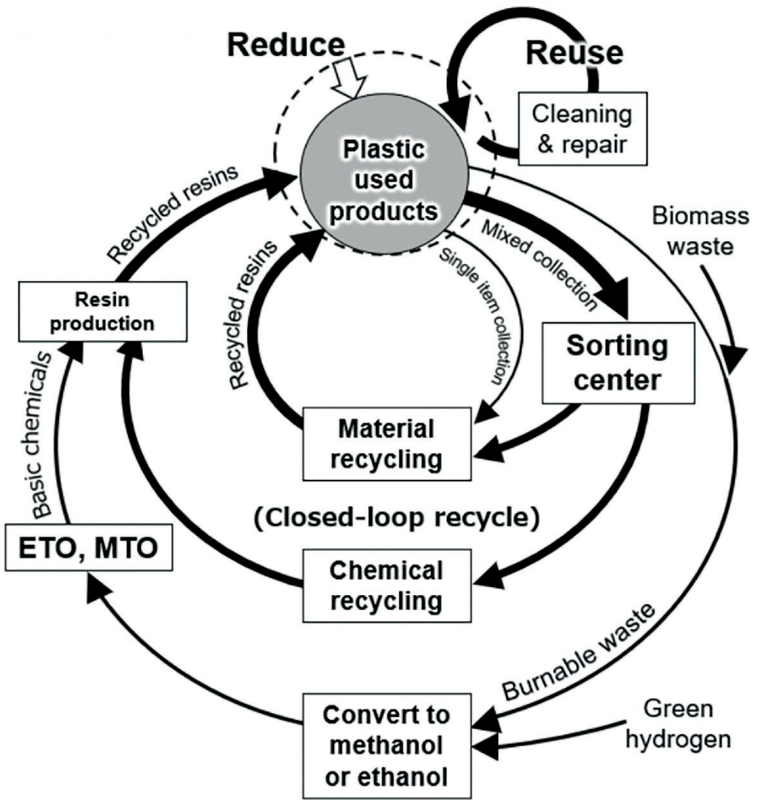

Figure 8: Closed loop carbon cycles [1]

Source: Furusawa, Y. Decarbonization of the Petrochemical Industry and Petrochemical Products; Renewable Energy Institute: 2023.

Charging producers based on the full quantity of embedded carbon in their products, rather than only point-source emissions, captures a greater share of potential lifecycle emissions and simultaneously deters reliance on incineration and landfill disposal in favor of recycling[11]. Carbon taxation at the point of production, coupled with incentives for companies to take active roles in lifecycle processing and the adoption of recycled feedstocks, represents a concrete upstream policy mechanism to accelerate this shift[11, 13].

The European Commission has already moved in this direction, establishing a 2030 target requiring that at least 20% of carbon used in products derive from sustainable, non-fossil sources, demonstrating that ambitious cyclical carbon policy is achievable at scale[7]. Pairing such policies with the lower-carbon technological advancements discussed in prior sections could unlock the fuller decarbonization potential that currently remains unrealized in the industry[11, 13].

6.2 Shifting to a Circular Economy

Technological advancements alone are insufficient to decarbonize the petrochemical industry at the scale required; an accompanying structural economic shift is necessary to amplify their impact. The circular economy model, built on the principles of demand reduction, reuse, recycling, and energy recovery, directly supports lower-carbon production by closing the gap between consumption and waste[3,4].

Applied together, demand reduction, reuse, and recycling can meaningfully reduce both the production of fossil fuel-derived petrochemicals and the energy intensity of processes such as plastic manufacturing[3]. Energy recovery, while more difficult to execute without generating emissions, can be made viable through integration with CCUS technologies, enabling waste plastics to be recovered and converted without releasing excessive CO_2 into the atmosphere[3].

Critically, however, transitioning to a circular economy requires substantial upstream infrastructure investment. Currently, less than 0.1% of plastics are chemically recycled globally, and mechanical recycling remains dominant, largely because the economics of chemical recycling are not yet favorable and impurity management poses significant operational challenges[4]. Policies restricting single-use plastics, extending producer responsibility, and mandating recycled content thresholds have been adopted in several regions and represent proven upstream levers for accelerating this transition[11].

Additionally, expanding large-scale, high-purity sorting infrastructure, such as the European model of resin and color-specific sorting centers, is essential for supplying the quality of feedstock that advanced chemical recycling requires[4]. Without these foundational investments in infrastructure and producer accountability, circular economy principles remain aspirational rather than operational[4, 6].

6.3 Bridging the Gap between Consumers and Actors Concerning Decarbonization Efforts

Decarbonizing the petrochemical industry cannot be achieved by the industry alone; it requires coordinated effort across producers, policymakers, adjacent industries, research institutions, and consumers[4, 7]. On the upstream side, public investment in research, development, and demonstration of advanced production technologies is a prerequisite for commercial viability, particularly for technologies such as green hydrogen, bio-based feedstocks, and electrified cracking, where cost competitiveness with fossil fuel-based methods has not yet been achieved[7]. Governments can also play a structural role by developing transition plans for incumbent producers, for example, supporting ethanol producers in shifting toward petrochemical feedstock production as vehicle electrification reduces traditional fuel markets[7]. Academia-industry collaboration is equally critical, as researchers operating without direct knowledge of industrial bottlenecks are less likely to produce innovations that translate to practical deployment[8]. On the demand side, while consumer behavior alone is insufficient to drive systemic decarbonization, informed consumers can reinforce upstream efforts. Clearer petrochemical product labeling that accounts for lifecycle greenhouse gas emissions and end-of-life disposal impacts would provide a more honest accounting of environmental costs, enabling procurement policies, voluntary purchasing incentives, and product standards to function more effectively[7]. Ultimately, the coordination of upstream policy mechanisms, including carbon pricing, infrastructure investment, producer accountability, and research and development support, reinforced by broader societal engagement, will determine the pace and scale of the petrochemical industry's transition to lower-carbon production[4, 7, 11].

Conclusion

The petrochemical industry has faced remarkable shifts in demand in terms of producing more environmentally sustainable products as part of growing concerns revolving around climate change and growing carbon emissions[10]. As a result, the industry has had to shift from fossil fuel dependency to fortifying lower-carbon pathways that can meet demand, supply, and environmental concerns[10].

This review illustrates key technological innovations that have aided this transition. Advancements in catalytic systems and catalysts themselves have improved efficiency, selectivity, and energy use in refining processes, giving way to lower emissions[2,4,7]. Furthermore, research focusing on the diversification of alternative feedstocks, such as recycled plastic waste, biomass-based resources, and CO_2, highlight lower-carbon and circular economy alternatives to fossil fuels[1,4,11]. Chemical recycling, bio-based production, and CO_2 utilization pathways jointly strengthen circular and sustainable carbon framework for petrochemical production[4,11].

Even though these advancements have been birthed, some challenges last concerning energy requirements, economic barriers, and widespread application[1,2,4,13]. The successful implementation of these technologies will rely on access to low-carbon energy and the continual evolution of process efficiency. In addition, coordinated policy aid and investment will be foundational to push adoption and power industry-wide transformation.

Ultimately, the integration of advanced catalysis, alternative feedstocks, and carbon recycling techniques garners a promising pathway towards a more sustainable and carbon-conscious petrochemical industry.

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