# Mitigating Pathways to Decarbonize Petroleum Refineries: Challenges and Opportunities for Achieving Sustainability in Fluid Catalytic Cracking (FCC) Units in Brazil.

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**Abstract:** Fluid Catalytic Cracking (FCC) units are among the most carbon-intensive assets in Brazilian refineries, chiefly because coke oxidation in the regenerator yields concentrated $CO_2$ streams. Based on a scientometric review of Scopus and Web of Science (2007–2025), screened via PRISMA and mapped with VOSviewer, this work synthesizes the state of the art and proposes a Brazil-tailored decarbonization roadmap. We diagnose FCC as an emissions hot spot and evaluate four complementary axes: (i) source reduction via catalytic/operational measures that suppress coke formation; (ii) deep electrification of process heat using a predominantly renewable power matrix; (iii) co-processing of short-cycle carbon feeds (bio-oils/HVO/plastics-to-oil) to displace fossil carbon; and (iv) post-regenerator carbon capture, utilization, and storage (CCUS). Isolated implementations deliver bounded gains—~20% via coke minimization, up to ~40% with renewable electrification, and ~6–10% by co-processing—while regenerator capture routinely exceeds 90% but carries a notable energy penalty. Integration is decisive: electrification and coke suppression reduce the $CO_2$ load to be captured; low-carbon co-feeds shrink the fossil fraction at the source; and CCUS secures neutrality for residual streams. Network and Sankey analyses reveal an emerging division of expertise (electrification/hydrogen, CCUS, bioeconomy, FCC catalysis) and highlight Brazil's comparative advantages in biomass and grid renewability, alongside bottlenecks in logistics, market instruments, and regulation. The roadmap couples catalyst/kinetic advances with electrified heaters, flexible co-processing windows, and fit-for-purpose capture chains, supported by techno-economic assessment and policy alignment. Re-engineering FCC from a bottleneck into a circular-carbon platform—linking molecules, electrons, and atoms—offers a credible path to align refining with 1.5 °C trajectories while protecting margins and product slates.

**Keywords:** Fluid Catalytic Cracking (FCC). Decarbonization. Electrification. Bio-oil co-processing. CCUS

## 1. Introduction

The mitigation of climate change is widely acknowledged as one of the most significant global challenges of our time, with the industrial sector playing a pivotal role due to the high carbon intensity of conventional production processes. The most recent Intergovernmental Panel on Climate Change report (IPCC AR6) reiterates the urgent imperative to limit the average global temperature increase to 1.5 °C above pre-industrial levels, stipulating that global net emissions must reach zero by 2050 [1]. In this context, energy- and carbon-intensive industries, including oil refining, are under growing pressure to significantly accelerate their decarbonization efforts through the deployment of robust and economically viable technological solutions.

According to the IPCC (2022) [2], global greenhouse gas emissions totaled 59 $GtCO_2eq$ in 2019. Of that amount, 24% (14 $GtCO_2eq$) originated from industry, making the industrial sector the second-largest direct emitter, surpassed only by the energy sector (33%, 20 $GtCO_2eq$). When both direct and indirect emissions are considered, industry becomes the principal source of global emissions [2], [3].

Petroleum refineries worldwide account for approximately 1% of global anthropogenic greenhouse gas (GHG) emissions.[2]. Although ostensibly modest in percentage terms, this share is highly significant in absolute magnitude and technical complexity, since these sectors are frequently designated as "hard-to-abate" owing to the technological and economic challenges associated with substituting fossil fuels with low-carbon alternatives.

Within the Brazilian context, the oil and gas sector occupies a central position in the national economic matrix, functioning both as a driver of economic growth and as a substantial source of the country's emissions. Refining operations account for approximately 50% of the total emissions from the oil and gas sector in Brazil.[4]. Among the various processes carried out in domestic refineries, Fluid Catalytic Cracking (FCC) units emerge as particularly significant sources of direct $CO_2$ emissions. This high emission intensity in FCC is primarily attributable to the catalyst regeneration step, during which the deposited coke is combusted, producing substantial $CO_2$ releases.

Furthermore, Brazilian refineries face distinctive challenges related to logistical infrastructure, access to advanced technologies, the still-developing maturity of the carbon market, and a regulatory framework that remains in consolidation. These factors make an indispensable technological and regulatory approach tailored to the Brazilian context, seeking bespoke solutions that reconcile efficiency, economic viability, and environmental sustainability.

Considering the technological complexity and environmental impact of Fluid Catalytic Cracking (FCC) units, this review article aims to assess current and future strategies for their decarbonization in Brazilian refineries. We'll focus on key areas like advanced catalysis, the deep electrification of industrial processes, and the integration of these efforts with national public policies.

## 2. Methodology

The scientometric methodology employed a structured bibliographic approach. We retrieved scientific articles from Scopus and Web of Science, covering the period from 2007 to 2025. To ensure the relevance and quality of the dataset, we applied stringent inclusion criteria based on an advanced Boolean search strategy using the terms "fluid catalytic cracking," "$CO_2$ mitigation," "decarbonization," and "refinery".

Duplicates were removed using the Bibliometrix 4.1.3 package [5] implemented in R 3.4.1 [6]. Subsequently, by the PRISMA statement [7], the records were screened and assessed for eligibility based on thematic relevance. Review articles and meta-analyses were excluded from the analysis.

The data were processed using the bibliometric software VOSviewer to generate co-occurrence maps, bibliographic coupling, and thematic cluster analyses. This approach aims to identify gaps, interdisciplinary convergences, and emerging opportunities for the decarbonization of FCC in Brazil.

## 3. Scientific and Technological Foundations

Fluidized Catalytic Cracking (FCC) has historically served as the workhorse of high-complexity refineries: it converts heavy fractions (vacuum gas oils, hydrotreated residues, bio-oils, or pyrolysis oils derived from plastics) into higher-value products, notably gasoline, light distillates, and petrochemical olefins. The process operates continuously in two coupled sections—the riser (500–540 °C) and the catalyst regenerator (680–730 °C)—linked by a fluidized-bed catalyst circulation loop that transfers catalyst between zones within a matter of seconds. Owing to its exceptional operational flexibility, FCC alone is responsible for 40–50% of gasoline production and up to 30% of olefinic feedstock in a typical refinery, exerting a direct influence on refining margins, hydrogen management, and the petrochemical slate.

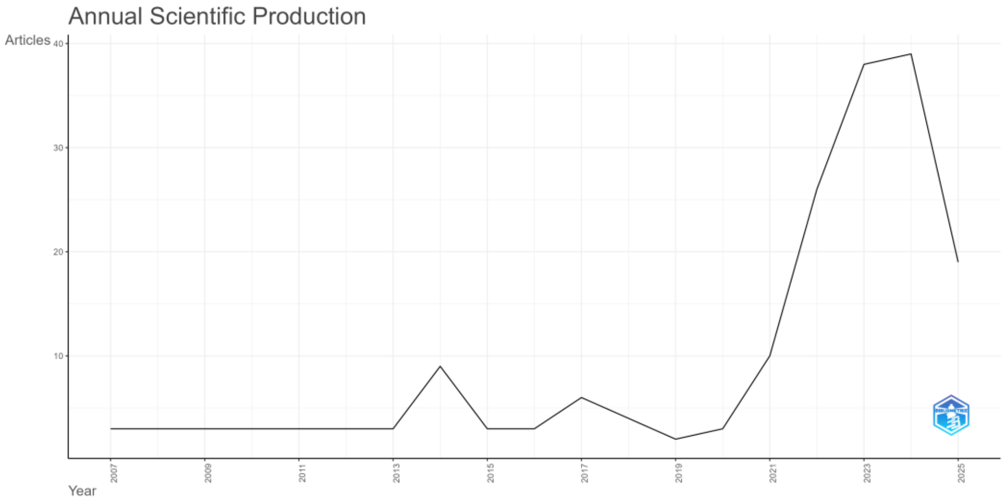
From a climate perspective, however, the unit constitutes an emissions hot spot [8], [9]:

- Coke formation – During the cracking reaction, approximately 1–6 wt.% of the feed carbon is deposited on the catalyst in the form of coke.
- Oxidative regeneration – The coke is combusted with air in the regenerator; this highly exothermic reaction supplies the required process heat while producing concentrated streams of $CO_2$ (and, to a lesser extent, CO, $NO_x$, and $SO_x$).
- Auxiliary furnaces – Slurry heaters or fuel vaporizer units, fired with natural gas or fuel oil, are employed to supplement the overall thermal demand.

In Brazilian coking-complex refineries (capacity >200 kbpd), FCC regenerators account for 20–30% of the site's direct $CO_2$ emissions, corresponding to 0.10–0.15 tons of $CO_2$ per ton of feed processed [10]–[12]. The magnitude stems from (i) the high regeneration air flow required to manage the thermal balance, (ii) the partial oxidation of CO (when the air-to-coke ratio is reduced), and (iii) the absence, in most facilities, of carbon recovery or capture systems. Thus, the Fluid Catalytic Cracking (FCC) unit emerges as an environmental bottleneck due to the combination of high thermal intensity, the inevitable formation of coke, and the necessity for oxidative regeneration. Targeted measures—operational tuning, fuel switching in auxiliary furnaces, or downstream capture—produce only marginal gains and are insufficient to align the sector with the IPCC's 1.5 °C trajectory.

## 4. Scientific Advancement of Decarbonization in Petroleum Refining

The timeline of scientific advancements in decarbonization within petroleum refining is illustrated in **Graphic 1.**



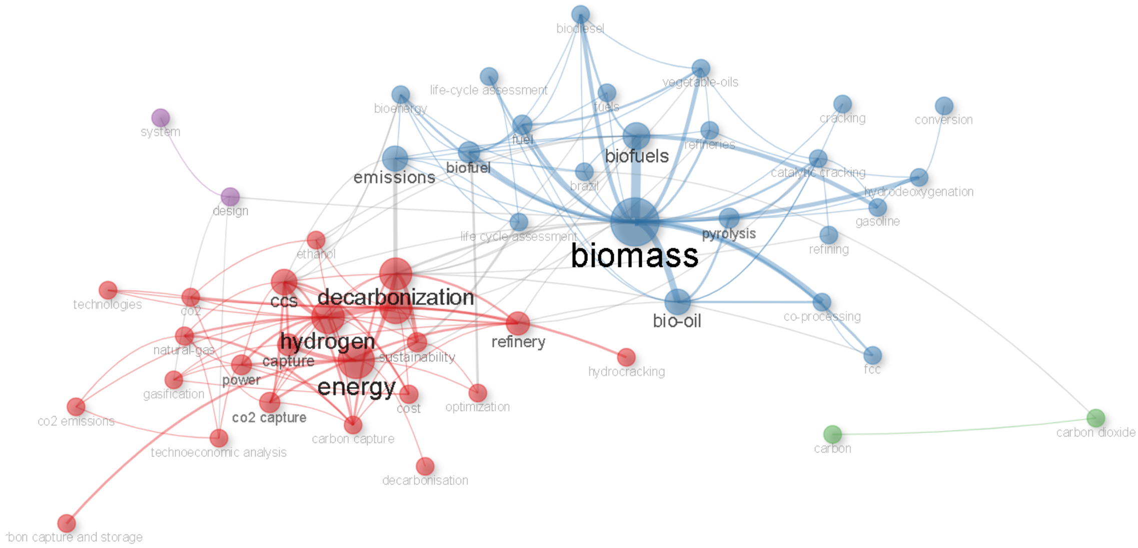

**Graphic 1.** Annual Evolution of Scientific Production on Decarbonization in Oil Refining.

**Graphic 1** reveals exponential growth beginning in 2020, culminating in a peak of nearly 40 annual publications in 2023–2024. This trajectory reflects not only the technical maturation of the field but also the escalating global urgency driven by carbon neutrality commitments and international regulatory pressure. Before that interval, the output was sparse and episodic, indicating that the topic occupied a marginal position within research agendas. The abrupt inflection in publication volume coincides with the strengthening of climate pledges by major economic blocs (such as the European Union and the United States), together with the emergence of public policies and private investments targeting the energy transition in hard-to-abate sectors like refining.

This surge in scientific attention suggests that FCC decarbonization has risen as a strategic, interdisciplinary, and highly competitive domain with profound technological, economic, and geopolitical implications.

Thus, it is not merely a contemporary subject but a critical necessity for the sustainable future of the petroleum industry.

A scientific network map, derived from Scopus and Web of Science datasets and organized using modularity detection algorithms (Louvain method), provides a systemic perspective on recent research output concerning refinery decarbonization, with particular emphasis on FCC units (**Graphic 2**).




**Graphic 2.** Network map for research on refinery decarbonization.

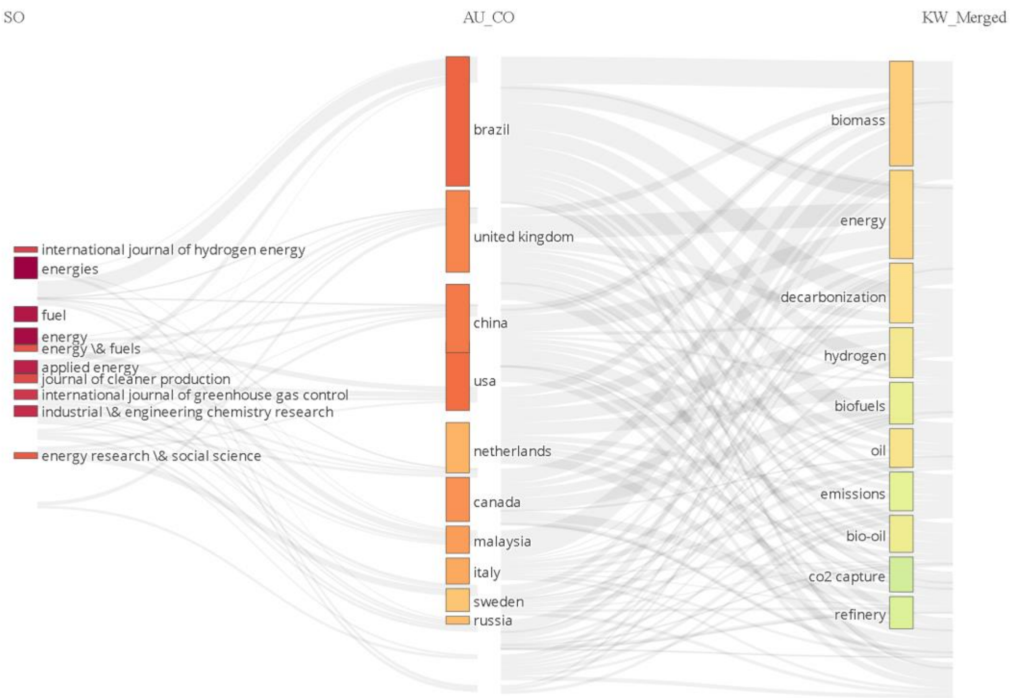
The nodes represent key concepts extracted from titles, abstracts, and keywords of indexed scientific articles, while the edges indicate the frequency of semantic co-occurrence. Node diameter is proportional to betweenness centrality, and coloring reflects distinct thematic groupings.

The blue cluster aggregates terms related to electrification, $CO_2$ capture (CCUS), and renewable energy, with prominent nodes such as "electric heating," "hydrogen," "carbon capture," and "$CO_2$ emissions." The red cluster is associated with the more traditional core of refining and heterogeneous catalysis, dominated by concepts like "FCC," "coke formation," "regenerator," and "zeolite catalyst." The green cluster, in turn, represents a subnetwork focused on the bioeconomy and co-processing of bio-oils, featuring terms such as "bio-oil," "biomass pyrolysis," and "hydrotreatment."

The intermediate positioning of the nodes "decarbonization," "refinery," "$CO_2$ mitigation," and "Brazil" underscores their bridging role across these themes, articulating multiple research domains and signaling the need for hybrid approaches.

This network architecture reveals that each mitigation axis has been investigated relatively independently, but it is at their conceptual intersection that the greatest potential for systemic transformation resides.

A Sankey-type diagram was constructed to link scientific journals (**SO**), authors' affiliation countries (**AU_CO**), and consolidated keywords (**KW_Merged**), providing a visual representation of the research ecosystem focused on the decarbonization of petroleum refining. (**Graphic 3**).




**Graphic 3.** Sankey diagram linking scientific journals (**SO**), authors' affiliation countries (**AU_CO**), and consolidated keywords (**KW_Merged**).

The first evidence is the thematic convergence around four technological pillars. The highest-relevance keywords (denoted by the largest node widths) align directly with the axes comprising the integrated mitigation strategy. Terms such as "biomass," "biofuels," and "bio-oil" reflect a growing effort to substitute fossil feedstocks with short-carbon-cycle carbon sources. Keywords like "energy" and "hydrogen" denote interest in deep electrification of process heat and the deployment of green hydrogen.

Meanwhile, "$CO_2$ capture," "decarbonization," and "emissions" signal the centrality of carbon capture, utilization, and storage (CCUS) technologies in abating regenerator-derived emissions.

Finally, "refinery" and "oil" underscore the continued relevance of source-reduction strategies via minimized coke formation and optimized oxygen/carbon monoxide ratios. This bibliographic convergence makes clear that isolated incremental gains are no longer sufficient: the scientific community is advancing toward a synergistic, integrated paradigm.

Secondly, Brazilian leadership is evident at the biomass–refining interface. The node "Brazil" is the most prominent among countries and exhibits strong connectivity with the keywords “biomass,” “biofuels,” and “bio-oil.” This pattern reflects Brazil’s structural advantages, including a highly renewable power matrix (≈85%) and abundant biomass availability. Such attributes position co-processing of low-carbon-footprint feedstocks as a priority axis for the decarbonization of Brazilian refineries, consistent with the National Agenda for Ecological Transition.

The third evidence point is the complementary international specialization across the remaining pillars. The United Kingdom and the Netherlands show strong associations with the terms “decarbonization” and “$CO_2$ capture,” indicating established expertise in carbon policy frameworks and CCUS technologies. In contrast, the United States and China are prominent in “hydrogen” and “energy,” signaling leadership in electrification and the production of green or blue hydrogen. The dense intercountry linkages reveal tangible opportunities for technology transfer and international cooperation, particularly in the domains of electrification and carbon capture implementation within Brazilian refining facilities.

Each mitigation axis delivers quantifiable benefits when implemented independently, yet is constrained by technical or economic limitations:

- **Source reduction** — by minimizing coke formation, the “fuel” for emissions is decreased. However, as documented in Fuel [13]–[16] and Industrial & Engineering Chemistry Research [17]–[19], isolated kinetic enhancements tend to exhibit diminishing returns, constraining reductions to approximately 20%.
- **Electrification** — can lower emissions by up to 40% when powered by renewable energy, as demonstrated in the International Journal of Hydrogen Energy [20], [21] and Energies [22]–[26]. Nonetheless, without effective management of peak demand, the associated capital expenditure (CAPEX) may render large-scale deployment economically unviable.
- **Co-processing of bio-feedstocks** — such as pyrolytic bio-oils or hydrotreated vegetable oils- enables additional carbon footprint reductions of 6–10%, according to the Journal of Cleaner Production [27]–[31]. Despite this, limitations persist in feedstock availability, catalyst compatibility, and operational stability.
- **CCUS** — studies reported in the International Journal of Greenhouse Gas Control [32]–[36] indicate capture efficiencies exceeding 90% in the regenerator. However, the additional energy penalty (parasitic load) and

elevated operating costs make its isolated implementation economically unfavorable.

The scientometric landscape, therefore, not only provides robust evidence of the technical and scientific viability of the four pillars but also reveals a natural partitioning of global expertise. When these four axes are deployed in an integrated fashion, their limitations are overcome through complementary synergies: the use of bio-oils reduces the quantity of fossil carbon requiring capture; electrification lowers the volume of gases needing amine treatment; reduced coke formation diminishes the energy demand for regeneration; and CCUS secures carbon neutrality even for residual emission streams.

## 5. The FCC as a Climate Innovation Platform

Transforming the FCC unit from an emissions bottleneck into an integrated circular carbon platform requires more than incremental innovation—it demands systemic reengineering and cross-sector coordination. A promising pathway is the deployment of integrated mitigation measures. Essentially, this approach combines (i) source reduction—diminishing coke formation itself and, therefore, the "fuel" for emissions; (ii) deep electrification of process heat, shifting the carbon footprint onto an electricity matrix dominated by renewables; (iii) co-processing of low-carbon-footprint feeds (bio-oils, plastic recycling streams, or hydrotreated vegetable oils) that replace a portion of fossil carbon with short-cycle carbon; and (iv) carbon capture, utilization, and storage (CCUS) applied to the residual regenerator stream.

Thus, electrification lowers the $CO_2$ load before capture. Co-processing biofeeds reduces the fossil carbon content of the feedstock. Carbon capture ensures neutrality even for the remaining emissions. Each mitigation axis consequently lessens the burden on the others.

Suppose the twentieth century was shaped by fuels produced from the FCC. In that case, the twenty-first century will require it to evolve into the operative core of the climate refinery, linking molecules, electrons, and atoms with the same sophistication with which it once delivered octane.

Alongside established pathways, emerging trends with disruptive potential for FCC unit operations are emerging. The use of predictive models based on artificial intelligence and real-time control systems already allows for the optimization of combustion in the regenerator, reducing coke formation and maximizing thermal efficiency. Simultaneously, new-generation regenerable catalysts are being developed with properties that favor selective CO oxidation and reduced carbon deposition, expanding operating windows with lower emissions.

In the long term, the FCC is expected to transform into a flexible, low-carbon platform capable of operating with coupled electrochemical reactors, integrating the use of green hydrogen, and synthesizing e-fuels from recycled feedstocks or upstream $CO_2$ capture. By 2050, the evolution of these technologies could redefine the role of the FCC: from a historical emitter to a hub for circularity and renewable synthesis in a climate-neutral refinery.

## 6. Final Considerations and Synergies with Public Policies and Economic Instruments of Transition

The decarbonization of oil refineries—and, in particular, FCC units—cannot be limited to technological innovations on the factory floor. For the solutions analyzed in this paper to reach industrial scale and become economically viable, they must be coordinated with consistent public policies and economic mechanisms to support the transition.

In Brazil, the advancement of Bill No. 412/2022, which establishes the regulated carbon market, lays the foundation for a national emissions pricing system. If approved, this mechanism could significantly alter the economic attractiveness of technological pathways such as $CO_2$ capture and utilization (CCUS), process electrification, and bio-oil co-processing. Furthermore, existing instruments, such as Decarbonization Credits (CBIOs) under RenovaBio, and green financing lines through BNDES, FINEP, and multilateral climate funds, offer concrete opportunities to cushion CAPEX and enable medium-term projects aimed at reducing emissions in the refining sector.

Structural initiatives such as the "Fuel of the Future" program and the "New Industry Brazil" industrial policy also indicate a strategic shift in the country's direction toward the energy transition. Both recognize the role of refineries as transformative assets and not merely environmental liabilities, provided that advanced biofuels, electrification, and carbon capture are incorporated into their operations.

The convergence of industrial policy, environmental regulation, and technological innovation should, therefore, be the central pillar of the FCC's reengineering. Rather than treating regulation as a barrier, the sector can reposition itself as a protagonist of low-carbon industrialization, leveraging the technical potential mapped in this article with the necessary institutional support for its implementation at scale.

The economic viability of the decarbonization pathways analyzed—especially $CO_2$ capture and deep electrification—still depends on advances in scale, regulatory maturity, and cost reduction. Recent estimates indicate avoided costs of between US\$50 and US\$180/t$CO_2$, making coordinated action across instruments such as carbon credits, fair emissions pricing, and incentives for innovation essential. In this scenario, the integration of industrial policy, climate finance, and technological solutions becomes a competitive differentiator, capable of aligning sustainability goals with the financial viability of transforming the FCC in Brazil.

## References

[1] B. Christopher *et al.*, "Defining 'abated' fossil fuel and industrial process emissions," *Energy Clim. Chang.*, vol. 6, p. 100203, Dec. 2025.

[2] "Climate Change 2022: Mitigation of Climate Change." [Online]. Available: https://www.ipcc.ch/report/ar6/wg3/. [Accessed: 17-Jul-2025].

[3] "AR6 Synthesis Report: Climate Change 2023." [Online]. Available: https://www.ipcc.ch/report/ar6/syr/. [Accessed: 17-Jul-2025].

[4] "Sistema de Estimativa de Emissões de Gases de Efeito Estufa (OC-SEEG)." .

[5] M. Aria and C. Cuccurullo, "bibliometrix: An R-tool for comprehensive science mapping analysis," *J. Informetr.*, vol. 11, no. 4, pp. 959–975, Nov. 2017.

[6] R. D. C. Team, "R: A language and environment for statistical computing. R Foundation for Statistical Computing," *Dendrochronologia*, vol. 3, pp. 1–12, 2023.

[7] A. Liberati *et al.*, "The PRISMA statement for reporting systematic reviews and meta-analyses of studies that evaluate healthcare interventions: explanation and elaboration," *BMJ*, vol. 339, Jul. 2009.

[8] Y. Mori, Z. Li, and G. Mogi, "Refinery Transition Process for a Carbon-Neutral Society," in *International Conference on Electrical, Computer, and Energy Technologies, ICECET 2024*, 2024.

[9] R. Sadeghbeigi, Ed., "Chapter 4 - FCC feed characterization," in *Fluid Catalytic Cracking Handbook (Fourth Edition)*, Fourth Edi., Butterworth-Heinemann, 2020, pp. 47–81.

[10] D. Leeson, N. Mac Dowell, N. Shah, C. Petit, and P. S. Fennell, "A Techno-economic analysis and systematic review of carbon capture and storage (CCS) applied to the iron and steel, cement, oil refining and pulp and paper industries, as well as other high purity sources," *Int. J. Greenh. Gas Control*, vol. 61, pp. 71–84, 2017.

[11] E. de P. Energética., "Bloco 7 – Descarbonização das Atividades de Refino de Petróleo.," Rio de Janeiro., 2024.

[12] F. Güleç, W. Meredith, and C. E. Snape, "Progress in the CO2 Capture Technologies for Fluid Catalytic Cracking (FCC) Units—A Review," *Frontiers in Energy Research*, vol. 8. Frontiers Media S.A., 23-Apr-2020.

[13] D. Braide, C. Panaritis, G. Patience, and D. C. Boffito, "Gas to liquids (GTL) microrefinery technologies: A review and perspective on socio-economic implications," *FUEL*, vol. 375, Nov. 2024.

[14] N. A. Carlson *et al.*, "Economic analysis of the benefits to petroleum refiners for low carbon boosted spark ignition biofuels," *FUEL*, vol. 334, no. 1, 2023.

[15] M. Wei *et al.*, "Study on the integration of fluid catalytic cracking unit in refinery with solvent-based carbon capture through process simulation," *FUEL*, vol. 219, pp. 364–374, 2018.

[16] S. H. Ng *et al.*, "FCC coprocessing oil sands heavy gas oil and canola oil. 1. Yield structure," *FUEL*, vol. 156, pp. 163–176, 2015.

[17] W. Shi, Y. Gao, S. Song, and Y. Zhao, "One-Pot Conversion of Bio-oil to Diesel- and Jet-Fuel-Range Hydrocarbons in Supercritical Cyclohexane," *Ind. \& Eng. Chem. Res.*, vol. 53, no. 28, pp. 11557–11565, Jul. 2014.

[18] A. Vonortas and N. Papayannakos, "Kinetic Study of the Hydrodesulfurization of a Heavy Gasoil in the Presence of Free Fatty Acids Using a CoMo/γ-Al2O3 Catalyst," *Ind. \& Eng. Chem. Res.*, vol. 53, no. 23, pp. 9646–9652, Jun. 2014.

[19] H. Wang, G. Wang, B. Shen, C. Xu, and J. Gao, "Upgrading Residue by Carbon Rejection in a Fluidized-Bed Reactor and Its Multiple Lump Kinetic Model," *Ind. \& Eng. Chem. Res.*, vol. 50, no. 22, pp. 12501–12511, Nov. 2011.

[20] T. T. G. de Rezende *et al.*, "Technical and economic potential for hydrogen production from biomass residue gasification in the state of Minas Gerais in Brazil," *Int. J. Hydrogen Energy*, vol. 101, pp. 358–378, 2025.

[21] V. Juarez-Casildo, I. Cervantes, and R. de G. Gonzalez-Huerta, "Harnessing offshore wind for decarbonization: A geospatial study of hydrogen production and heavy industry utilization in Mexico," *Int. J. Hydrogen Energy*, vol. 83, pp. 701–716, 2024.

[22] V. F. Dornelas, A. Nascimento, D. Z. Mantegazini, E. E. S. Lora, E. da C. Bortoni, and M. Amro, "Occurrences and Perspectives of Natural Hydrogen Extraction: The Brazilian Context," *ENERGIES*, vol. 18, no. 11, 2025.

[23] A. Dimitriadis and S. Bezergianni, "Towards Bio-Crude Refinery Integration: Hydrodeoxygenation and Co-Hydroprocessing with Light Cycle Oil," *ENERGIES*, vol. 17, no. 23, 2024.

[24] W. Thepsaskul *et al.*, "Potential Business Models of Carbon Capture and Storage (CCS) for the Oil Refining Industry in Thailand," *ENERGIES*, vol. 16, no. 19, 2023.

[25] E. P. Santos Junior *et al.*, "Potentialities and Impacts of Biomass Energy in the Brazilian Northeast Region," *ENERGIES*, vol. 16, no. 9, 2023.

[26] B. H. M. Silveira, H. K. M. Costa, and E. M. Santos, "Bioenergy with Carbon Capture and Storage (BECCS) in Brazil: A Review,"

*ENERGIES*, vol. 16, no. 4, 2023.

[27] J. Mota-Nieto, M. Brander, and P. Diaz-Herrera, "Carbon accounting methods for the system-wide evaluation of carbon capture, utilisation and storage: A case study in Mexico `s Southeast Region," *J. Clean. Prod.*, vol. 453, 2024.

[28] A. Bin Sahl, A. Orosz, B. S. How, F. Friedler, and S. Y. Teng, "Electrification of oil refineries through multi-objective multi-period graph-theoretical planning: A crude distillation unit case study," *J. Clean. Prod.*, vol. 434, Jan. 2024.

[29] M. Nahvi, A. D. Koohi, and M. Sedighi, "Thermodynamic analysis and techno-economic assessment of fluid catalytic cracking unit in the oil refining process," *J. Clean. Prod.*, vol. 413, 2023.

[30] T. Li, J. Long, W. Du, F. Qian, and V. Mahalec, "Three pathways towards elimination of CO2 emissions from industrial plants that use hydrocarbon fuels," *J. Clean. Prod.*, vol. 391, Mar. 2023.

[31] F. D'Amore, M. C. Romano, and F. Bezzo, "Carbon capture and storage from energy and industrial emission sources: A Europe-wide supply chain optimisation," *J. Clean. Prod.*, vol. 290, Mar. 2021.

[32] L. C. Coutinho *et al.*, "Climate strategies for oil and gas production under the lens of an Integrated Assessment Model: The case of Brazil," *Int. J. Greenh. GAS Control*, vol. 137, 2024.

[33] D. Cristiu, F. d'Amore, P. Mocellin, and F. Bezzo, "Multi-objective optimisation of a carbon capture and sequestration supply chain under seismic risk constraints. A case study considering industrial emissions in Italy," *Int. J. Greenh. GAS Control*, vol. 129, 2023.

[34] T. Lap, R. Benders, F. van der Hilst, and A. Faaji, "BECCS as climate mitigation option in a Brazilian low carbon energy system: Estimating potential and effect of gigatonne scale CO2 storage," *Int. J. Greenh. GAS Control*, vol. 128, 2023.

[35] V. Andersson, P.-A. Franck, and T. Berntsson, "Techno-economic analysis of excess heat driven post-combustion CCS at an oil refinery," *Int. J. Greenh. GAS Control*, vol. 45, pp. 130–138, 2016.

[36] F. Rezazadeh, W. F. Gale, K. J. Hughes, and M. Pourkashanian, "Performance viability of a natural gas fired combined cycle power plant integrated with post-combustion CO2 capture at part-load and temporary non-capture operations," *Int. J. Greenh. GAS Control*, vol. 39, pp. 397–406, 2015.

**Acknowledgement**

The authors are grateful for financial support from the Instituto Brasileiro de Tecnologia e Regulação (IBTR), Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq), and Programa de Recursos Humanos da Agência Nacional do Petróleo, Gás Natural e Biocombustíveis (PRH/ANP -- PRH36/UFBA), supported by resources from the investment of oil companies qualified in the PD&I Clause of ANP Resolution No. 50 /2015 ANP.