Refineries

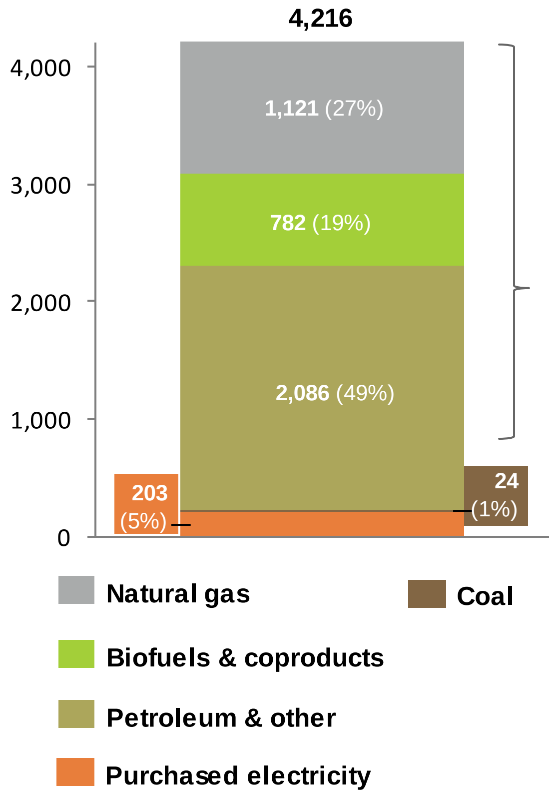
Sector Perspectives

RENEWABLE
THERMAL
COLLABORATIVE

~88% of emissions are generated <500ºC but majority of thermal energy is fueled by refinery fossil byproducts[4], which have few alternative uses

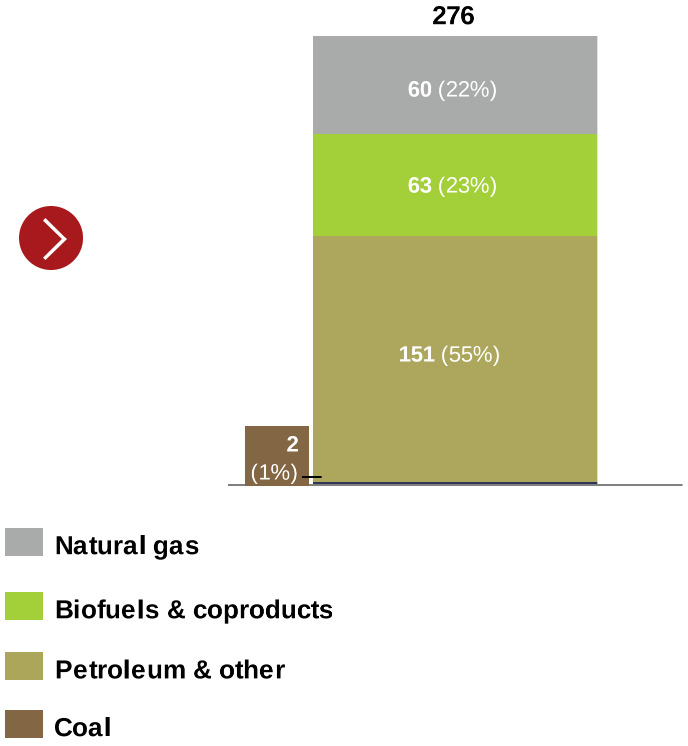
Total energy consumption (2018)[1]

Trillion Btu



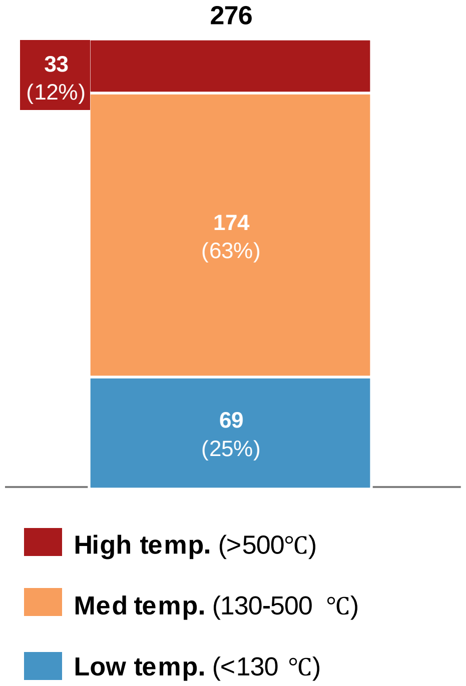
Thermal emissions (2018)[2]

Million Tonnes of CO2e



Estimated thermal emissions by process temperature (2018)[3]

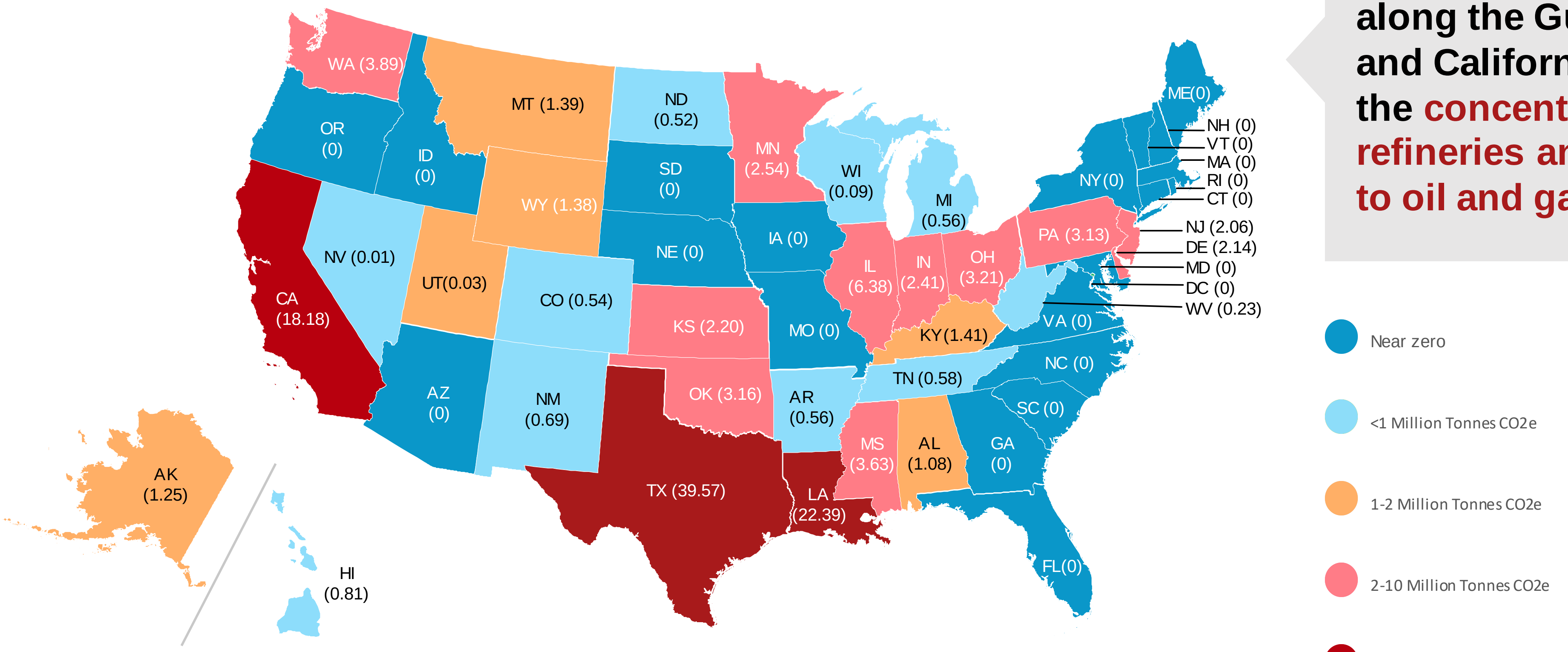
Million Tonnes of CO2e



1. EIA Annual Energy Outlook 2019 2. Based on AEO 2019 Outlook for 2018 energy consumption by combustible fuel (excludes purchased electricity) and EPA emissions intensity of individual fuels; RNG and green hydrogen are considered net zero, biomass is estimated at 15 kg CO2e/mmBtu 3. Calculated using the NREL MECS survey data for thermal energy use (2014) 4. Primarily composed of refinery process byproducts that are combusted as fuels (e.g. still gas) Source: EIA; EPA; NREL; BCG analysis

Thermal emissions are concentrated along the Gulf Coast and California

Refineries thermal emissions by state (Million Tonnes of CO2e)[1]



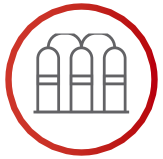
Thermal emissions in refineries are focused along the Gulf Coast and California due to the concentration of refineries and proximity to oil and gas production

1. EPA GHGRP Inventory FLIGHT Database (2018); captures actual onsite reported emissions for large emitters emitting >25K tonnes of CO2e/year

62% of thermal energy consumption occurs in the distillation and reactor temperature ranges

Distillation | ~150-370 ºC

Fractional distillation is used to separate the various components of crude oil in the refining process. Distillation towers are heated to specific temperatures to cause components of different boiling points to separate from each other.



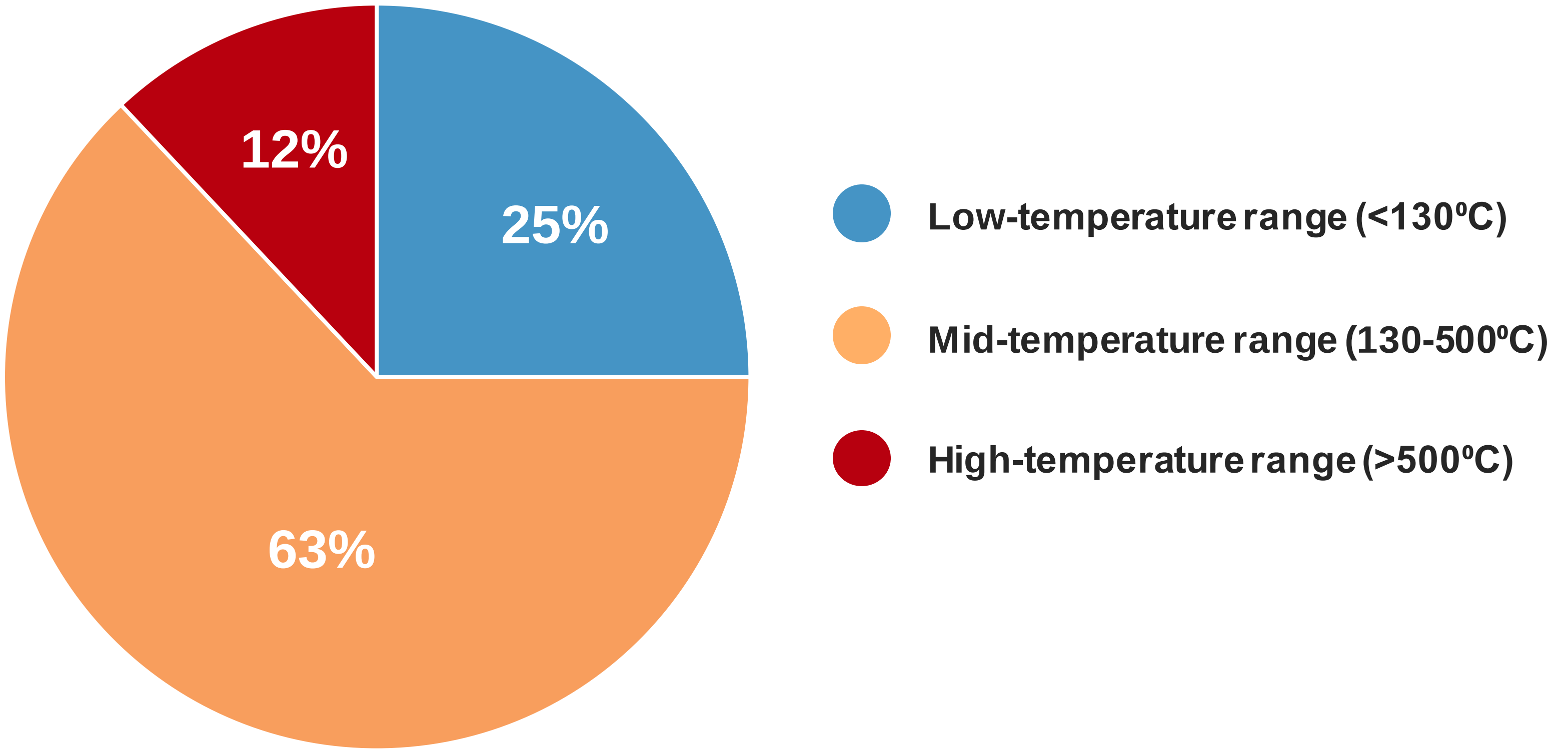
Reactors | ~260-480 ºC

Components that have been separated out in the distillation process may be sent to a **reactor** in order to remove or convert certain compounds. One of the most energy-intensive reactors is the naphtha hydrotreater, which takes in heavy naphtha from distillation columns and removes sulphur and nitrogen compounds in the naphtha.

Source: DOE (2022), industry reports and papers, BCG analysis

~88% of thermal energy consumption occurs in the low- and medium-temperature ranges

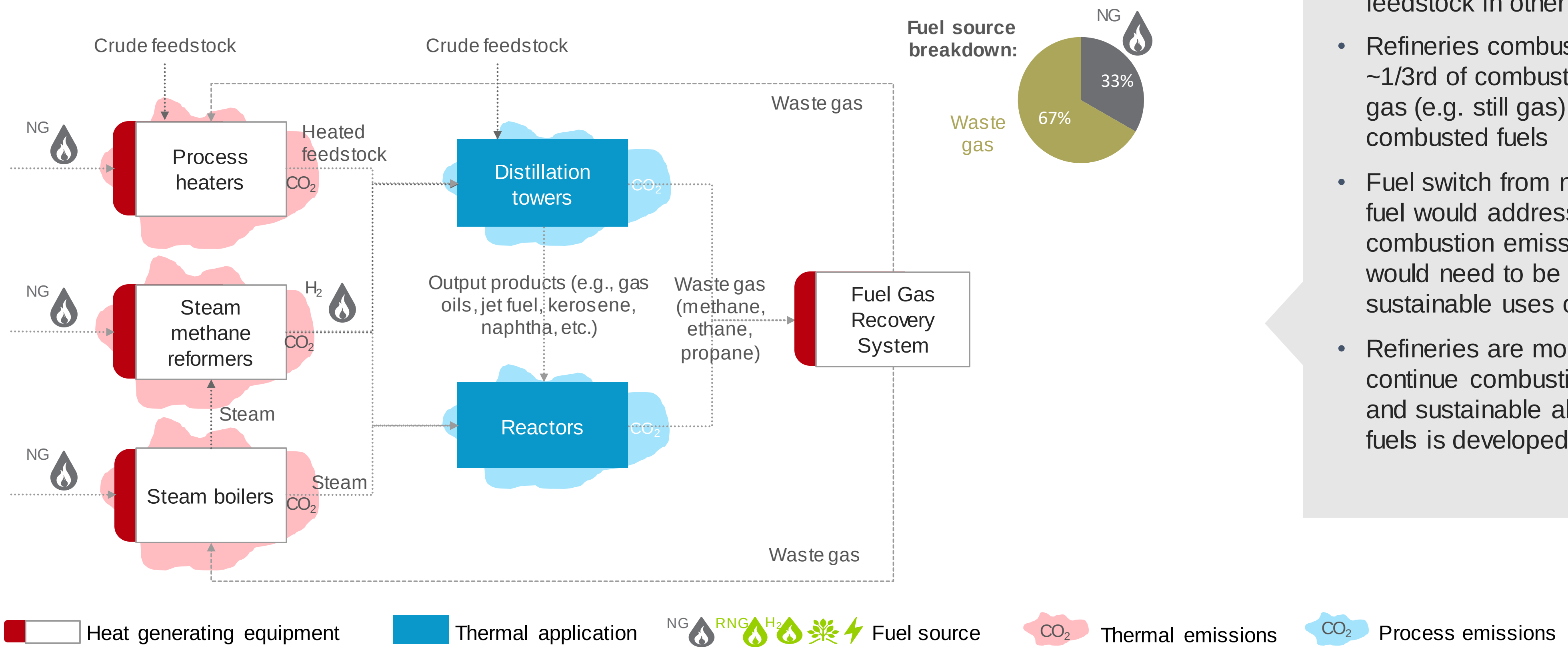
Thermal energy consumption (TBtu) by heat temperature range (ºC)[1]



1. NREL Manufacturing Thermal Energy Use in 2014
Source: DOE (2022), industry reports and papers, BCG analysis

Thermal decarbonization in petroleum refineries will likely require carbon capture to abate emissions in the near and medium term

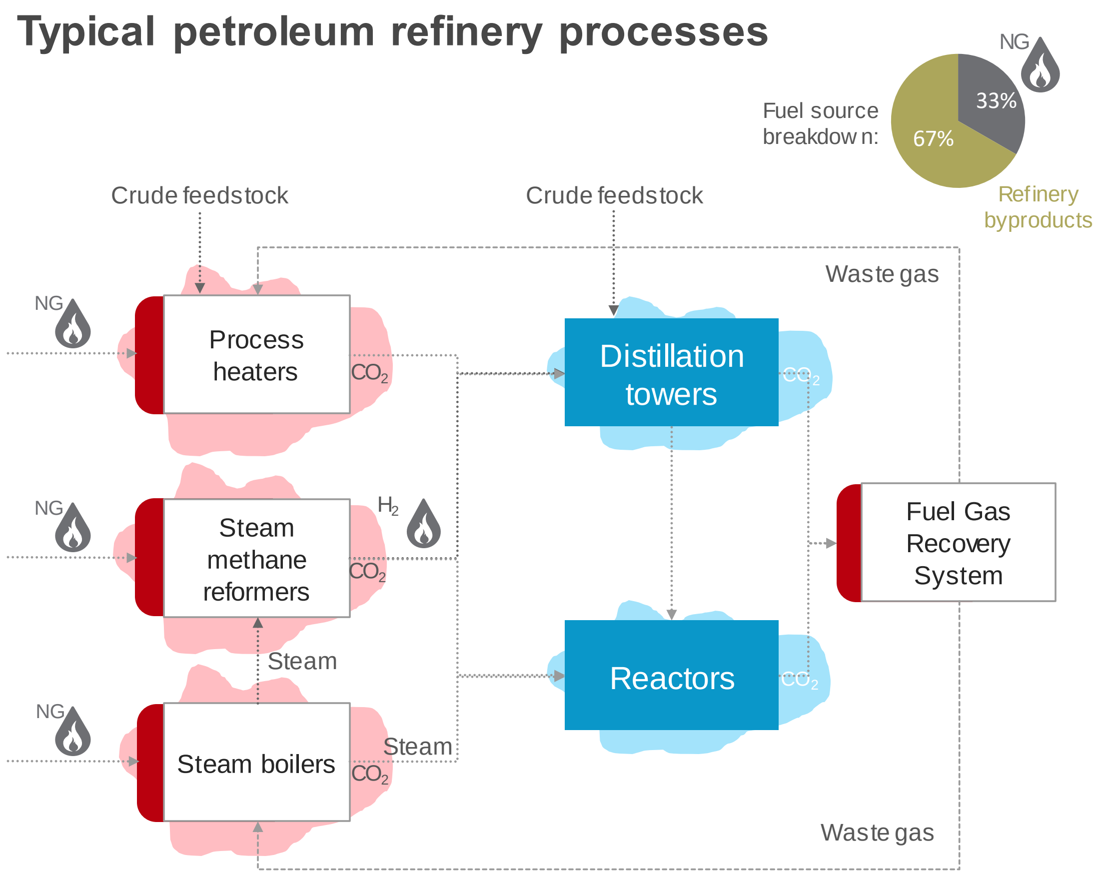
Current petroleum refinery processes

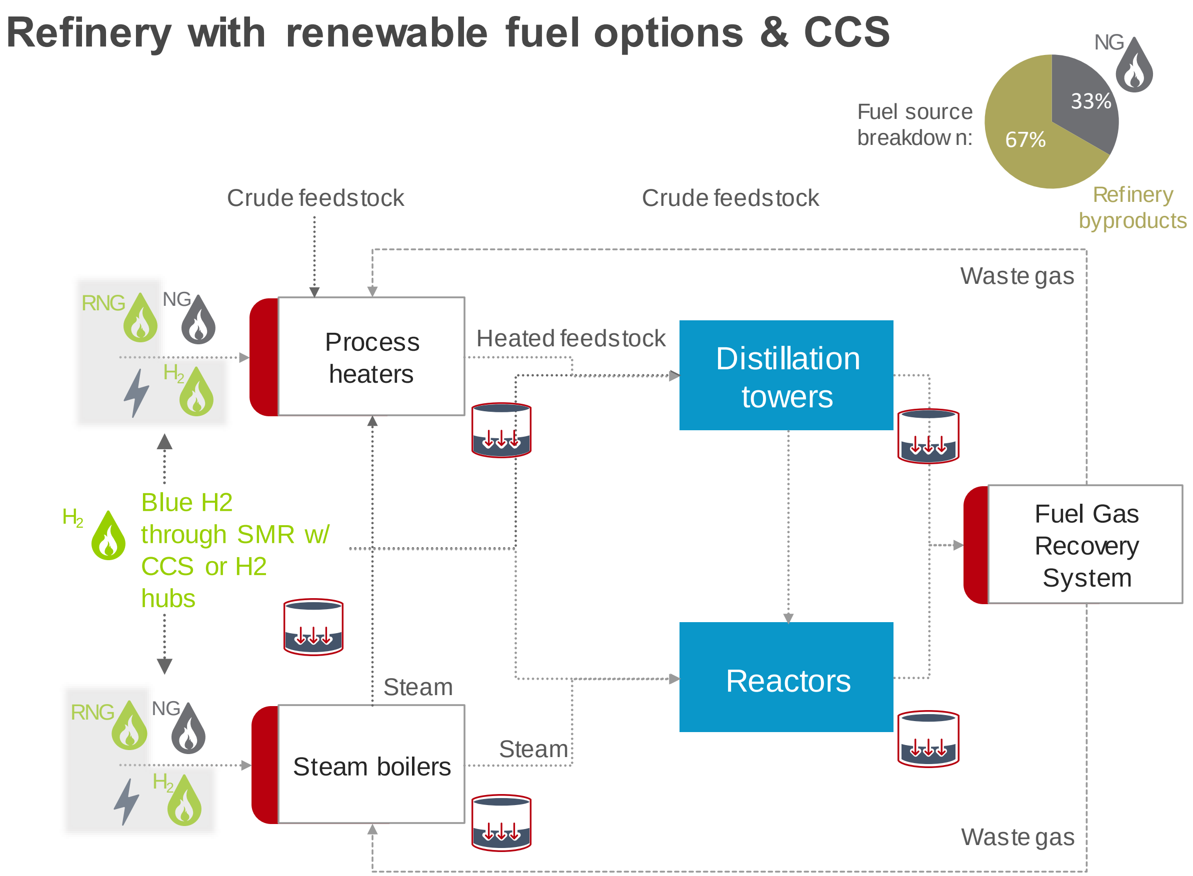


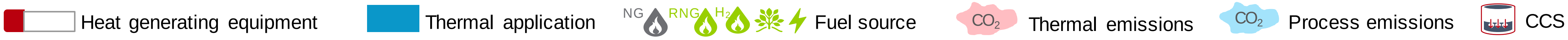
Source: DOE (2022), industry reports and papers, BCG analysis

- Petroleum refineries typically use process heaters and steam boilers that burn natural gas to create steam heat, which is moved around the facility through a steam network system distributing heated steam to applications
- Natural gas is also used in steam methane reformers to produce hydrogen; NG is used as a feedstock and combusted to produce heat for the reaction. Hydrogen is used as a feedstock in other refinery processes
- Refineries combust natural gas representing ~1/3rd of combusted fuels alongside waste gas (e.g. still gas) representing ~2/3rds of combusted fuels
- Fuel switch from natural gas to an alternative fuel would address ~33% of the total fuel combustion emissions in refineries; and this would need to be paired with alternative sustainable uses of the waste gas
- Refineries are more likely to deploy CCS and continue combusting waste fuels until a better and sustainable alternative use of these waste fuels is developed

Low carbon alternatives are available for NG but must be paired with CCS for waste gas decarbonization; low carbon fuel supply constraints may require refineries to deploy CCS at scale to capture all onsite emissions





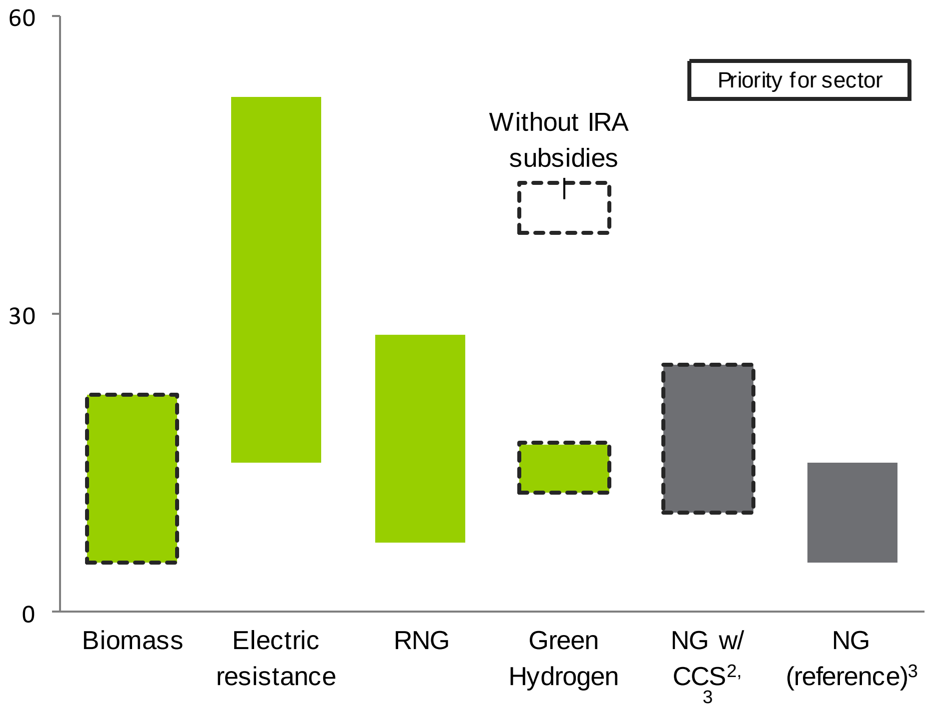


Source: DOE (2022), industry reports and papers, BCG analysis

Continued NG use with CCS appears likely in the short and medium term; hydrogen appears effective in long term when supply constraints alleviate

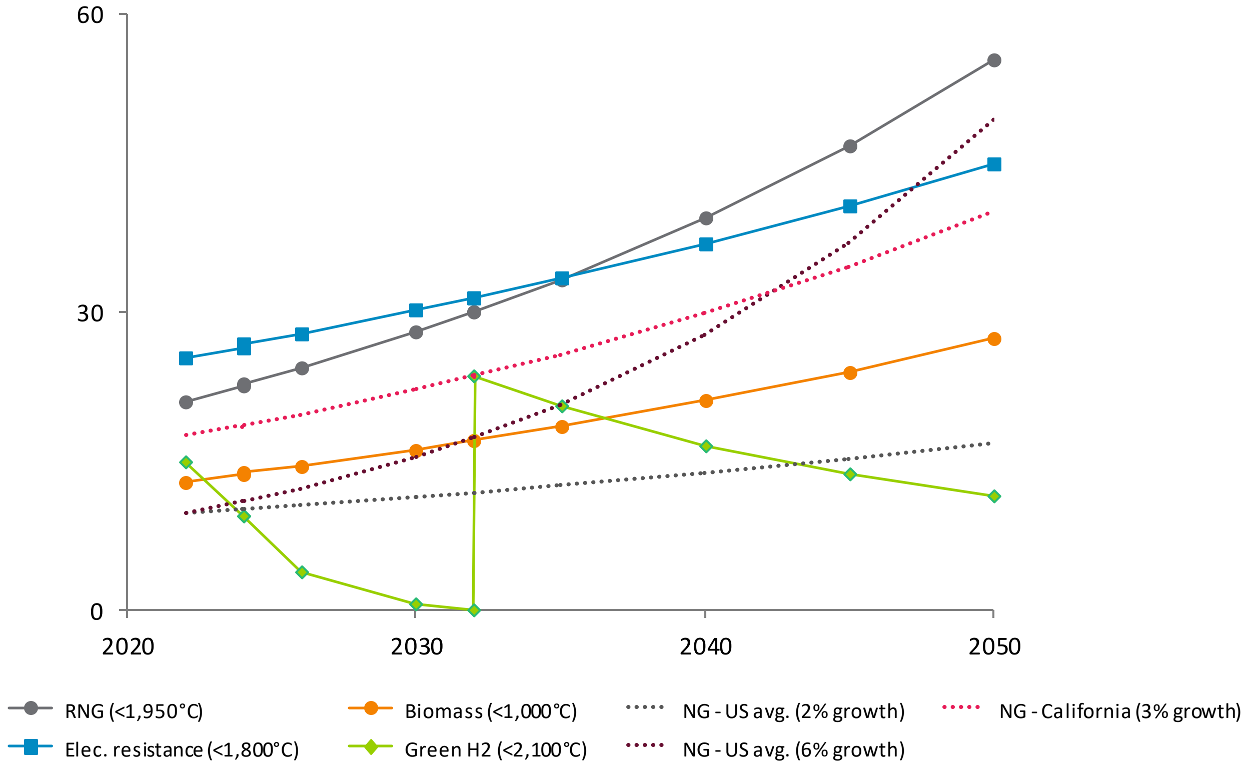
2022 LCOH for relevant technologies[1]

($/MMBtu)



Projected LCOH for relevant technologies[1]

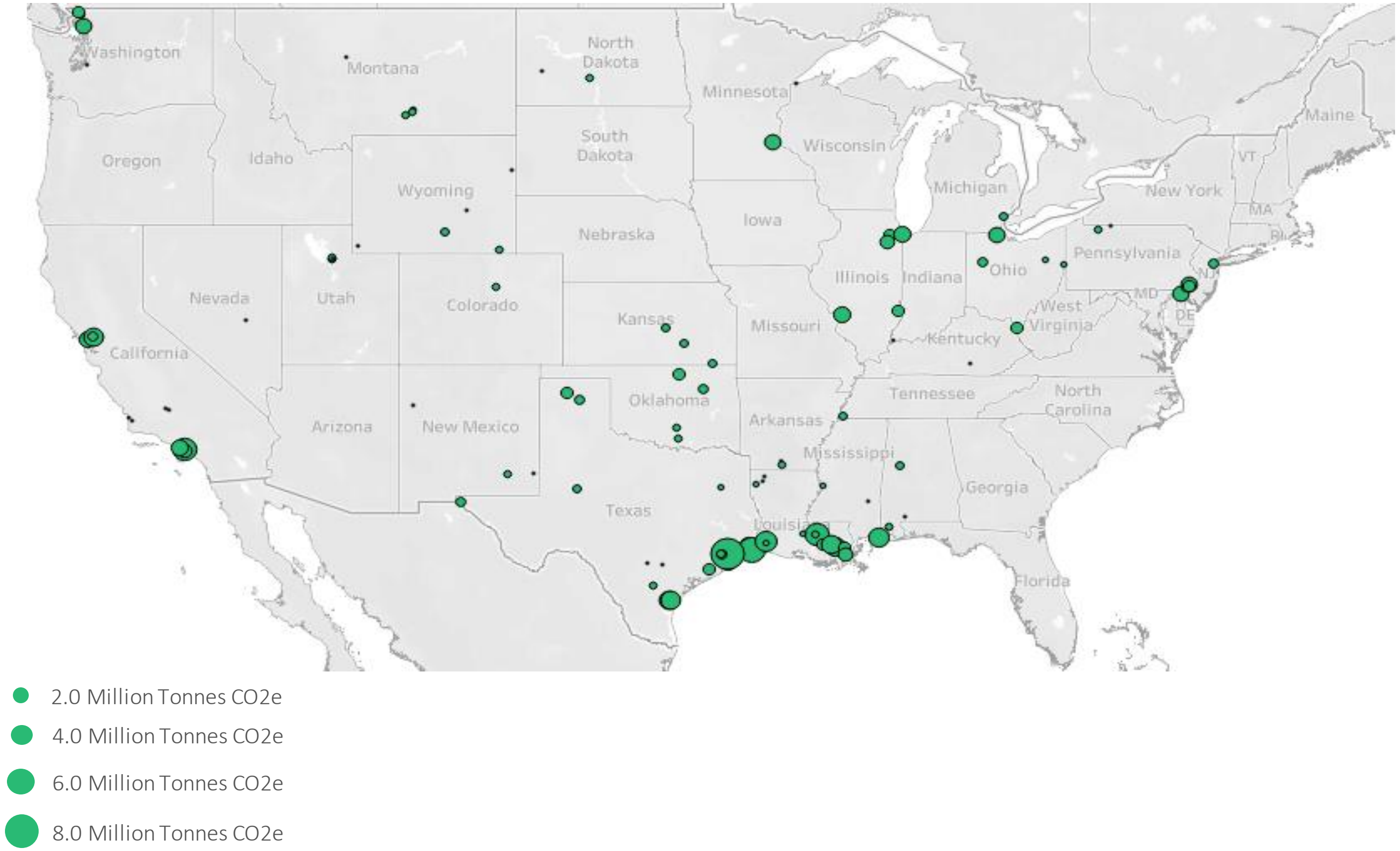
Average US LCOH ($/MMBtu)



1. LCOH compares project lifetime costs against lifetime energy produced; costs include capital expense of equipment, fuel costs, and maintenance expense assumptions over the usable life of the energy asset. Electricity and natural gas pricing is based on national weighted average wholesale industrial end user electricity and natural gas prices for the past 1 year as of June 2022 industrial electricity modeled to grow at 2% per year. Electric heat pumps, electric resistive, and natural gas heating efficiencies modeled at 300%, 99%, 75%, respectively. Includes Inflation Reduction Act incentives 2. Combined with natural gas combustion; includes $85/tonne 45Q tax credits from IRA 3. Uses weighted average US natural gas price for the past twelve months as of June 2022 (excludes Hawaii); assumes 75% combustion efficiency Source: EIA; EPA; Inflation Reduction Act; BCG analysis

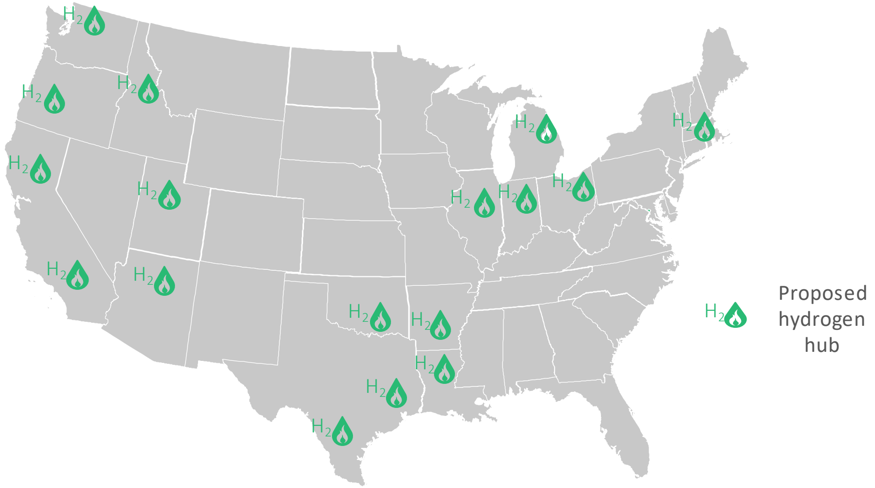
CCS and hydrogen are projected to be available in heavy-emissions areas

US Refineries thermal emissions by zip code[1]



CCS sequestration geographies[2]

Proposed hydrogen hubs[3]



1. EPA GHGRP Inventory FLIGHT Database (2018); captures actual onsite reported emissions for large emitters emitting >25k tonnes of CO2e per year 2. USGS, NETL NATCAB 3. CSIS (2022)

Decarbonization pathways

Natural Gas
Continue use and/or replace with clean hydrogen or other low carbon fuels based on supply availability

Carbon Capture & Sequestration
Implement to capture combustion emissions from fossil fuels and facility hydrocarbon byproducts (process emissions)

2022 — 2050

Considerations	Target First Movers
Concentration of CO2 in flue gas, government subsidies	Regions with refinery clusters and adequate geology for storage

Approximately ⅔ of thermal energy used in the Refineries sector originates from refining process byproducts; an alternative use for these fossil byproducts must be identified in order to displace these fuels

Although RNG, biomass and green hydrogen can potentially displace fossil fuel combustion, these fuels are supply constrained and may have higher impact if **prioritized for other sectors** that are not required to rely on carbon capture

The recommended thermal decarbonization strategy is **deployment of CCS**

Thermal decarbonization pathways

Refineries generate process heat by burning natural gas as well as refinery byproducts such as still gas. **Byproducts form the majority of combusted fuels, representing ~2/3rds of total fuel combustion; natural gas combustion represents ~1/3rd**

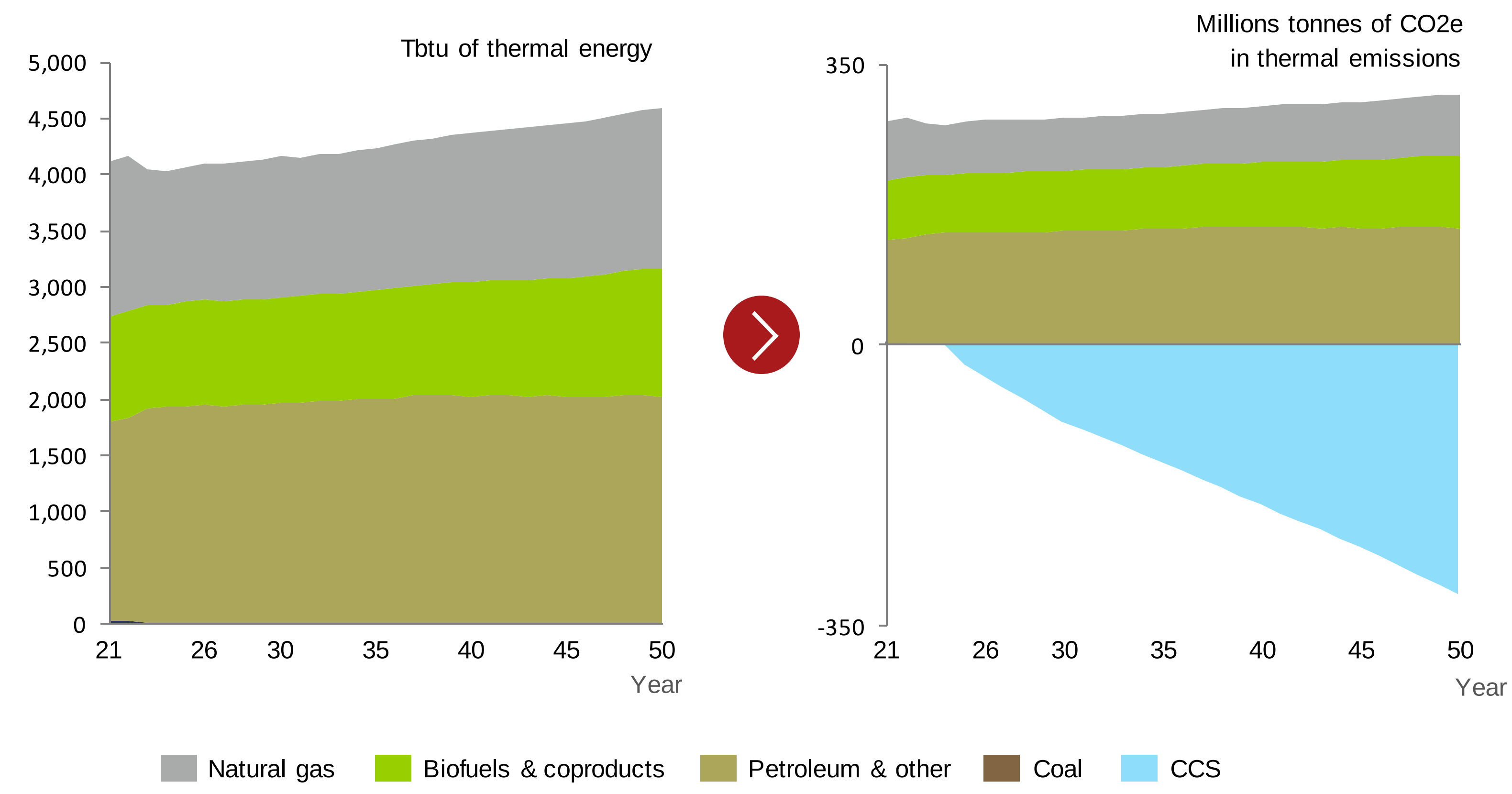
Refinery byproducts can typically be consumed as fuel (current case), flared (releases carbon), or potentially sequestered (CCS). **Refineries are likely to continue using byproducts as combustible fuels and deploy CCS to abate related emissions**

Natural gas combustion in refineries can be switched to low carbon fuels, but such fuels are supply constrained and may be better prioritized for other sectors (e.g., the refinery demand for green hydrogen to displace natural gas combustion would rival the demand for green hydrogen to replace NG combustion in all other industrial sectors combined)

As a result **carbon capture** is likely the primary decarbonization pathway for the sector

Thermal energy consumption[1]

Thermal emissions[2]



1. Total thermal energy consumption based on EIA 2022 Outlook; forecasted energy mix per BCG analysis 2. Thermal emissions calculated based on emissions intensity of individual fuels; RNG and clean hydrogen assumed to be net zero fuels, biomass assumed to have an emissions intensity of 15 kg CO2e per mmBtu, electricity modeled based on US electric grid emissions intensity 80% and 100% renewables by 2030 and 2050 Source: EIA out look; EIA emissions intensity; BCG analysis

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