

# Industrial Decarbonization Roadmap, Pt. 5, Petroleum Refining

*By John Benson*

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## 1. Introduction

The first part of this post was an Overview and is linked below:

<https://energycentral.com/c/cp/industrial-decarbonization-roadmap-part-1-overview>

Part 2 was about Iron and Steel Production Industries and is linked below.

<https://energycentral.com/c/ec/industrial-decarbonization-roadmap-part-2-iron-steel>

Part 3 was about Chemical Manufacturing and is linked below.

<https://energycentral.com/c/cp/industrial-decarbonization-roadmap-part-3-chemical-manufacturing>

Part 4 was about the Food and Beverage Manufacturing Industry, and is linked below.

<https://energycentral.com/c/ec/industrial-decarbonization-roadmap-pt-4-food-and-beverages>

Part 5 is on Petroleum Refining. In my first review on the source document (referenced at the end of this paragraph), I found that there are two adjacent sectors that are tightly connected to Petroleum Refining:<sup>1</sup>

- **Oil & Gas Extraction:** Actually the initial stages of refining occur in the Oil/Gas Well fields, so it's probably inevitable that the source document will cross-over into these areas.
- **Mobility:** Although many industries use the output of Petroleum Refining, Mobility is one of the largest users. Also these vehicles are rapidly transitioning to electric power, and quickly reducing their demand for petroleum-sourced products. Ironically, mobility may represent one future path for Petroleum Refining, that is producing plant- and electricity-based fuels with little-to-no net greenhouse gasses (GHG).

I have not written a post that was specifically about Petroleum Refining, although I have mentioned their products and processes in other posts.

## 2. Petroleum Refining

*The crosscutting decarbonization pillars identified in this work are energy efficiency, industrial electrification and electrification low-carbon fuels, feedstocks, and energy sources (LCFFES) from non-fossil fuel or low-carbon emitting sources, and carbon capture, utilization, and storage (CCUS), where electrification and LCFFES are highly connected and evaluated together for this roadmap. The U.S. refining industry is the largest producer of liquid transportation fuels and refined petroleum products in the*

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<sup>1</sup> Full List of authors, reviewers and supporting groups is contained on this document's front-matter pages xi -- xiv, U.S. Department of Energy, "Industrial Decarbonization Roadmap," September 2022, <https://www.energy.gov/sites/default/files/2022-09/Industrial%20Decarbonization%20Roadmap.pdf>

world; about 16.6 million barrels of oil per day (BPD) were refined in 2019 in the United States.<sup>2</sup> The subsector was comprised of 135 individual refineries in 2019 that refine raw materials, mostly crude oils supplemented by other natural or semi-processed hydrocarbon mixtures, into a range of petroleum products that includes transport fuels, heating and industrial fuels, chemical feedstocks, lubricant base-stocks, and asphalts. Feedstock and product slate, process unit complexity, energy efficiency, and fuel carbon content are essential factors that govern the CO<sub>2</sub> intensity of a particular refinery.

**Author's comment:** Note the above wide-range of products produced by these refineries. This industry has tentacles that reach into many other industries. Also note the amount of oil refined: almost 700 million gallons per day. The oil refining industry has also become very economically efficient. Thus replacing the above products with low greenhouse gas (GHG) alternatives will have impacts that will ripple through our economy. Read on for details.

*Although engagement and feedback regarding the petroleum refining subsector was sparse in the stakeholder meetings, valuable feedback to guide research development and demonstration (RD&D) needs across near-commercial, emerging, and transformative low-carbon technologies was provided. Key learnings and RD&D opportunities from the meetings include:*

- In 2020, U.S. petroleum refining emissions accounted for 5% of the 4,563 million MT total U.S. energy-related CO<sub>2</sub> emissions, equivalent to 235 million MT (metric tons or tonnes) CO<sub>2</sub>; the U.S. transportation sector's energy-related CO<sub>2</sub> emissions were 1,591 million MT CO<sub>2</sub>, 35% of total U.S. energy-related emissions.<sup>3</sup> Although refinery energy and material efficiency, electrification, and CO<sub>2</sub> capture (for sequestration or reuse) investments are within refiner's control, the maximum benefit of decarbonizing U.S. refineries towards the goal of net-zero CO<sub>2</sub> emissions is 5% of the total energy-related CO<sub>2</sub> emissions throughout the U.S. economy. Competing options for reducing the 35% of the U.S. economy's total petroleum-based transportation CO<sub>2</sub> emissions – such as vehicle technologies, electric vehicles fueled by decarbonized electricity (the most common transportation decarbonization pathway found in the literature) as well as low-carbon feedstocks and supply chain alternative to crude oil – are outside refiners' control. Considering the capital-intensive investments required to revamp refineries, refinery decarbonization could be one of the least cost-effective options towards the goal of achieving net-zero CO<sub>2</sub> emissions.*

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<sup>2</sup> "Petroleum and Other Liquids: Number and Capacity of Petroleum Refineries, Atmospheric Crude Oil Distillation Capacity," U.S. Energy Information Administration, last modified June 25, 2021, [https://www.eia.gov/dnav/pet/pet\\_pnp\\_cap1\\_dcu\\_nus\\_a.htm](https://www.eia.gov/dnav/pet/pet_pnp_cap1_dcu_nus_a.htm). By comparison, in 2018 refineries in the European Union refined 12.7 million barrels per day, China refined 13.4 million barrels per day, and ~ 8.5 million barrels per day were refined in the Middle East (See page 30 of BP, BP Statistical Review of World Energy 2021, 2021, <https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2021-full-report.pdf> ).

<sup>3</sup> "Annual Energy Outlook 2021 with Projections to 2050," U.S. Energy Information Administration, February 3, 2021, <https://www.eia.gov/outlooks/archive/aeo21/>. See Table 19. Energy-Related Carbon Dioxide Emissions by End Use.

- *The refining subsector is integral to transportation sector decarbonization by providing options such as low-carbon fuels, and net-zero GHG aviation fuels.<sup>4</sup>*
  - *To viably achieve net-zero GHG emissions across the U.S economy, options to reduce refinery CO<sub>2</sub> emissions must be within refiners' control and harmonize with competing options across the U.S economy that are outside refiners' control.*
  - *Harmonizing cost-effective net-zero CO<sub>2</sub> emission solutions across the U.S economy requires a holistic life cycle-based "wells-to-wheels" governance structure that a) monitors and accounts for net CO<sub>2</sub> reductions, and b) rewards those making the necessary investments, such as refiners, manufacturers, or consumers. Moving forward without such mechanisms risks dwarfing, or even negating, the potential benefits of "siloed" refining subsector decarbonization investment decisions.*

*Key learnings and RD&D opportunities from the roadmap meetings include:*

- *The RD&D needed to reduce refinery CO<sub>2</sub> emissions range from early-stage RD&D to detailed development and deployment support. For example, carbon capture technologies are relatively mature, yet their deployment requires RD&D to develop cost-effective options to revamp current refinery configurations and complexities, whereas the use of captured carbon as feedstocks for producing low-carbon fuels requires earlier stage RD&D.*
- *Both government-supported RD&D and industry adoption of RD&D results require long-term active engagement and partnerships with industrial companies. This engagement and partnership will help identify cost-effective options, develop a strategic approach to the transition to net-zero CO<sub>2</sub> emissions across the U.S. economy, determine a strategic approach to private and public RD&D investments, and test and scale the most promising RD&D results and technologies.*
  - *Techno-economic studies are needed to understand the applicability of technologies (even at pre-commercial stages) and to provide cost-effectiveness targets, as well as timelines and milestones for RD&D results.*
  - *RD&D decisions for both refining and transportation decarbonization technologies should be pursued together. They should be informed by a holistic transportation decarbonization roadmap that compares CO<sub>2</sub> reduction potential and cost scenarios across multiple sectors of the U.S. economy and reflect the most cost-effective net-zero CO<sub>2</sub> reduction options...*

**Author's comment:** Although I have mentioned this earlier, it bears repeating. Under the best circumstances the transition to EVs will have a residual number of owners that refuse to transition as we approach 2050. Although this will probably be the single-digit percentages, it will provide one niche for current Petroleum Refiners to embrace this as a high-margin product: a fuel for high-affinity autos, motorcycles, etc. that has net-zero GHG emissions. Although there will be many other products and functions this segment can assume, this will certainly be a sizable and lucrative future market.

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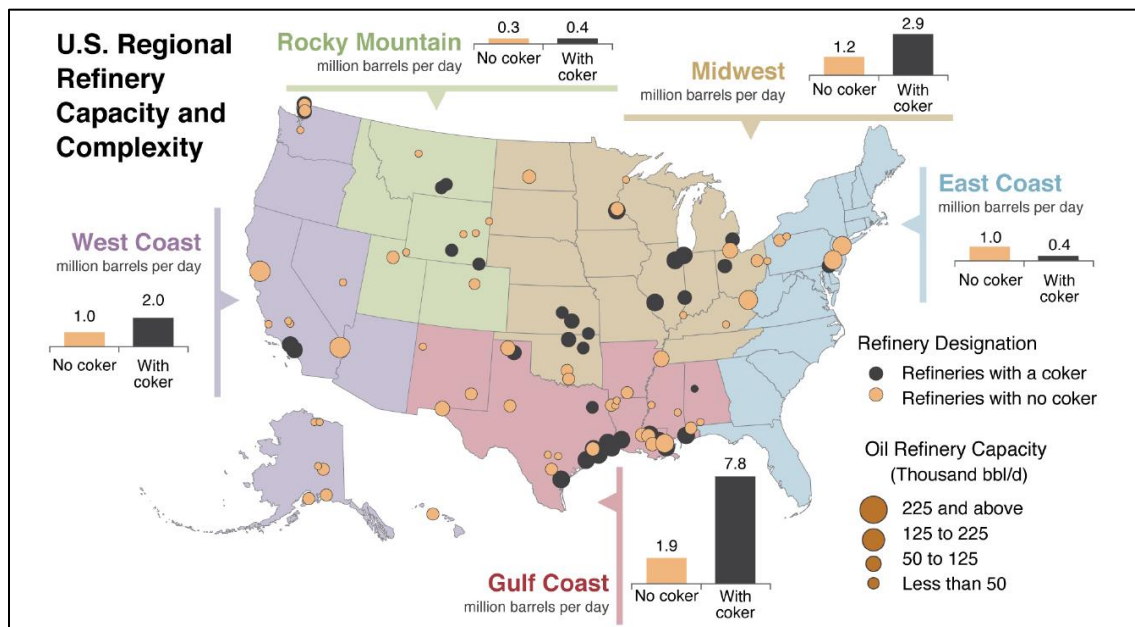
<sup>4</sup> Robert Lempert et al., Pathways to 2050: Scenarios for Decarbonizing the U.S. Economy, Center for Climate and Energy Solutions, May 2019, <https://www.c2es.org/site/assets/uploads/2019/05/pathways-to-2050-scenarios-for-decarbonizing-the-us-economy-final.pdf>, note that there were three references for this footnote in the source text, the above was the most recent.

### 3. Status of U.S. Petroleum Refining

Petroleum refining products are an essential part of the world economy, providing a large source of energy and other value-added products to key U.S. sectors such as chemical and transportation. The United States consumed about 20.5 million barrels (86 million gallons) per day in 2019. About 70% of petroleum is consumed in transportation, making that sector particularly vulnerable to changes in production and pricing. In addition, manufacturing industries consume about 24% of petroleum as fuels and as feedstock in the production processes.

Refinery activities have significant direct and indirect impacts on the U.S. economy. For example, in 2020, the total value of U.S. petroleum refining products shipped amounted to \$315 billion (6% of manufacturing value of shipments), and direct employment of the petroleum refining industry was approximately 63 thousand workers.

Although refineries have similar processes, each is unique due to various aspects such as its evolution, accessibility of specific crude oils, product specification constraints, market demands and profitability. Furthermore, each refinery is subject to unique regional policies and regulations, such as regional air quality regulations. Thus, many U.S. refineries are configured for specific crude oils and U.S. regions as figure below shows, reflecting unique historical policies, environmental performance regulations, and regionally specific vehicles stocks and product demands. Further, refining technology has changed over time, coevolving with vehicle technology. As a result, U.S. refineries often have one-of-kind equipment processing configurations.



**Author's comment:** From the above figure, note that a "coker" is <sup>5</sup>an oil refinery processing unit that converts the residual oil from the vacuum distillation column into low molecular weight hydrocarbon gases, naphtha, light and heavy gas oils, and petroleum coke. Ultimately the latter product is further produced to make anode coke, and the anodes are mainly used in the aluminum and steel industries.

<sup>5</sup> [https://en.wikipedia.org/wiki/Coker\\_unit](https://en.wikipedia.org/wiki/Coker_unit)

### 3.1. Energy Use and CO<sub>2</sub> Emissions

*Refinery feedstocks and refinery products are both comprised of a range of hydrocarbons with small quantities of other elements, such as sulfur and nitrogen. And most refineries have a similar array of process units that rearrange carbon and hydrogen atoms to obtain final products through:*

- *Physical separation of hydrocarbon fractions.*
- *Treatment of fractions (e.g., to remove undesirable compounds such as sulfur).*
- *Modification of molecular structure (e.g., cracking large molecules into smaller molecules, reformulating and hydro-treating branching molecules to address octane and enable more uniform combustion in vehicles).*

*The energy intensity of a refinery is a function of its complexity or configuration of the combination of processes operated, which in turn determines which crude oils can be processed as well as the type, yield, and quality of the refined products that can be manufactured. As a rule, more conversions of heavy streams into light products will lead to cleaner finished products and higher energy intensity; in other words, a complex refinery will consume more energy than a simple refinery with the same crude throughput.*

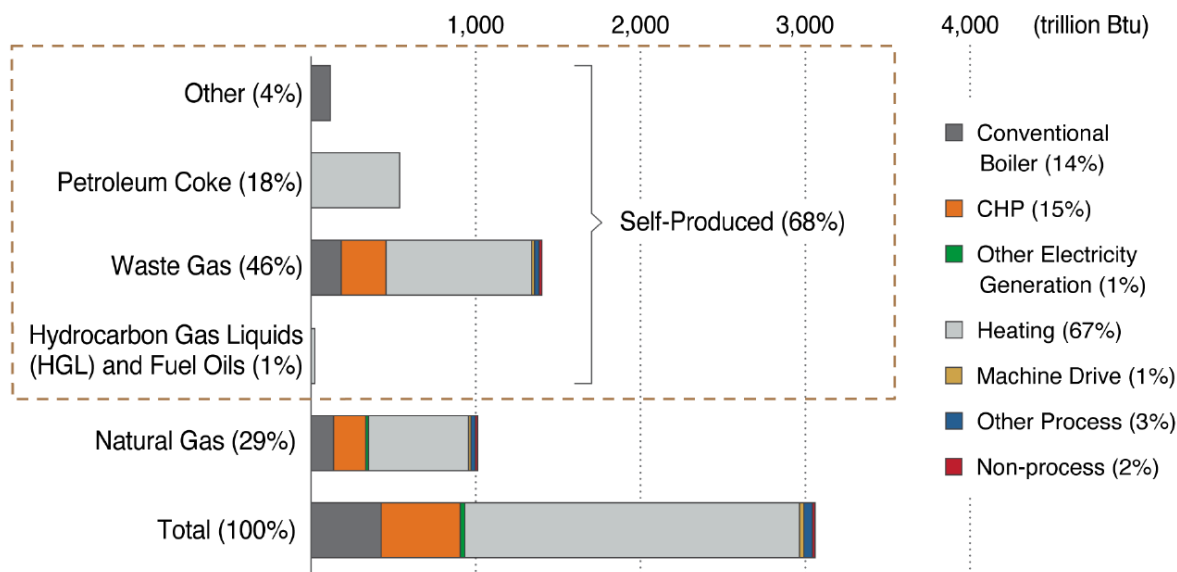
*As a result of market developments, refineries have steadily become more complex, incorporating more process units dedicated to treating and converting heavy fractions into lighter ones. Further, the hydrogen-to-carbon ratio of combined refinery products has increased significantly beyond that of combined feedstocks, requiring a net addition of hydrogen, removal of carbon in the form of coke, or both...*

*Most refining process units produce undesirable hydrocarbons, such as waste gas (also referred to as refinery gas or still gas) and petroleum coke, as byproducts of crude oil refining. Most refineries capture and use these streams to avoid hazardous air emissions from flaring of the waste gases and costly waste treatment of petroleum coke, which represents avoided-cost sources of supplemental fuel, feedstocks, or both. Often, refinery process equipment (e.g., reactors and furnaces) and facility utility equipment (e.g., boilers and CHP (Combined Heat and electric Power) units) are designed to enable the use of these byproducts as fuel. As a result, many refinery process operations represent a finely-tuned balance of heat and electricity—including direct heating (fired furnaces), indirect heating (steam from boilers or CHP), and electricity (from CHP). Fuel or electricity that have demands that cannot be met by these sources are supplied pipeline gas and electricity purchases, respectively.*

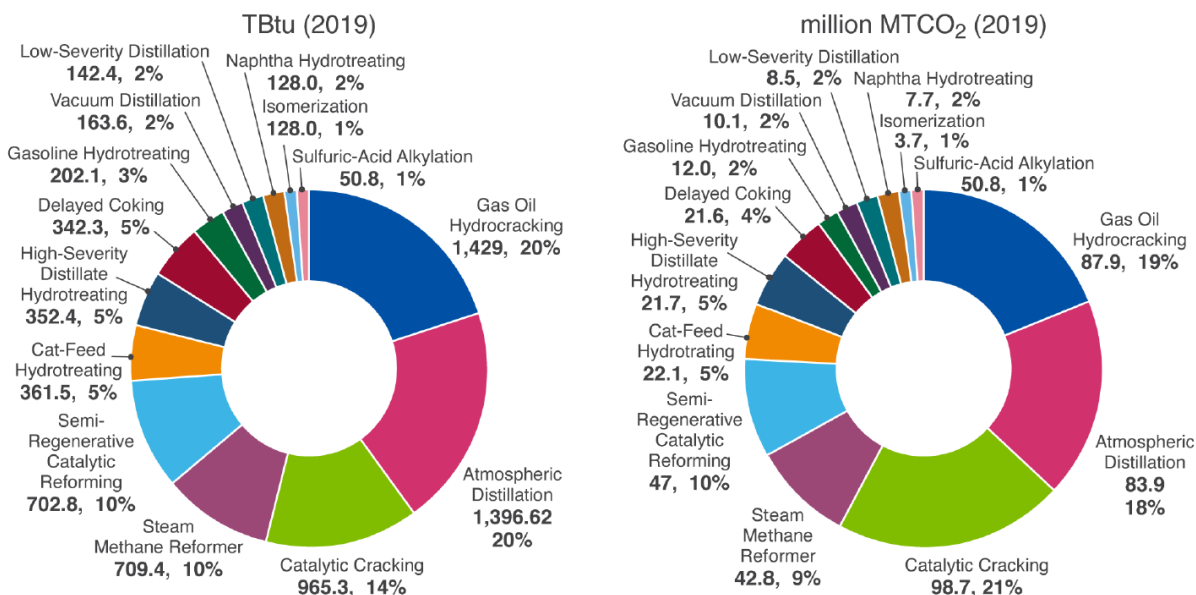
*As the top figure below (next page) shows, 68% of fuel energy used by the U.S. refining industry in 2018 was self-produced. Most fuel gas is used for process heating or to generate steam and electricity in CHP units, while most electricity is used for machine drive. Where hydrogen is required to achieve product specifications or to convert heavier fractions of the crude oil into suitable processing feedstocks, it is primarily obtained by removing the carbon from light hydrocarbons such as natural gas, which produces process CO<sub>2</sub> emissions in addition to CO<sub>2</sub> emissions from fuel consumption. Thus, the reduction of refinery facility CO<sub>2</sub> will require decarbonizing process heating, onsite power generation, and onsite hydrogen production.*

Self-produced fuel gas use is the major source of CO<sub>2</sub> emissions from a refinery; however, the carbon content of these fossil-fuel derived emissions is less than that of natural gas because of the presence of residual hydrogen gas from some of the processing units.

The bottom figure below shows estimated energy consumption by the largest energy-consuming petroleum refining unit processes in 2019. The five largest energy-consuming refinery processes account for 85% of refinery energy consumption and associated CO<sub>2</sub> emissions.



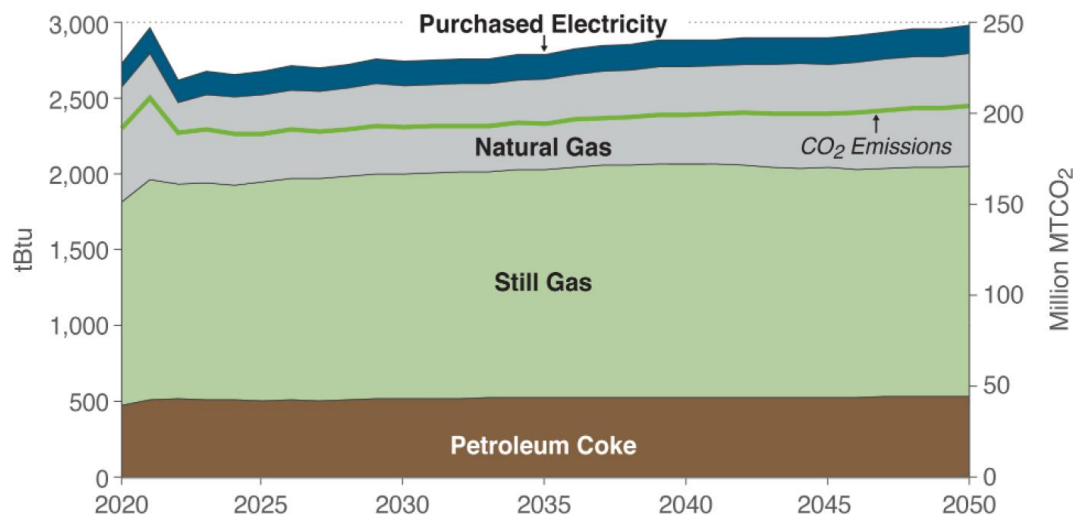
Fuel Energy Consumption at U.S. Petroleum Refineries in 2018, Broken out by fuel and end use.



U.S. Petroleum Refining energy consumption (left) and CO<sub>2</sub> Emissions (right) by Process in 2019. Note that TBtu is trillion British thermal units.

As Figure below shows, EIA's Annual Energy Outlook 2020 Reference Case projects U.S. petroleum refinery energy consumption and CO<sub>2</sub> emissions out to 2050. The total energy consumption is a function of demand for liquid transportation fuels, with both the ratio of energy source and associated CO<sub>2</sub> emissions remaining relatively constant.

The figure below is based on the EIA AEO (Energy Information Administration, Annual Energy Outlook) Reference Case which assumes business as usual, where petroleum production and consumption remains constant.



EIA Annual Energy Outlook 2020 Reference Case projection of U.S. petroleum refining energy consumption (in trillions of BTU) and CO<sub>2</sub> emissions (in million MT (metric tons or tonnes)) to 2050.

## 4. Decarbonization Pathways

Refineries will see similar opportunities; however, the range of decarbonization options will depend on each refinery's location, local policy, design, history, and technologies employed. The opportunities to reduce refinery GHG emissions can be grouped into the following areas:

- Improve energy efficiency both in processes and onsite steam and power generation.
- Lower the carbon footprint of energy sources and feedstocks by using lower-carbon fossil energy and introducing low-fossil carbon sources such as nuclear heat and electricity, clean electricity, clean hydrogen, or biofuels.
- Capture CO<sub>2</sub> for either long-term storage or utilization.

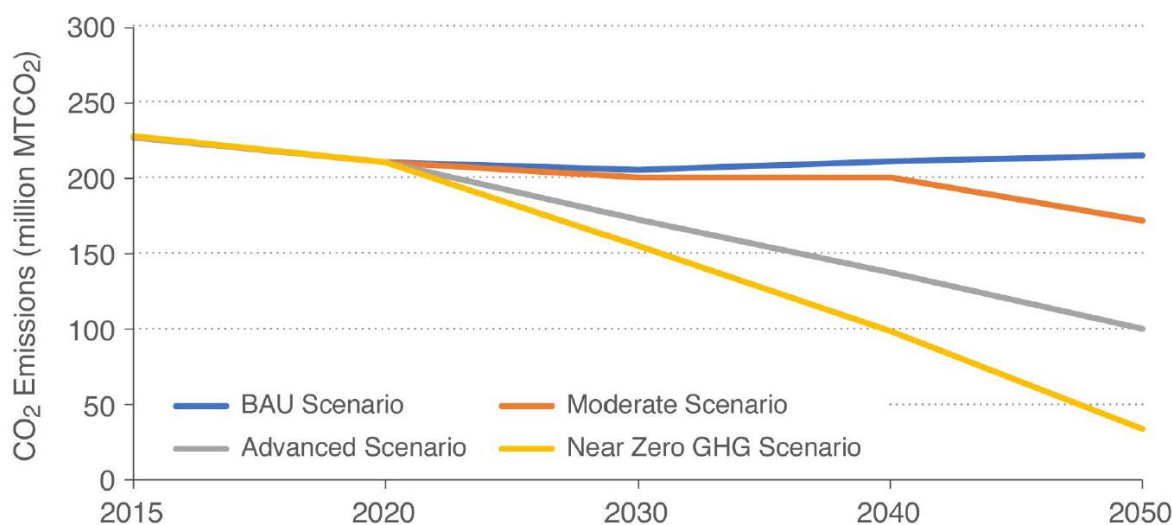
Improving refinery energy efficiency is within refineries' control and builds on ongoing efforts by the industry. For example, if efficiency measures were cost-effective, they could reduce GHG emissions from fuel use by 50%. Even if major revamp or expansion projects were not specifically aimed at energy efficiency, they could provide decarbonization opportunities; however, drivers other than decarbonization may dictate the nature and timing of a potential implementation. Although the combustion of internally produced fuels generates GHGs, extracting useful energy from waste gases is significantly more efficient than the alternative, flaring; U.S. Environmental Protection Agency and state regulations limit routine flaring of gas. Furthermore, large changes to current refinery configurations often require new permitting which can discourage capital

investments that are only marginally profitable. As a result, using waste gases is often the only available option. However, large integrated refineries also have the opportunity to change their product slate—through revamps—to more petrochemicals than fuels and use such revamps as a basis for decarbonization.<sup>6</sup>

**Author’s comment:** Note in the above paragraph, “...large integrated refineries also have the opportunity to change their product slate—through revamps—to more petrochemicals than fuels...” As transportation (and other industries) move from fuel-based energy electric-energy over the next decade or two, this will propel this change.

The other areas of opportunity relate to the industry’s potential ability to take advantage of external opportunities (e.g., availability of affordable low-carbon feedstocks, technologies such as clean hydrogen, and carbon storage). Some of the potential technologies are not economic today, so the business case for them relies on cost reductions and regulatory or incentive frameworks. There are also uncertainties and tradeoffs between site potential (i.e., the degree to which a specific refinery could implement a specific option) and industry potential (i.e., the number of refineries that might have access to the external network or infrastructure supporting that option).

To understand how the application of the decarbonization pillars could help phase out net GHG emissions, the potential CO<sub>2</sub> reductions possible for refineries were examined, and several scenarios were developed and analyzed that were like those described for the other subsectors (see the introduction to this section). The figure below shows the results for scenarios in which energy intensity (gigajoules/barrel of oil) and potential CO<sub>2</sub> mitigation ranges found in the literature were applied to AEO 2021 (Annual Energy Outlook for year 2021) projections of crude oil inputs to U.S. refinery distillation units and AEO 2021 projections petroleum fuel outputs quantities and mix of fuels do not change.



<sup>6</sup> William R. Morrow III et al., “Efficiency Improvement and CO<sub>2</sub> Emission Reduction Potentials in the United States Petroleum Refining Industry,” Energy 93, Part 1 (December 2015): 95-105.  
<https://doi.org/10.1016/j.energy.2015.08.097>

**Key message:** Based on a recent in-depth analysis of EU refinery decarbonization RD&D options.<sup>7</sup> Similar U.S. technology RD&D has the potential to decarbonize roughly 80% of U.S. petroleum refining subsector CO<sub>2</sub> emissions by 2050.

The business as usual (BAU) scenario assumes AEO 2021 projections of crude oil inputs are refined at the same energy intensity (GJ/barrel of oil)<sup>8</sup> and carbon intensity (million MT CO<sub>2</sub>/GJ) of U.S. refineries in 2015. The variation in BAU CO<sub>2</sub> emissions only reflects the variation in AEO 2021 projections of crude oil inputs between 2015 & 2050.

The Moderate Scenario applies AEO 2021 projections of refinery energy and carbon intensity through 2040, but it assumes the refining industry is 13% more energy efficient in 2050 than in 2015, based on the best available technology opportunities in a DOE refinery study. The Advanced Scenario and the Near Zero GHG Scenario maintain the same efficiency improvements as the Moderate Scenario by 2020, but they ramp up to a more energy efficient refining industry by 2050 (relative to 2015) than the Moderate Scenario. Relative to 2015, the Advanced Scenario assumes a 28% more energy efficient refining industry by 2050. The 28% efficiency improvement is based on a recent EU refinery industry analysis for decarbonizing the EU refinery industry by 2050 that developed low, median, and maximum CO<sub>2</sub> mitigation scenarios through engagement with EU refiners.<sup>7</sup> For reference, EU refinery capacity is approximately 70% the size of U.S. refinery capacity.

The Near Zero GHG Scenario assumes a 38% more energy efficient refining industry by 2050 based on state-of-the-art technology opportunities in DOE's refinery energy bandwidth study. A 38% more energy efficient refining industry in 2050 relative to 2015 represents an additional 33% efficiency improvement beyond the 4% improvement found in AEO 2021 projections for 2050.

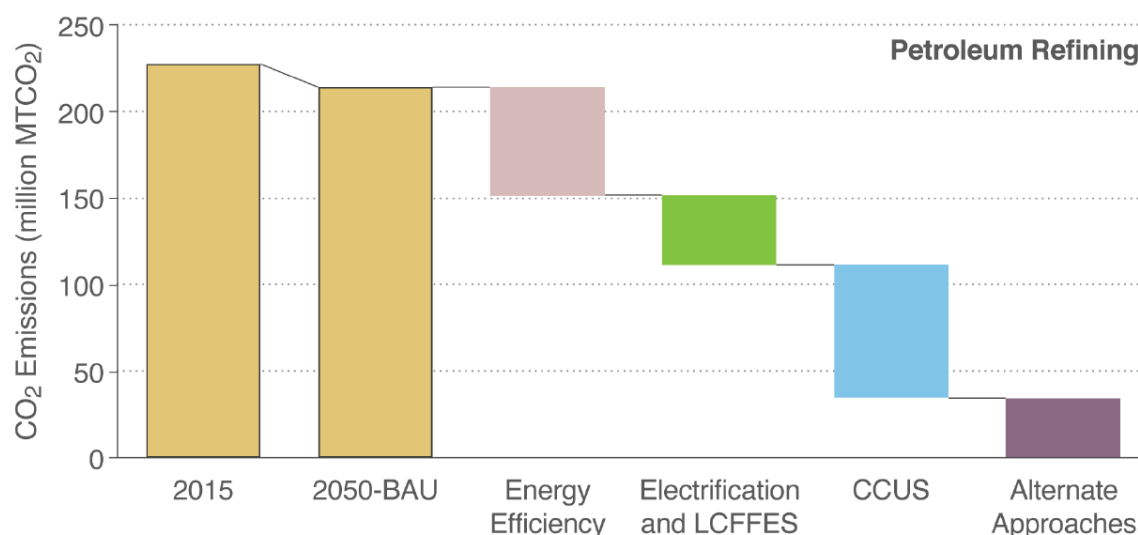
The Advanced Scenario and the Near Zero GHG Scenario both assume electrification, fuel switching, and carbon capture can reduce U.S. refinery energy consumption and CO<sub>2</sub> emissions by an amount similar to levels anticipated to be possible in the EU refining industry. These levels are based on a recent EU refinery industry analysis for decarbonizing the EU refinery industry by 2050 that developed low, median, and maximum CO<sub>2</sub> mitigation scenarios through engagement with EU refiners.<sup>7</sup> In the EU mitigation scenarios, energy savings from electrification and fuel switching range from 18% to 28%, and carbon capture range from 21 to 87 million MT CO<sub>2</sub> in 2050. The Advanced Scenario assumes an 18% energy reduction from electrification and fuel switching by 2050 and that 35 million MT CO<sub>2</sub> are captured in 2050. The Near Zero GHG Scenario assumes a 21% energy reduction from electrification and fuel switching by 2050 and that 80 million MT CO<sub>2</sub> are captured in 2050.

Figure below shows the Near Zero GHG Scenario mitigation potential for the pillars in 2050 where a concerted effort is applied to further develop these solutions with focused research, development and demonstration (RD&D) efforts, trials, and a drive for deployment...

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<sup>7</sup> Concawe, CO<sub>2</sub> Reduction Technologies: Opportunities within the EU Refining System (2030/2050): Qualitative and Quantitative Assessment for the Production of Conventional Fossil Fuels (Scope 1 & 2), Concawe Report No. 8/19, July 2019, [https://www.concawe.eu/wp-content/uploads/Rpt\\_19-8.pdf](https://www.concawe.eu/wp-content/uploads/Rpt_19-8.pdf)

<sup>8</sup> A gigajoule (GJ) is one billion Joules. One GJ is equivalent to 278 kWh or 947,817 BTUs.



*Impact of The Decarbonization Pillars on CO<sub>2</sub> Emissions (Million MT/year) for the U.S. Petroleum Refining Subsector, 2015–2050.*

*These scenarios illustrate that the decarbonization pillars combined can dramatically reduce CO<sub>2</sub> emissions, yet even with CCUS (carbon capture, utilization, and storage), a small emissions footprint will need to be offset. Energy efficiency can play a significant role throughout the 30-year transformation with a proportionally large early impact. Hence, it is important to push early RD&D on ways to realize these reductions. Electrification of process heat, processes, motors, and other applications with the electricity coming from low-carbon sources can have contributed to CO<sub>2</sub> reductions across the decades. The generation of hydrogen from these sources (e.g., electrolysis) can substantially contribute to this reduction potential. As already noted, the levels of electrification and LCFES (low-carbon fuels, feedstocks, and energy sources) assumed were moderate based on the literature. The level of CCUS reductions will depend on the successful capture of the remaining CO<sub>2</sub> from large emitters, as well as aggregation of some other sources. As with chemical manufacturing, petroleum refining can involve thousands of emissions sources and capture from all of them would unlikely be feasible or economic. Applying low net GHG emission feedstock alternatives to crude oil, including converting captured CO<sub>2</sub> into liquid fuels, requires sustained RD&D throughout the 30-year time frame to obtain their benefits by 2050.*

## 5. Barriers and Opportunities

*Numerous barriers, many of which have connections to RD&D needs, were mentioned during the stakeholder meetings. For example, refineries rarely decommission an existing process unit unless it is no longer needed. And expansion is only driven by market expansion, refinery consolidation, or regulatory changes related to point sources emissions or fuel specifications. Considering the challenge of long equipment lifetimes and strategies that use existing capital and infrastructure (e.g., LCFES, electrification, and energy-efficiency) will be crucial for near- and mid-term progress. Some low-net carbon resources like biomass are limited and or finite, and therefore must be used efficiently. The transition to transformative options will be challenged by capital intensity constraints, the interconnected footprint of refinery processes, market economics, and regulatory issues such as permitting—even if demonstrations prove that options are commercially viable.*

*Waste gas and petroleum coke are self-produced, captive sources of energy and therefore modifying current uses of waste gas and petroleum coke in refineries is limited by physical constraints – waste gas and petroleum coke will be produced due to the physics of refining crude oil. Subject to technological constraints – most refineries depend on waste gas and petroleum coke for process heating. And regulatory constraints – air quality flaring waste gas and permitting costs often exceed natural gas prices and international environmental laws increasingly restrict the use of petroleum coke in maritime shipping). These physical and technical constraints create unique microeconomics constraints which present a high hurdle for refinery capital investments.*

*Similarly, high capital investment makes it difficult to justify major investments at scale without significant performance and cost improvements (i.e., a high hurdle for newer technology). Smaller, modular, distributed production systems will have a hard time competing with the scale, integration, and high-capacity factors of current refineries, as all these elements are crucial to competitive economics. Likewise, the misconception of what low-carbon electricity can provide creates a barrier to electrification. For example, there is a misconception that the variable nature of some renewables is incompatible with current refinery processes and operations. Although the future costs for renewables might become competitive, grid-supplied electricity can be expensive on an equivalent Btu basis to less-expensive hydrocarbons such as self-produced waste gas. Many refineries export excess CHP-generated electricity to their local grid and recognize that they could become a net exporter of decarbonized electricity by adding carbon capture to their CHP capacity. While selling decarbonized electricity to the grid provides revenue (rather than the expenses of purchasing decarbonized electricity from the grid), being a net electricity supplier to the grid post-CCUS might not be cost-effective for refineries. If grid-scale, low-carbon, and or renewable electricity is inexpensive enough to displace refiner's waste gas fuels, then it is unlikely that the refiner's onsite CHP with CCS can generate low-carbon electricity inexpensive enough to be competitive in electric grid energy markets or capacity markets. Even if a refiner's low-carbon resource is competitive in an ancillary services market or spinning reserve market, a low return-on-investment might preclude the refiner's participation.*

Author's comment: Note the following:

Carbon capture and storage (CCS) is any of several technologies that trap carbon dioxide (CO<sub>2</sub>) emitted from large industrial plants before this greenhouse gas can enter the atmosphere. CCS projects typically target 90 percent efficiency, meaning that 90 percent of the carbon dioxide from the power plant will be captured and stored. However, CCS could capture more CO<sub>2</sub>, and thus do more to combat climate change, if industries and governments decide not only to invest in CCS at a large scale but also to pay extra to maximize its potential.<sup>9</sup>

Also, if the utilized carbon capture is only 90% efficient, carbon offsets can be used to cover the remaining 10%.<sup>10</sup>

*For many refinery capital investments, self-produced fuels frequently dominate cost-effectiveness metrics and capital investment decisions. Depending on the individual refinery operations, refinery cost-effectiveness price points can range from a) current*

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<sup>9</sup> Andrew Moseman, MIT, "How efficient is carbon capture and storage?" <https://climate.mit.edu/ask-mit/how-efficient-carbon-capture-and-storage>

<sup>10</sup> See <https://energycentral.com/c/cp/carbon-offsets>

*natural gas spark spread prices, down to b) \$0/kWh, or \$0/therm if the refinery has excess CHP capacity, or c) a negative price point (e.g., -\$30/MT NOX equivalent) if a refinery must incinerate self-produced fuels to purchase low-carbon and or renewable electricity from the grid.*

*Understanding the unique petroleum refining microeconomics will be crucial in improving refineries GHG emission reduction efforts. For example, energy efficiency measures that reduce both fuel and electricity end use demands without disrupting this energy ratio are the most viable strategies to implement.*

*By incorporating nuclear energy into a refinery, the low cost, high quality thermal energy can displace emissions produced by burning waste gas for heat. Instead of burning waste gas for heat, the waste gas may be recycled into refining processes for improving product yield or sequestering the carbon in material products. Nuclear plants produce electricity that is competitive on the grid, but nuclear plants produce heat first, at a much lower cost per Btu. The nuclear plant can produce very low cost, clean heat for the chemical processes, as well as electricity for production of large quantities of clean hydrogen used in refining, further reducing carbon emissions at the refinery. Finally, nuclear plants can provide clean electricity for the refinery as well.*

*The best strategy for overcoming a refiner's cost-effectiveness metric (which is dictated by self-produced fuels) is finding new markets for waste gas and petroleum coke as feedstock revenue value streams that stay above the cost of natural gas while sequestering carbon in products like plastics, resins, and carbon fibers. The RD&D (research, development and demonstration) opportunity is to expand material markets or develop new materials that can sequester the carbon content of the ethane, propane, propylene components of refinery waste gases into products, instead of fuels.*

*The misconception that thermodynamics—such as equilibrium constraints in reverse water gas shift and methanol synthesis—prohibits cost and energetically efficient chemical reduction of CO<sub>2</sub> to CO can be overcome through novel biological and photochemical strategies, commonly referred to as “artificial photosynthesis” and conversion to liquid fuels. As RD&D on chemical, electrochemical,<sup>11</sup> and bio-electrochemical reduction of CO<sub>2</sub> to CO expands internationally, advancements in artificial photosynthesis and/or bio-electro catalysts are overcoming this misconception. Though CCUS requires national coordination, efforts to utilize CO<sub>2</sub> locally could reduce the larger cost burdens of CCUS while also providing useful carbon for feedstock purposes. The use of captured CO<sub>2</sub> as a low-carbon refinery feedstock could be a game changer across multiple U.S. sectors once efficient reduction and conversion processes are developed. However, CO<sub>2</sub> conversion to liquid fuels is a long-term strategy with a need for continuous RD&D over a range of time horizons.*

## **6. RD&D Needs and Opportunities**

**Author's comment:** I'm running close to my word-limit for this paper, so I will mostly summarize this section (section 2.4.4 in reference 1) if readers would like to drill deeper, go through the link in reference 1 on page 1 and click on section 2.4.4 in the TOC.

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<sup>11</sup> Stephanie Nitopi et al., "Progress and Perspectives of Electrochemical CO<sub>2</sub> Reduction on Copper in Aqueous Electrolyte," *Chemical Reviews* 119, no. 12 (2019): 7610-7672.  
<https://doi.org/10.1021/acs.chemrev.8b00705>

### **Petroleum Refining Industry: Priority Approaches:**

*Technology breakthroughs needed in the petroleum refining industry include integration and control with variable power that can be implemented reliably 24/7, electrolyzer efficiency, and drop-in low-carbon processes. Transformative process innovations are needed to yield new low-carbon ways of making hydrocarbon liquid fuels (including enhanced reuse of CO<sub>2</sub>), lubricants, and other products. Priority approaches include:*

- *RD&D (research, development and demonstration) to enhance the impact of low-capital solutions (energy, materials, system efficiency), distillation and separations innovations, and thermal transfer efficiency.*
- *Reduce fugitive methane emissions to near zero.*
- *Pursue zero-hydrogen desulfurization processes through RD&D for adsorbents, oxidative desulfurization, and electro-desulfurization.*
- *Provide RD&D support for a persistent push to improve the energy efficiency of processes, eliminate waste, and lower product-embodied carbon.*
- *Develop capabilities for produce low-net carbon emission liquid transportation fuels from low-net carbon feedstocks (such as CO<sub>2</sub> and clean hydrogen, biomass, and other wastes streams) at scales comparable to current refinery capacities.*
- *Develop capabilities for centralized carbon capture.*
- *Develop capabilities for use of hydrogen for combustion in high-temperature process heat.*

### **Other important opportunities:**

- *Hydrogen-related needs include embrittlement, unified standards for retrofits, applicability at furnaces with higher hydrogen in blends, material safeguarding and temperature control and management, and moisture post-combustion.*
- *CCUS could help meet multiple refinery decarbonization challenges by addressing scale and process, pulling multiple streams from smaller point sources, and tackling investment challenges.*
- *Non-thermal separation approaches continue to be a significant opportunity (e.g., using electrochemical potential or membranes to drive the process, instead of distillation). This could include dewatering, desulfurizing electrically driven processes such as ion separation, or generating induced charges on compounds to aid separation.*
- *Better analysis and metrics on carbon intensity across subsectors are needed, and consistency of metrics and assumptions is a key need for life cycle assessments. For example, understandable, transparent, and generally accepted standardized metrics for GHG reporting would be beneficial to understanding the avoided carbon cost and would enable decarbonization. Such clarity could help aid market pull for low-carbon products.*
- *Energy efficiency for distillation includes multicolumn progressive distillation, dividing wall columns (DWC), and heat-integrated distillation columns (HiDiC); these are*

*mechanically complicated and better suited to fractionation of light products than crude. All are primarily new-build options.*

- *Separation technologies can achieve even greater energy efficiency improvements if RD&D overcomes membrane fouling and allows better separations of liquid streams (in addition to gaseous streams), including crude oil.*
- *Electro-desulfurization could be a disruptive concept for oil refining. RD&D activity is low, and it is barely beyond proof-of-concept using simple model feeds. Even if this were a research priority, it would take several decades to scale-up to practical application. It would also need large amounts of low-carbon electricity and its implications for product quality are not yet apparent.*
- *Low-carbon energy can be refined into the current slate of refinery products (i.e., composition and energy density identical to petroleum-based gasoline, diesel, and aviation fuel) from non-fossil fuel feedstocks – such as biomass and or direct air captured CO<sub>2</sub> – using current conversion technologies. This is a realistic near-term option for lowering the carbon intensity of fuels. Especially some liquid transportation fuel markets that require energy dense fuels and or have limited options for fuel switching.<sup>12</sup>*

**Final author's comment:** As I did with prior industries, I'm skipping the RD&D Action Plan.

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<sup>12</sup> U.S. Department of Energy Bioenergy Technologies Office, Sustainable Aviation Fuel: Review of Technical Pathways, September 2020, <https://doi.org/10.2172/1660415>  
Ralph Sims et al., Fifth Assessment Report: Mitigation of Climate Change, Chapter 8 Transport, Intergovernmental Panel on Climate Change, 2014, [https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc\\_wg3\\_ar5\\_chapter8.pdf](https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_chapter8.pdf)