Synergize FCCUs and hydrocracking processing units to maximize refining margins—Part 1

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The capacity to add value to bottom-of-the-barrel streams represents a significant competitive advantage among refiners, especially considering strict regulations like the International Maritime Organization's (IMO's) 2020 regulation that has imposed a significant reduction in the sulfur content of marine fuel oils (bunker). This requires even more capacity to treat bottom-of-the-barrel streams—especially for refiners processing heavier crude oils—and puts refining margins under pressure that are still in recovery in the post pandemic scenario, as illustrated for the U.S. market in **FIG. 1.**

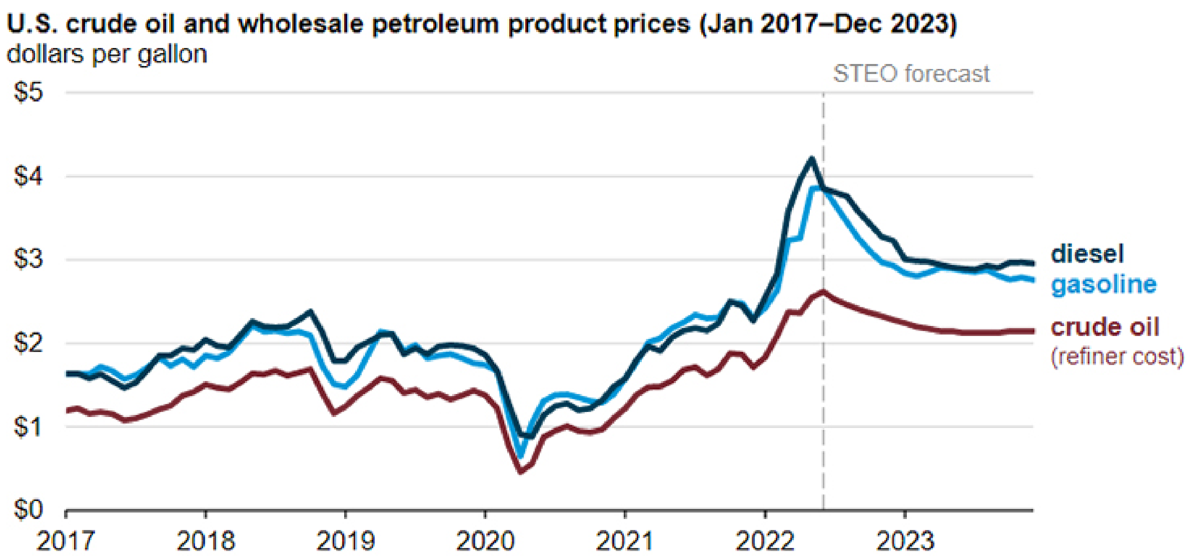


FIG. 1. U.S. refining margins, 2017–2023. Source: U.S. Energy Information Administration (EIA).

Under this scenario, process units that can improve the quality of crude oil residue streams (vacuum residue, gasoils, etc.) or convert them to higher added-value products gain strategic importance, mainly in countries with large heavy crude oil reserves. These process units are fundamental for compliance with environmental and quality regulations and ensure the profitability and competitiveness of refiners by increasing refining margins. Recently, the reduction in transportation fuels demand is impelling refiners to seek closer integration with petrochemical assets and maximize the yield of petrochemicals in the refinery. The use of residue upgrading technologies to produce petrochemicals against transportation fuels can be an attractive route in some markets.

Processing bottom-of-the-barrel streams involves technologies that aim to raise the hydrogen (H_2)/carbon relation in the molecule, either by reducing carbon quantity (processes based on carbon rejection) or through H_2 addition. Technologies that involve H_2 addition encompass hydrotreating and hydrocracking processes, while technologies based on carbon rejection include thermal cracking processes like visbreaking, delayed coking and fluid coking, catalytic cracking processes like fluid catalytic cracking (FCC), and physical separation processes like solvent deasphalting.

Some refining schemes can synergize various residue upgrading technologies with the goals of adding value to processed crude oils, complying with regulations and ensuring higher refining margins in the downstream sector.

An interesting case is the combination of hydrocracking and FCC technologies. Normally these technologies are viewed as competing technologies due to the feed streams that are processed; however, in some cases, the synergy between hydrocracking and FCC technologies can ensure high bottom-of-the-barrel conversion capacity and profitability despite the relatively high capital investment (CAPEX).

The continuous supply of adequate crude oil to the facility is one of the aspects refiners must consider when installing assets or conducting an economic analysis of already installed units. However, depending on geopolitical scenarios, the supply of adequate crude oil to the refinery can be seriously threatened, mainly to refiners that operate with lighter and high-cost crudes.

Considering this, more flexible refining equipment in relation to the processed crude slate is an important competitive advantage in the downstream sector, specifically the processing of heavy and extra-heavy crudes due to the lower acquisition cost when compared with lighter crude oils. The difference in the acquisition cost between these oils is based on the yield of high added-value streams in the distillation process. Lighter crudes normally show higher yields of distillates than heavier crudes, so their market value tends to be higher. **FIG. 2** presents the evolution of the discount of West Canadian Select (WCS) crude oil to West Texas Intermediate (WTI) crude oil in 2021–2022.

FIG. 2. An example of the price gap between WTI and WCS crude oils in 2021–2022. Source: CBC News.

WCS is considered a heavy crude [with an American Petroleum Institute (API) grade of 19–22 and a sulfur content of ~3%], while WTI is considered a reference crude [with a medium API grade of ~40 with very low sulfur content (~0.3%)].

FIG. 1 shows a significant price gap between these crudes, giving an advantage to refiners capable of adding value to these crudes, especially considering the IMO 2020 regulation that requires even more refining capacity to add value to the bottom-of-the-barrel streams.

Normally, the valuation of crude is defined by its quality, the available market, whether refiners can process it and the transportation options to the consumer market. Heavier crudes tend to present discounts related to lighter crudes due to three main variables:

- **Quality:** Heavier crudes offer a lower yield of distillates and high added-value derivatives like diesel, kerosene and gasoline.
- **Consumer market:** Refiners able to process heavier crudes must rely on adequate bottom-of-the-barrel conversion capacity (i.e., more complex facilities), which restricts the consumer market.
- **Transportation:** Heavier crudes necessitate higher logistics costs due to increased energy consumption.

Despite these characteristics, refiners with adequate refining capabilities and easy access to heavier crudes can use the price gap as an opportunity to improve their margins—stricter regulations like IMO 2020 further reduce the acquisition costs of heavier and sourer crudes.

FCC technologies: The carbon rejection route. The installation of catalytic cracking units allows refiners to process heavier (i.e., cheaper) crude oils and increase margins when access to light oils proves difficult. The typical catalytic cracking unit feed stream comprises gasoils from the vacuum distillation process. However, some variations exist, such as sending heavy coke naphtha, coke gasoils and deasphalted oils from deasphalting units to processing in an FCCU.

In a conventional scheme, the catalyst regeneration process consists of carbon partial burning deposited over catalyst, according to the chemical reaction in Eq. 1:

$$C + \frac{1}{2} O_2 \rightarrow CO \qquad (1)$$

The carbon monoxide (CO) burns in a boiler capable of generating higher pressure steam that supplies others process units in the refinery. **FIG. 3** shows a process scheme for a typical FCCU.

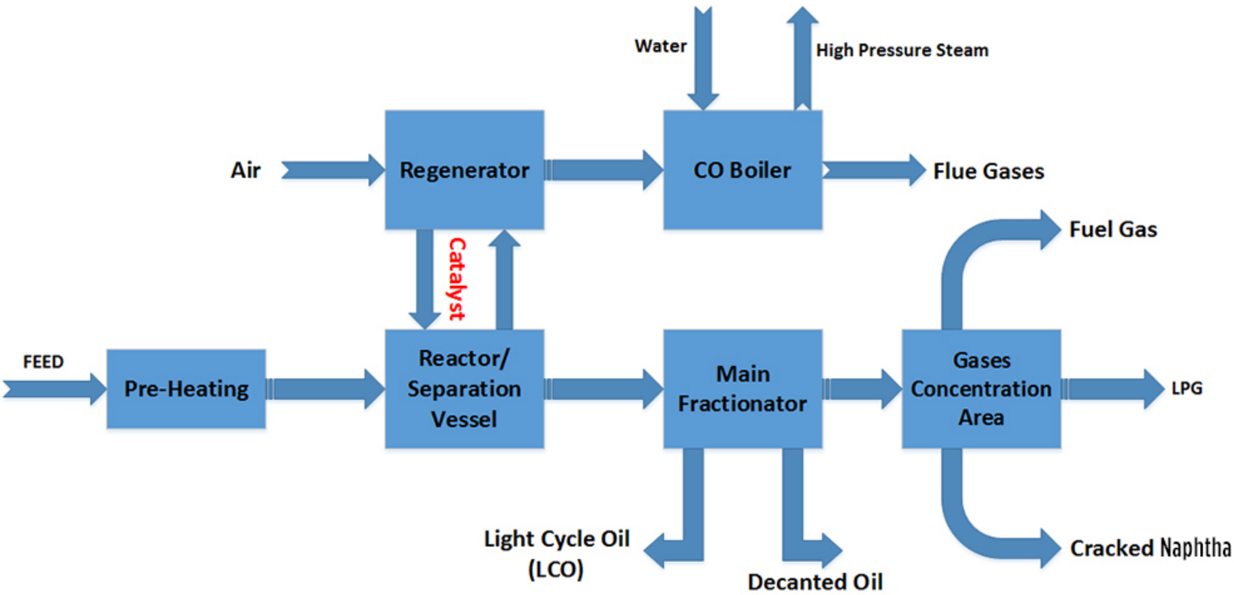


FIG. 3. The process flow for a typical FCCU.

The principal operational variables in an FCCU are reaction temperature [normally considered the temperature in the top of the reactor (riser)], feed stream temperature, feed stream quality (mainly carbon residue), feed stream flowrate and catalyst quality. Feedstock quality is particularly relevant, but this variable is a function of the crude oil processed by the refinery. Changing the feed quality is difficult and not always within the refiner's control; for example, feedstocks with high metals content are refractory to cracking and conducive to quick catalyst deactivation.

An important variation of FCC technology is the residue FCCU (RFCCU). In this case, the feedstock to the process is basically residue from the atmospheric distillation column. Due to high carbon residue and contaminants (metals, sulfur, nitrogen, etc.), it is necessary to adapt the unit (e.g., using catalyst with a higher resistance to metals, and nitrogen and catalyst coolers). Special metallurgy should be used due to the higher temperatures reached in the catalyst regeneration step (due to the higher coke quantity deposited on the catalyst)—this significantly increases the CAPEX of the unit installation. Nitrogen is a strong contaminant to the FCC catalyst because it neutralizes the acid sites of the catalyst that are responsible for the cracking reactions.

When the residue has a high contaminants content, it is common in the feed stream treatment in hydrotreating units to reduce the metals and heteroatoms concentration to protect the FCC catalyst. Typically, the average yield in FCCUs is 55 vol% in cracked naphtha and 30 vol% in liquefied petroleum gas (LPG).

Usually, catalytic cracking units are optimized to produce fuels (mainly gasoline); however, some process units are optimized to maximize light olefins production (propylene and ethylene). The process units must change their operational conditions once the process severity increases. Reaction temperatures can reach 600°C (1,112°F) and the higher catalyst circulation rate increases gas production, which requires a scaling up of the gas separation section.

Over the last few decades, FCC technology has been intensively studied, mainly to develop units capable of producing light olefins (deep catalytic cracking) and processing heavier feedstocks.

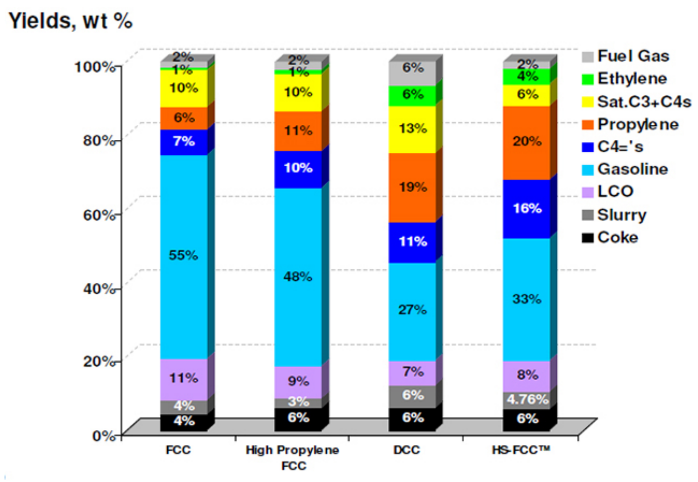
Despite the operational flexibility FCC technology offers refineries, some new projects have dismissed these units in their refining schemes, mainly when the new refinery objective is to maximize middle distillates products (diesel and kerosene), which is generally not the focus for an FCCU.

Improving the yield of petrochemicals in refineries: Petrochemical FCC technologies.

As discussed above, in markets with high petrochemicals demand, petrochemical FCCUs can be an attractive alternative for refiners aiming to ensure higher added value to bottom-of-the-barrel streams. Several FCC technologies have been developed to maximize the production of petrochemical intermediates.

In petrochemical FCCUs, reaction temperatures reach 600°C (1,112°F) and higher catalyst circulation rates increase gas production—this requires a scaling-up of the gas separation section. The higher thermal demand makes it advantageous to operate the catalyst regenerator in total combustion mode, which requires the installation of a catalyst cooler system.

FIG. 4 presents the results of a comparative study carried out by Technip Energies that shows the yields obtained by conventional FCCUs, optimized to olefins (FCC to olefins), and the company's high-severity FCC process[a] that has been designed to maximize the production of petrochemical intermediates.



	Conv. FCC	HP FCC	DCC	HS-FCC[a]
ROT	530°C (986°F)	550°C (1022°F)	580°C (1076°F)	600°C+ (1112°F+)
Contact time	2 - 5 s	2 - 5 s	10 s	0.5 - 1 s
C/O	5	10	15	25
Recycle	None	LCN	LCN	None

FIG. 4. A comparative study of conventional FCCUs, and a proprietary

petrochemical FCCU[a].

When comparing the conventional process units and the petrochemical FCCU[a], a higher reaction temperature (TRX) and a cat/oil ratio five times higher were observed, leading to an increased light olefins yield (e.g., ethylene, propylene, C_4) from 14% to 40%.

The installation of petrochemical catalytic cracking units requires a thorough economic study that considers both increased CAPEX and operational costs (OPEX). Some forecasts indicate growth of 4%/yr in the petrochemical intermediates market until 2025. This can be attractive for any refiner seeking to increase its market share in the petrochemical sector and maximize production of petrochemical intermediates.

In refineries with conventional FCCUs, the higher temperatures and catalyst circulation rates enable the addition of catalysts additives (e.g., zeolitic material ZSM-5) that can, in some cases, increase the olefins yield close to 9% when compared with the original catalyst. While this can increase OPEX, it remains economically attractive considering petrochemical market forecasts. **FIG. 5** presents optimization strategies to improve the petrochemical yield in conventional FCCUs.

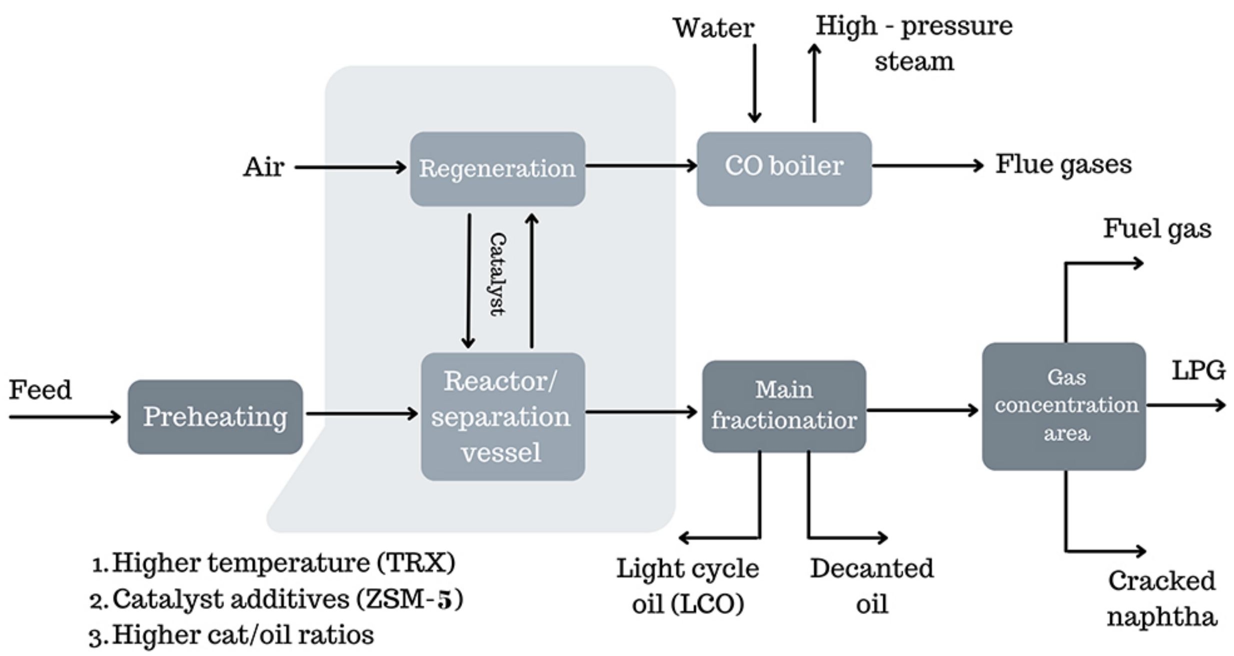


FIG. 5. The optimization of process variables in FCCUs to improve the yield of petrochemicals intermediates.

The use of FCC catalyst additives such as ZSM-5 can increase unit propylene production by up to 8%.

The installation of a catalyst cooler system can increase the profitability of FCC processing units by upgrading the total conversion and selectivity to higher added-value derivatives like propylene and naphtha vs. other products like coke. The catalyst cooler is necessary when the unit is designed to operate in total combustion mode due to the higher heat release rate, as shown in Eqs. 2 and 3:

$$C + \frac{1}{2}\,O_2 \rightarrow CO\ \textit{(partial combustion)}\ \Delta H = -27\ kcal/mol \qquad (2)$$

$$C + O_2 \rightarrow CO_2\ \textit{(total combustion)}\ \Delta H = -94\ kcal/mol \qquad (3)$$

In this case, the temperature of the regeneration vessel can reach ~760°C (~1,292°F), leading to higher risks of catalyst damage, which can be minimized through catalyst cooler installation. The use of total combustion mode must consider the refinery's thermal balance:

- It is not possible to produce steam in the CO boiler
- The higher temperatures in the regenerator require materials with improved metallurgy
- Installation costs increase significantly, which can be prohibitive to some refiners with restricted capital.

Due to the increased production of light olefins, mainly ethylene, another important difference between conventional and petrochemical FCCUs is related to the gas recovery section. In conventional FCCUs, gas recovery occurs in the absorber columns, while petrochemical units apply cryogenic processes through refrigeration cycles in similar conditions to steam cracking units.

The cryogenic processes applied to olefins recovery further increases the CAPEX of petrochemical FCCUs compared to conventional FCCs; despite this, the growing market for petrochemicals and falling demand for transportation fuels compensates for the higher investment.

According to consultancy analysis[b], the global installed FCC capacity in 2022 was ~14 MMbpd with an average annual growth rate (AAGR) of 3% until 2027. This growth will be led by regions such as Asia and the Middle East.

Deep hydrocracking technologies: The H_2 addition route. Refiners processing heavy and extra-heavy (or high-sulfur) crudes face challenges to meet the IMO 2020 regulations. Because compliance with the new regulations through carbon rejection technologies is difficult, H_2 addition technologies are fundamental.

The hydroprocessing of residual streams presents additional challenges when compared with the treating of lighter streams, mainly due to the higher contaminants content and residual carbon (RCR) related to the high concentration of resins and asphaltenes in bottom-of-the-barrel streams. FIG. 6 shows a schematic diagram of the residue upgrading technologies applied according to the metals and asphaltenes content in the feed stream.

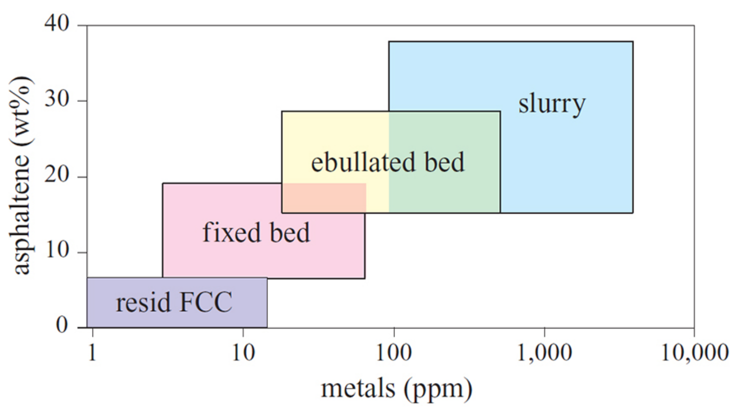


FIG. 6. Residue upgrading technologies according to contaminants content in the feed stream.[1]

Higher metals and asphaltenes content can lead to a quick deactivation of catalysts through a high coke deposition rate, catalytic matrix degradation by metals like nickel and vanadium, or even by the plugging of catalyst pores produced by the adsorption of metals and high molecular weight molecules on the catalyst's surface. Depending on the content of asphaltenes and metals in the feed stream, more versatile technologies should be adopted to ensure an adequate operational campaign and effective treatment.

Despite their high performance, fixed-bed hydrocracking technologies are not economically effective to treat residue from heavy and extra-heavy crudes due to their short operating lifecycle. Technologies that use ebullated bed reactors and continuum catalyst replacement allow a longer campaign period and higher conversion rates. These reactors operate at temperatures > 450°C (> 842°F) and pressures to 250 bar.

Catalysts applied in hydrocracking processes can be amorphous (alumina and silica-alumina) and crystalline (zeolites) and have bifunctional characteristics, once the cracking reactions (in the acid sites) and hydrogenation (in the metals sites) occur simultaneously.

An improvement to ebullated bed technologies is the slurry phase reactors, which can achieve conversions > 95%.

In slurry phase hydrocracking units, the catalysts are injected with the feedstock and activated in-situ while the reactions are carried out in slurry phase reactors, minimizing the reactivation issue and ensuring higher conversions and operating lifecycle.

Aiming to meet new bunker quality requirements, highest-quality streams, normally directed to produce middle distillates, can be applied to produce low-sulfur fuel oil (LSFO). This can lead to a shortage of intermediate streams to produce these derivatives, raising prices. The market for high-sulfur content fuel oil (HSFO) should decline due to the higher prices gap when compared with diesel, and production tends to be economically unattractive.

According to consultancy analysis[b], the global installed hydrocracking capacity in 2022 was around ~12.5 MMbpd with an AAGR of 5% until 2027.

Petrochemical integration: Strong dependence of high bottom-of-the-barrel conversion. The focus of the closer integration between refining and petrochemical industries is to promote and exploit the synergies between both downstream sectors to generate value for the entire crude oil production chain. TABLE 1 presents the main characteristics and potential synergies of the refining and petrochemical industries.

TABLE 1. Main characteristics of the refining and petrochemical industries

Refining industry	Petrochemical industry
Large feedstock flexibility	Raw material from naphtha/natural gas liquids (NGL)
High capacities	Higher operating margins
Self-sufficient in power/steam	High electricity consumption
High H_2 consumption	High availability of H_2
Streams with low added value (unsaturated gases and C_2)	Streams with low added value (heavy aromatics, pyrolysis gasoline, C_4s)
Strict regulations (benzene in gasoline, etc.)	Strict specifications (difficult separation processes)
Certain transportation fuels demand declining globally	High-demand products

For the last few years, the petrochemical industry has been growing considerably faster than the transportation fuels market, as the products are less environmentally aggressive, have higher added value and offer better circularity potential than crude oil derivatives. Refining and petrochemical technologies are similar, presenting potential synergies that can reduce OPEX and add value to derivatives produced in the refineries.

FIG. 7 shows some integration possibilities between refining processes and the petrochemical industry.

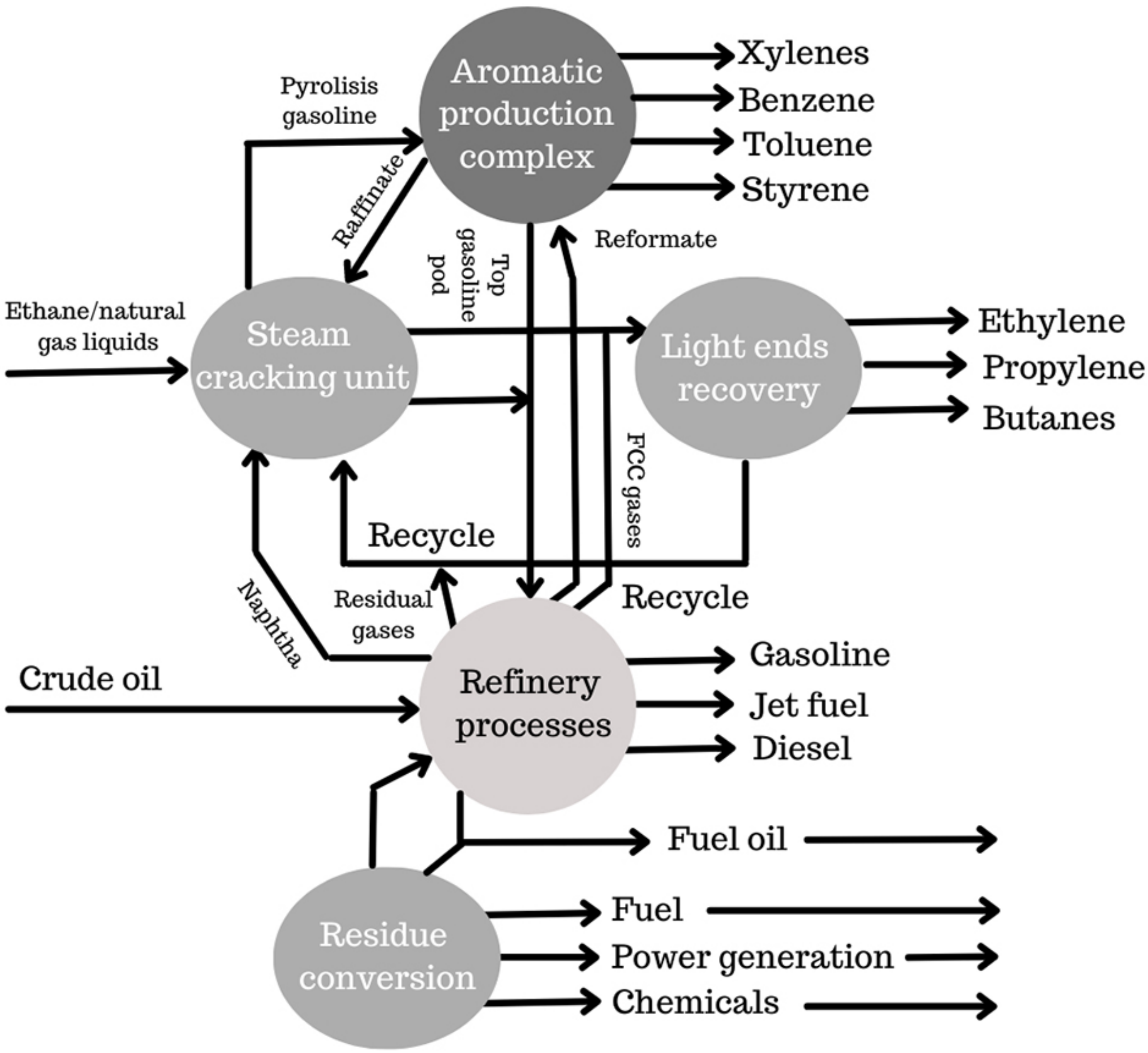


FIG. 7. Synergies between refining and petrochemical processes.

Process streams that are considered low added value to refiners [e.g., fuel gas (C_2)] are attractive raw materials to the petrochemical industry. Streams considered residual to the petrochemical industry (e.g., butanes, pyrolisis gasoline, heavy aromatics) can be applied to the refining industry to produce high-quality transportation fuels, helping it meet the environmental and quality regulations for derivatives.

The integration potential and synergy among the processes are dictated by refining schemes and the consumer market. FCCUs and catalytic reforming can be optimized to produce petrochemical intermediates; however, this is to the detriment of streams that will be incorporated into the fuels pool. In the case of FCC, the installation of units dedicated to producing petrochemical intermediates (PFCCUs) aim to minimize streams that produce transportation fuels; however, the CAPEX is high once the severity of the process requires the use of materials with superior metallurgical characteristics.

A classification of the petrochemical integration grades is proposed in **FIG. 8.**

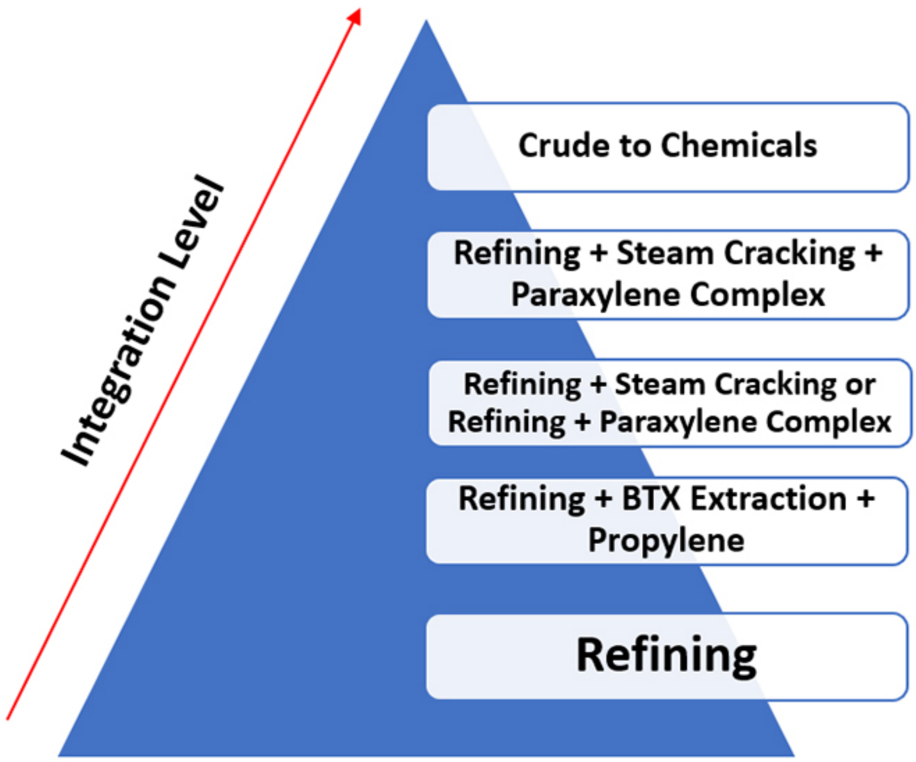


FIG. 8. Levels of petrochemical integration. Source: IHS Markit, 2018.

According to the classification proposed, the crude-to-chemicals facility is considered the optimum level of petrochemical integration.

Part 2, which will appear in the March issue of *Hydrocarbon Processing*, will explore the role of FCC and hydrocracking in crude-to-chemicals and the challenges of cracked feeds, among other topics. **HP**

NOTES

a. TechnipEnergies' HS-FCC™
b. GlobalData

LITERATURE CITED

1. Becarri, M. and U. Romano, *Encyclopaedia of hydrocarbons: Refining and petrochemicals*, Vol. 2, ENI, 2006.

MARCIO WAGNER DA SILVA is Process Engineering Manager at a crude oil refinery based in São José dos Campos, Brazil. Dr. da Silva has extensive experience in research, design and construction in the oil and gas industry, including developing and coordinating projects for operational improvements and debottlenecking to bottom-of-the-barrel units. He earned a BS degree in chemical engineering from the University of Maringa (UEM), Brazil and a PhD in chemical engineering from the University of Campinas (UNICAMP), Brazil. Dr. da Silva also earned MBAs in project management from the Federal University of Rio de Janeiro (UFRJ); operations and production management at the University of Sao Paulo (USP); and digital transformation at Pontifical Catholic

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