Cement

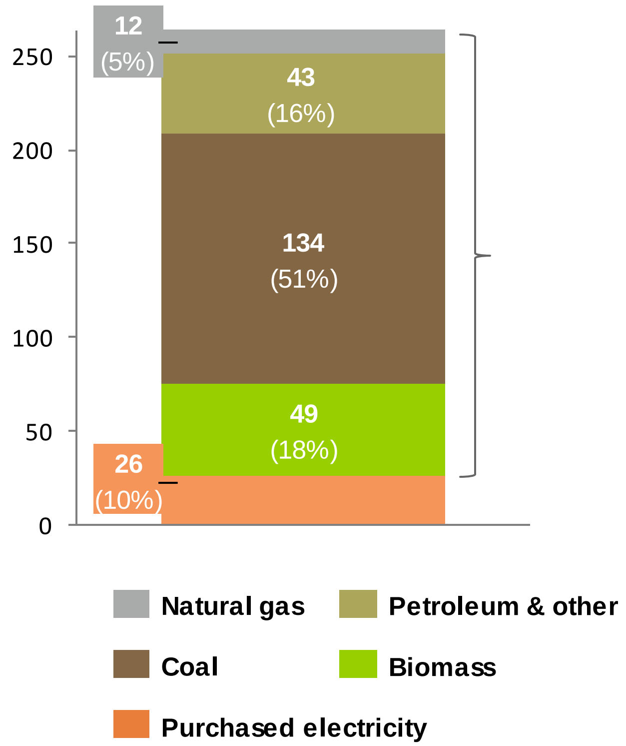
Sector Perspectives

RENEWABLE
THERMAL
COLLABORATIVE

Coal is the primary fuel and source of emissions; 83% of thermal emissions are produced at high temperatures

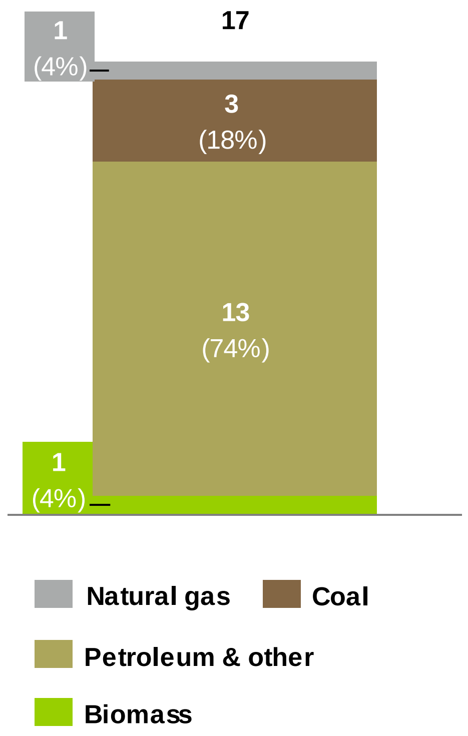
Total energy consumption (2018)[1]

Trillion Btu



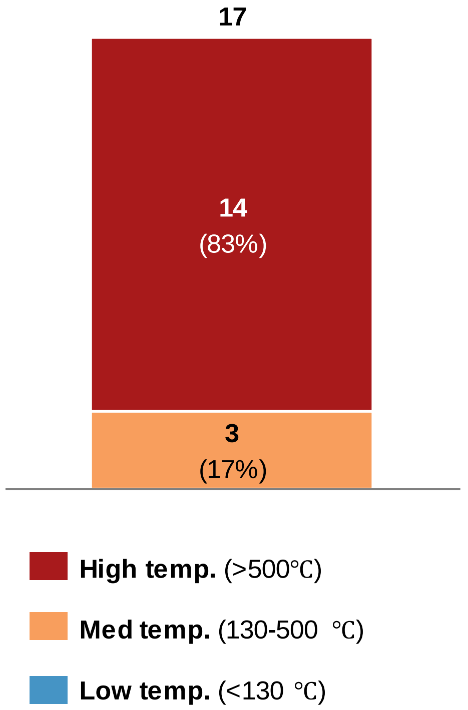
Thermal emissions (2018)[2]

Million Tonnes of CO2e



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

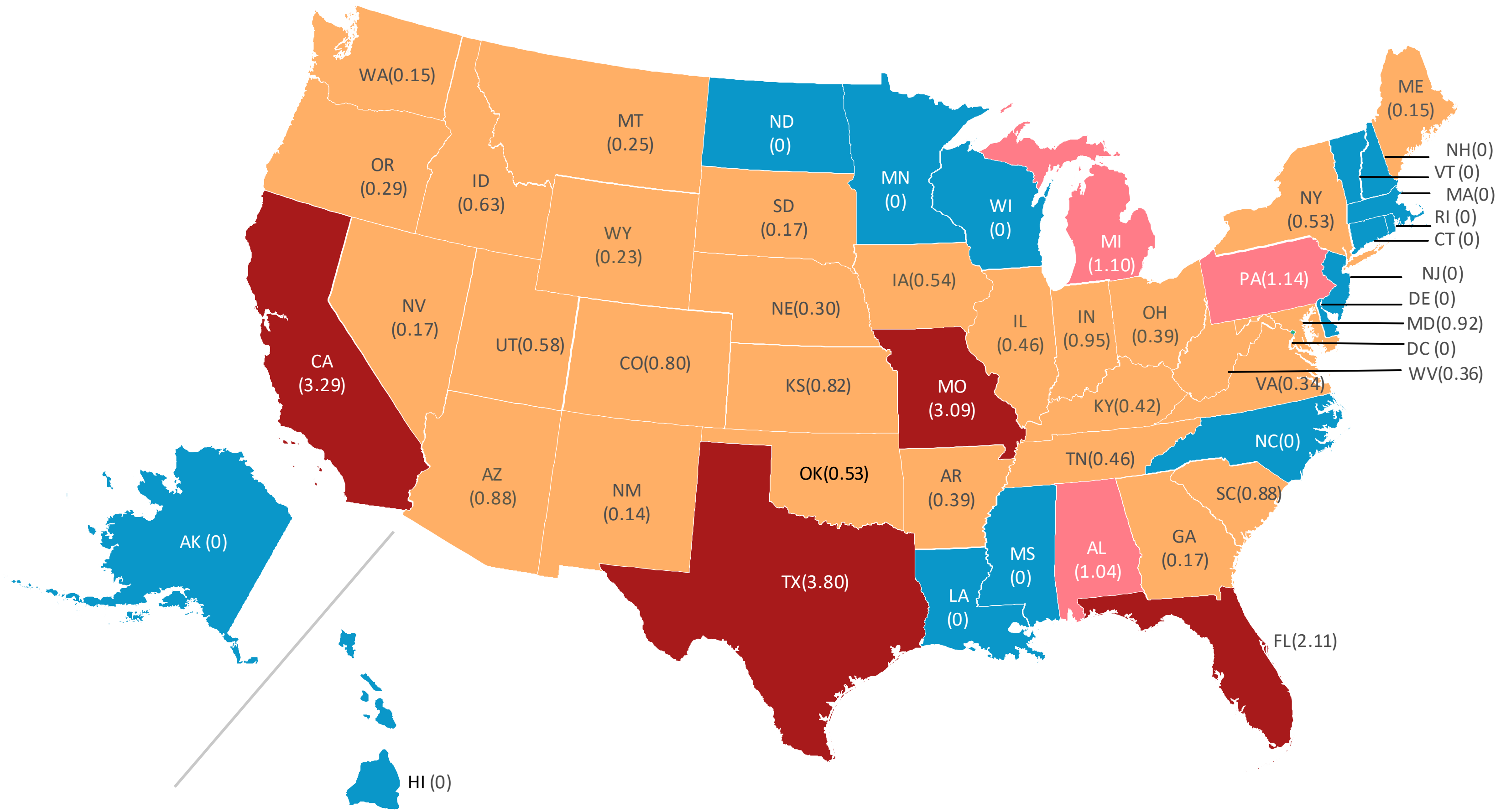
Million Tonnes of CO2e



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)
Source: EIA; EPA; NREL; BCG analysis

Thermal emissions are evenly distributed across the country

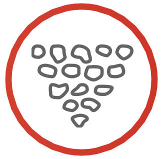
Cement thermal emissions by state (Million Tonnes of CO2e)[1]



Due to high transportation costs relative to material prices, cement production and emissions are relatively evenly distributed across the US

1. EPA GHGRP Inventory FLIGHT Database (2018); captures actual onsite reported emissions for large emitters emitting >25K tonnes of CO_2e/year

Key thermal applications in cement manufacturing occur at high temperatures



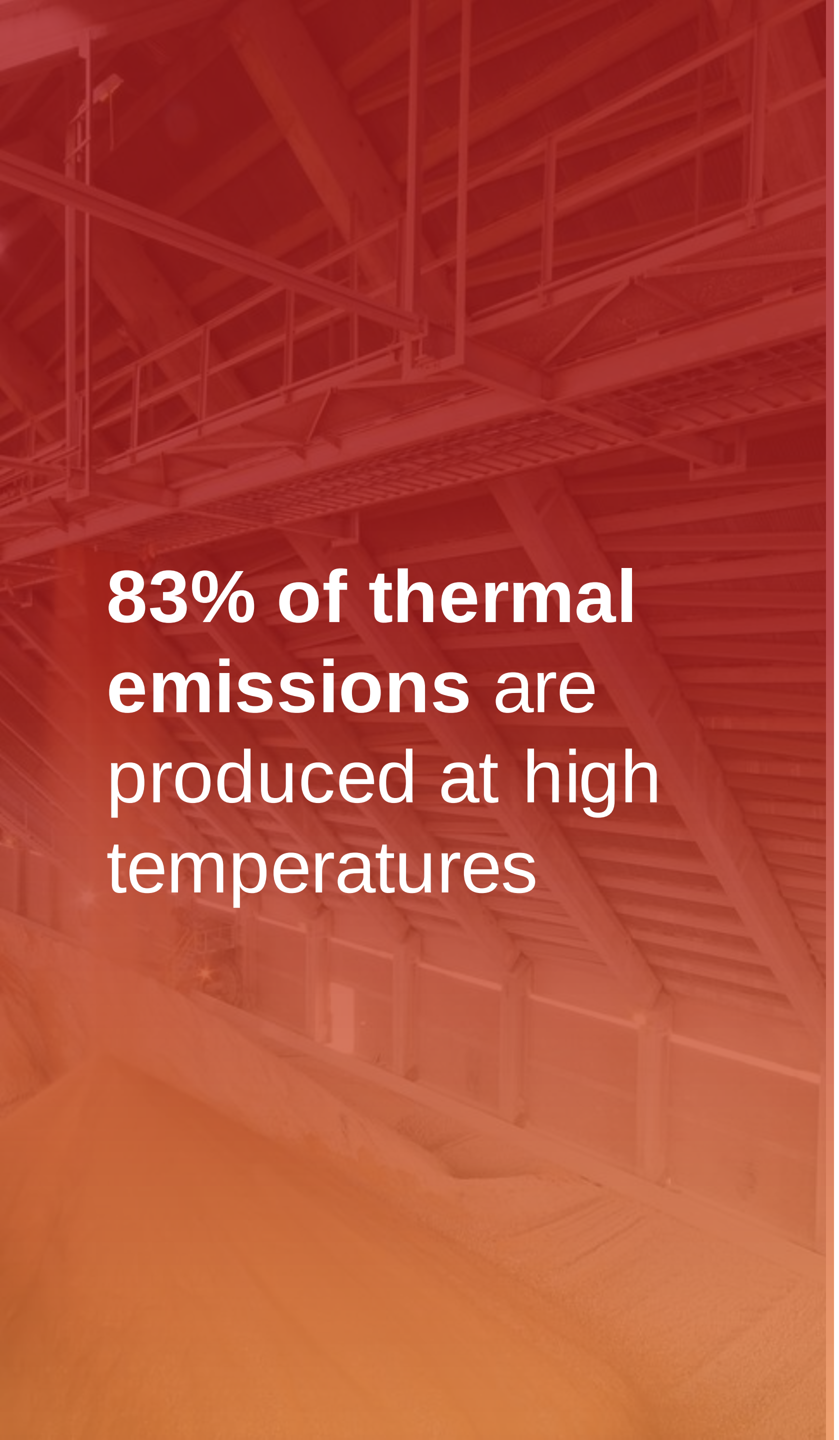
Pre-Calciners | ~600-700 ºC

Before entering the kiln, the cement rawmix goes through a **pre-calciner**, which disperses and suspends the rawmix with fuel (coal, waste gas) and hot air. The resultant heat calcines (decomposes the calcium carbonate) of the rawmix, which reduces the heat load of the rotary kiln.

Rotary Kilns | ~1200-1500 ºC

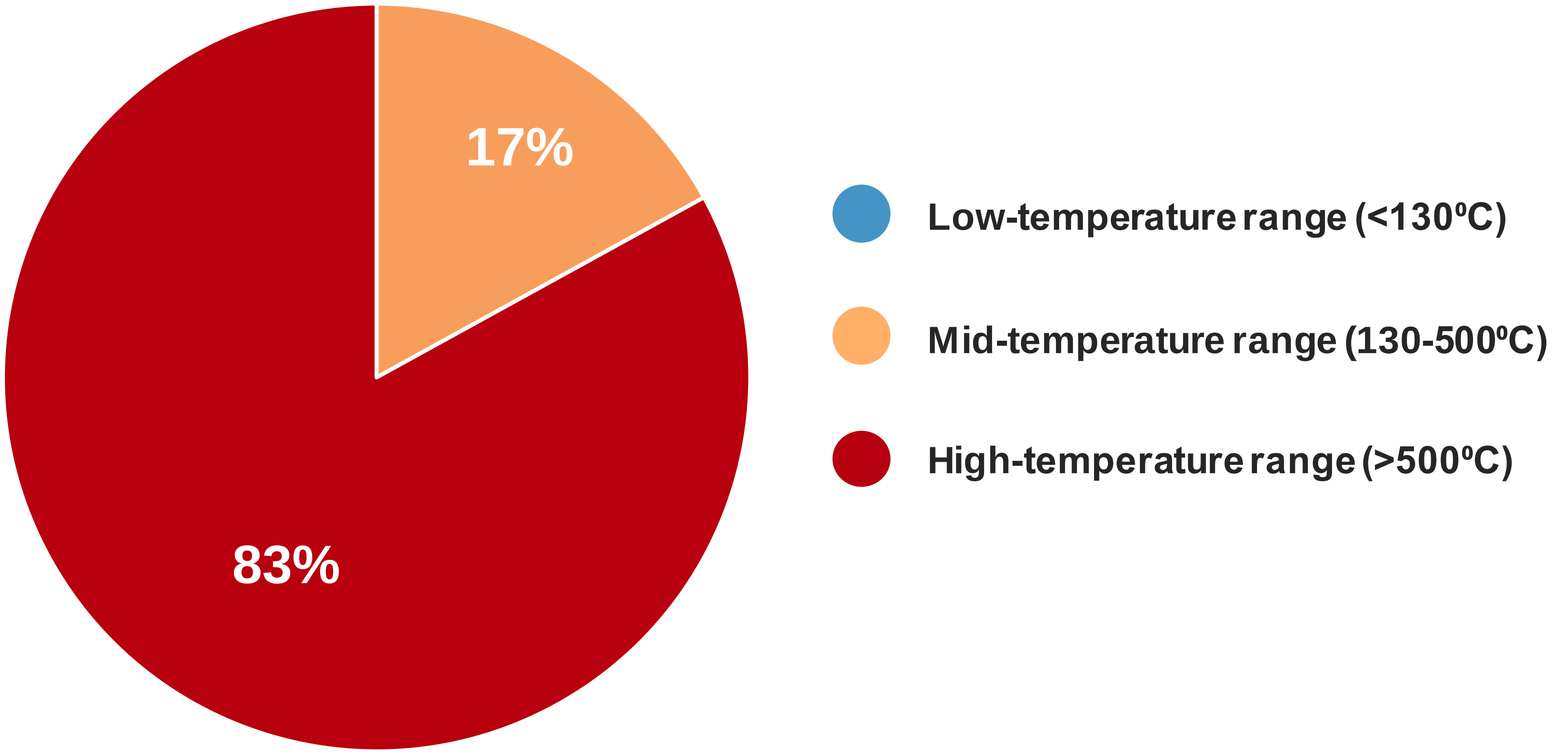
Once raw materials such as limestone and clay are grinded into a fine powder called raw meal, it is heated in a cement **kiln** to form clinker, which are round lumps or nodules. The clinker is then ground to a powder and mixed with gypsum to create cement.

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



83% of thermal emissions are produced at high temperatures

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



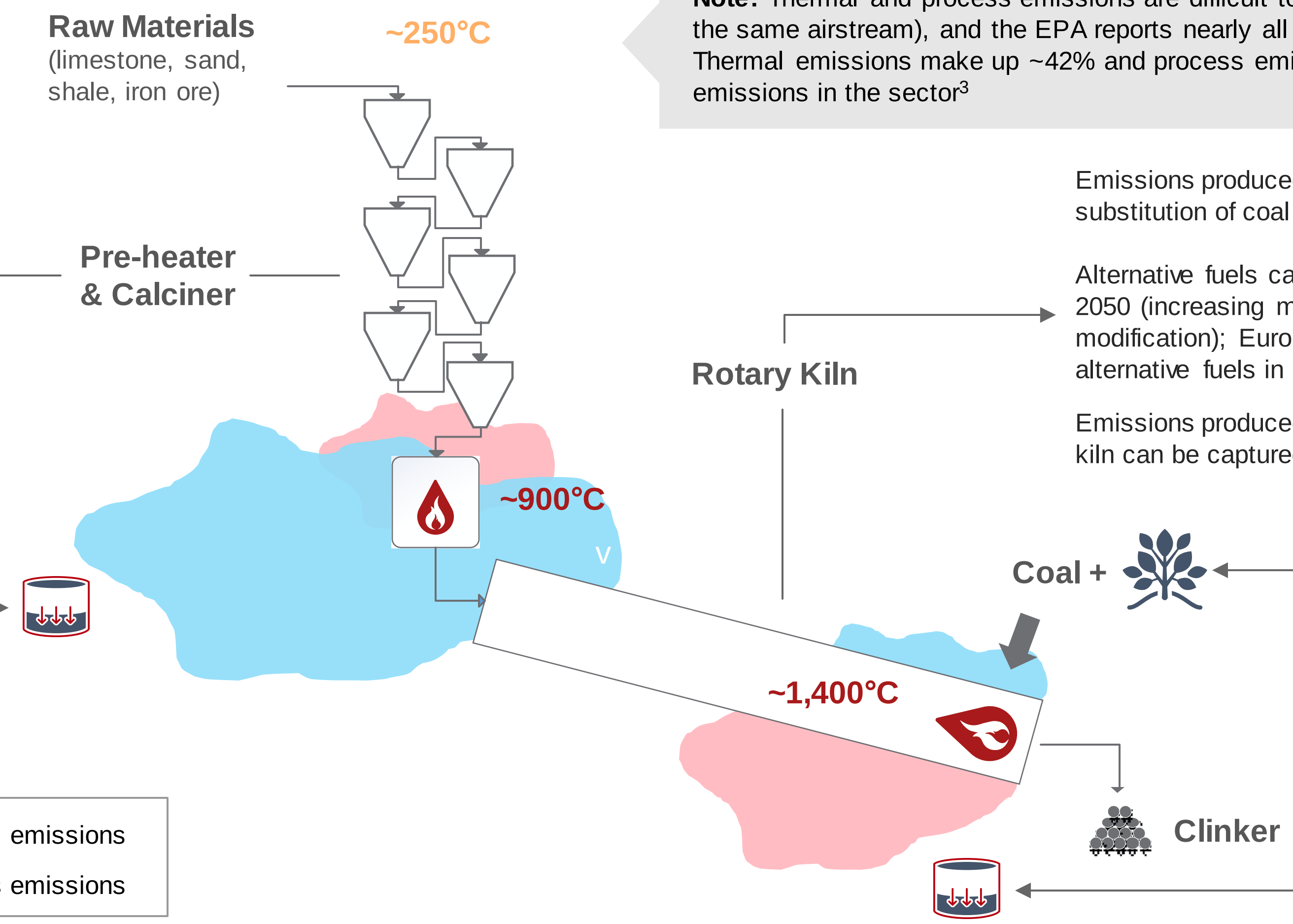
1. Calculated using the NREL MECS survey data for thermal energy use (2014)
Source: EIA; EPA; NREL; BCG analysis

Fuel combustion in manufacturing process occurs in the pre-calciner and rotary kiln; thermal & process emissions are difficult to distinguish

Note: Thermal and process emissions are difficult to distinguish (e.g., released in the same airstream), and the EPA reports nearly all emissions as process emissions Thermal emissions make up ~42% and process emissions make up ~58% of total emissions in the sector[3]

The pre-calciner produces 60-70% of total emissions in cement, most of which are process emissions[1]

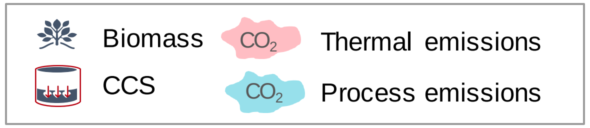
These emissions can likely be captured with CCS



Emissions produced by the rotary kiln can be reduced with fuel substitution of coal with alternative fuels such as biomass

Alternative fuels can compose up to 50% of the total fuel mix by 2050 (increasing mix of alternative fuels will require kiln modification); European cement manufacturers use ~60% alternative fuels in kiln mix[2]

Emissions produced by the remaining coal used in the rotary kiln can be captured with CCS

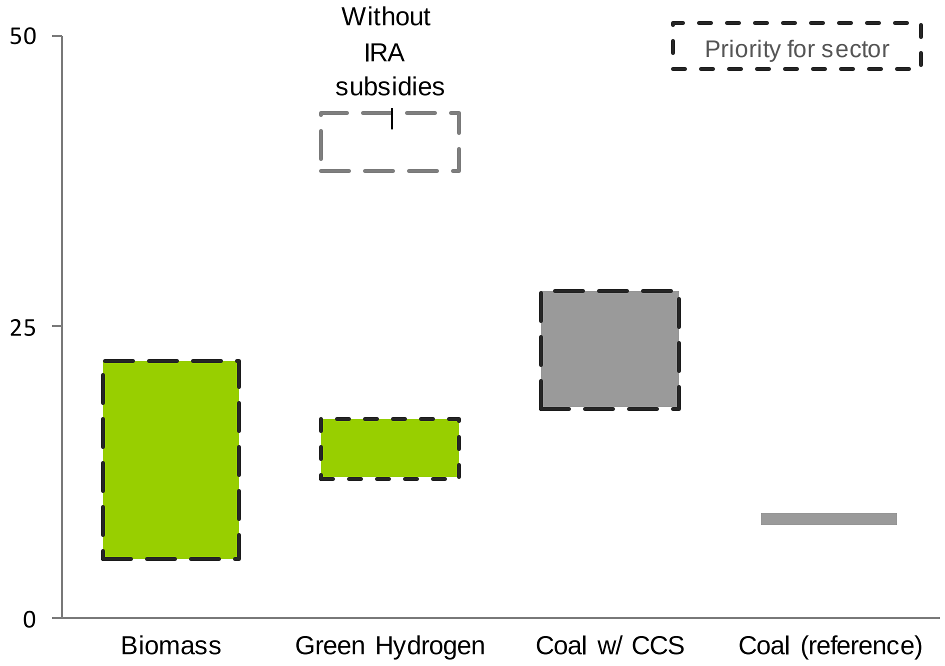


1. IEA Technology Roadmap (2021); 2. PCA Roadmap to Carbon Neutrality (2021); 3. DOE Industrial Decarbonization Roadmap (2022)

Biomass & green H2 appear most economic renewable-fuel alternatives

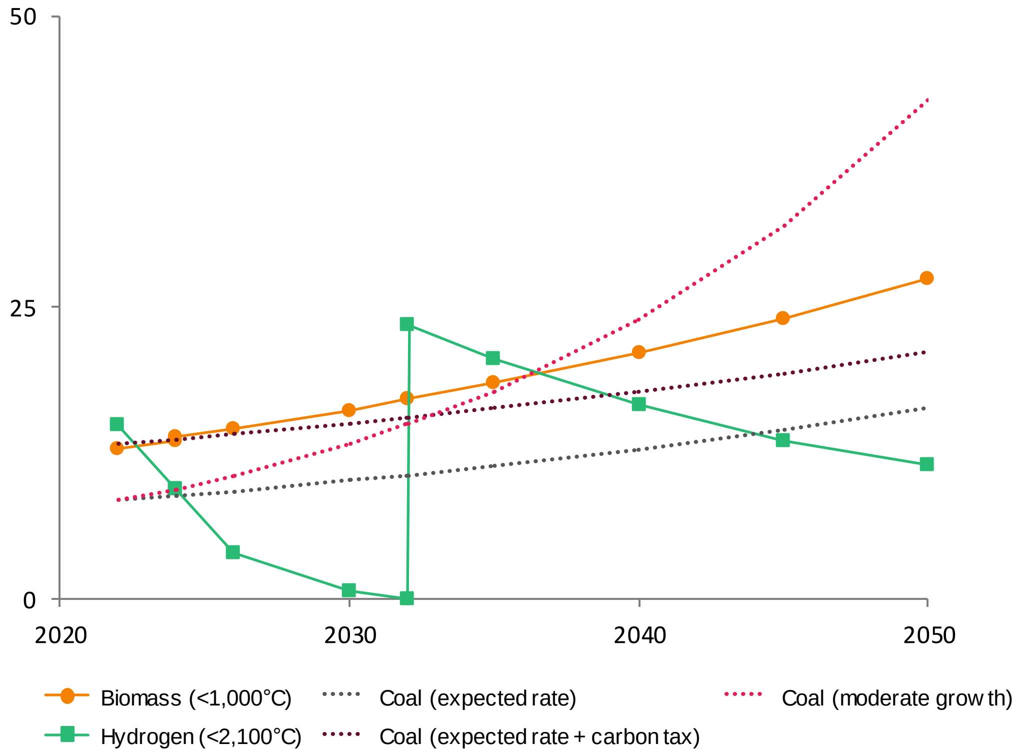
2022 LCOH for relevant technologies[1]

($/MMBtu)



Projected LCOH for relevant technologies[1]

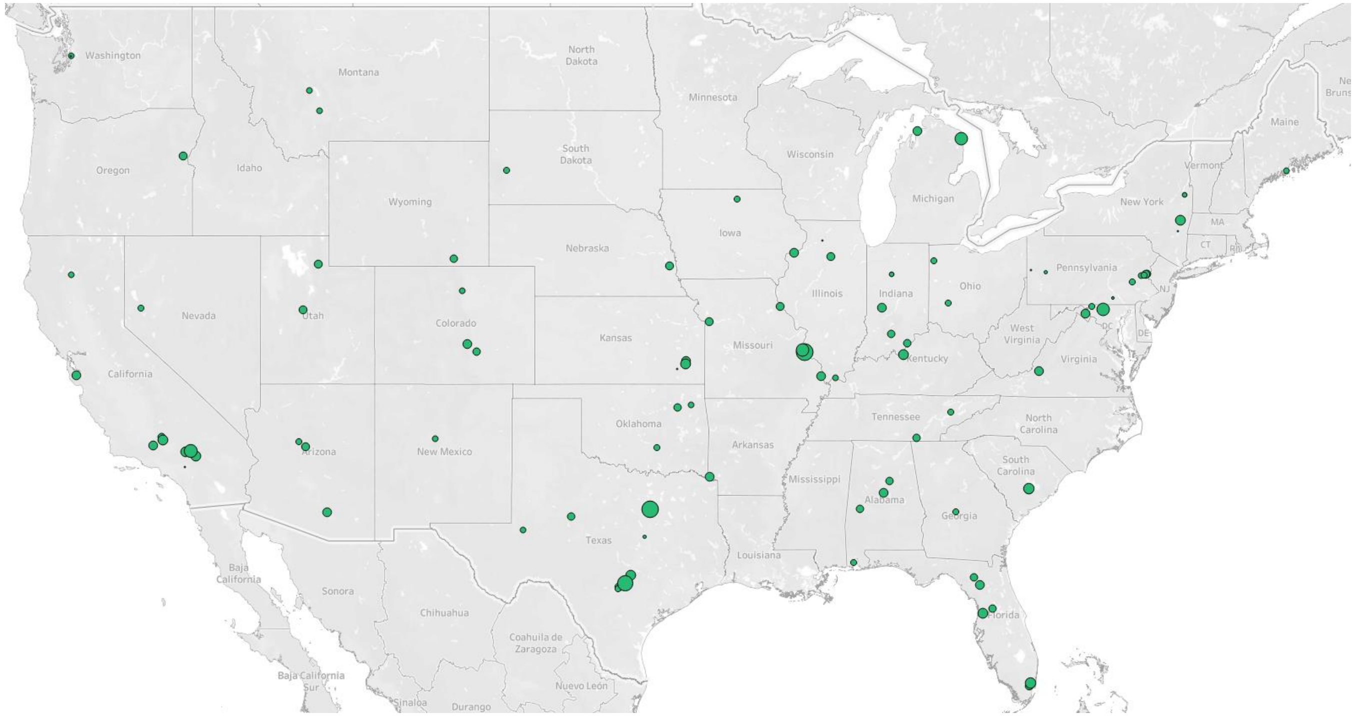
Average US LCOH ($/MMBtu)



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

Facilities are distributed across the US; site analysis likely required to determine fuel and CCS availability

US Cement thermal emissions by zip code[1]

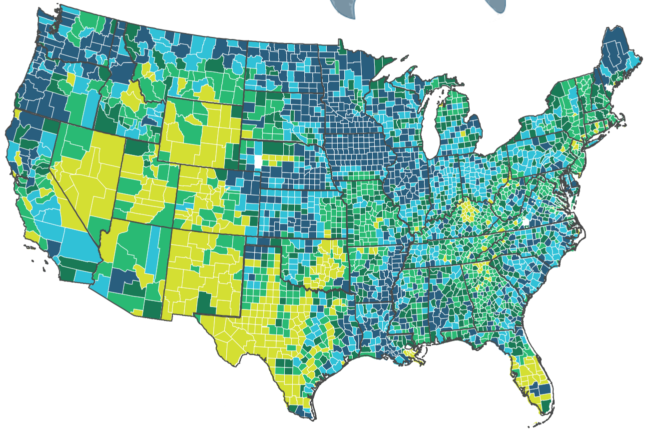


- 0.5 Million Tonnes CO2e
- 1.0 Million Tonnes CO2e
- 1.4 Million Tonnes CO2e

Carbon sequestration availability [2]

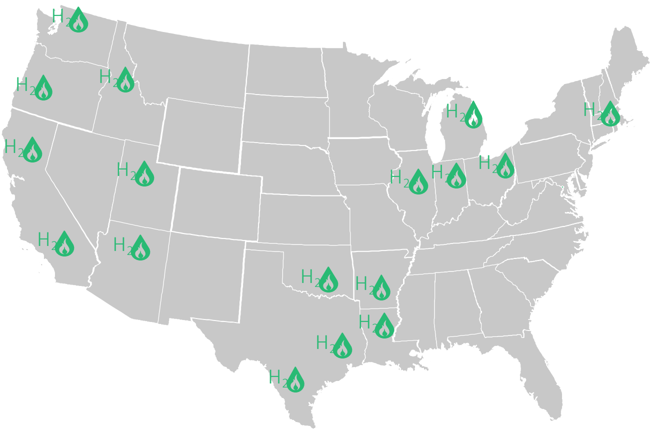
Saline aquifers

Biomass supply[3]



- >100
- 50-100
- 25-50
- 5-25
- <5

Proposed hydrogen hubs[4]



H_2 Proposed hydrogen hub

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. NREL Biofuels Atlas 4. CSIS (2022)

Decarbonization pathways

Coal
Displace partially with renewable fuels (e.g. biomass)

Biomass
Develop and deploy use of biomass to reduce coal usage

RNG
Increase use as blend in NG supply until supply constraints are met and costs are prohibitive

Hydrogen
As supplies are available for industrial thermal, ramp up use to maximum extent

CCS & Other Carbon Capture
Implement to capture combustion emissions from remaining fossil fuels

2022 → 2050

Considerations	Target First Movers
Adequate fuel supply, permitting for new fuel combustion	Local proximity to feedstocks (Midwest, Southeast)
Adequate supply of fuel	Regions with grid RNG blending (Midwest, Southeast)
Adequate fuel supply, viable economics, government subsidies	Regions with planned H2 hubs and industrial clusters
Concentration of CO2 in flue gas, government subsidies	Regions with industrial. clusters and adequate geology for storage

The Cement sector uses coal as the primary fuel in its kilns, where process and combustion emissions are intermixed. To reduce thermal emissions, **cement producers should displace fossil fuels with renewables to the maximum extent possible** to maintain clinker composition while also deploying CCS

Thermal decarbonization pathways

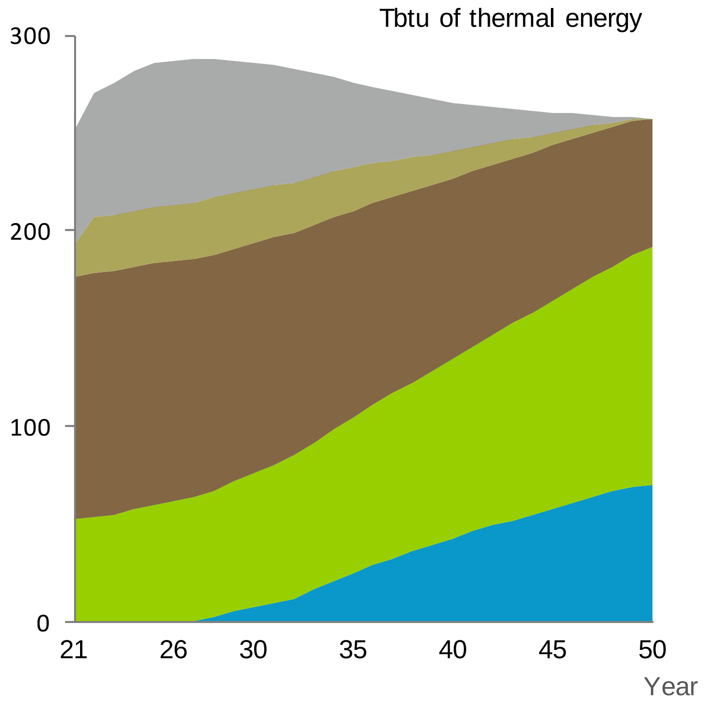
The Cement sector creates more process emissions than thermal emissions, and both emissions are typically emitted in the same air stream. As a result, **it is difficult to distinguish between process and thermal emissions** and the EPA GHGRP flight database does not identify meaningful thermal emissions. However, thermal emissions make up ~42% of total emissions (process emissions make up ~58%)[3]

The cement industry heat process applications require heat driven by fossil fuel combustion as well as fossil coal as a feedstock

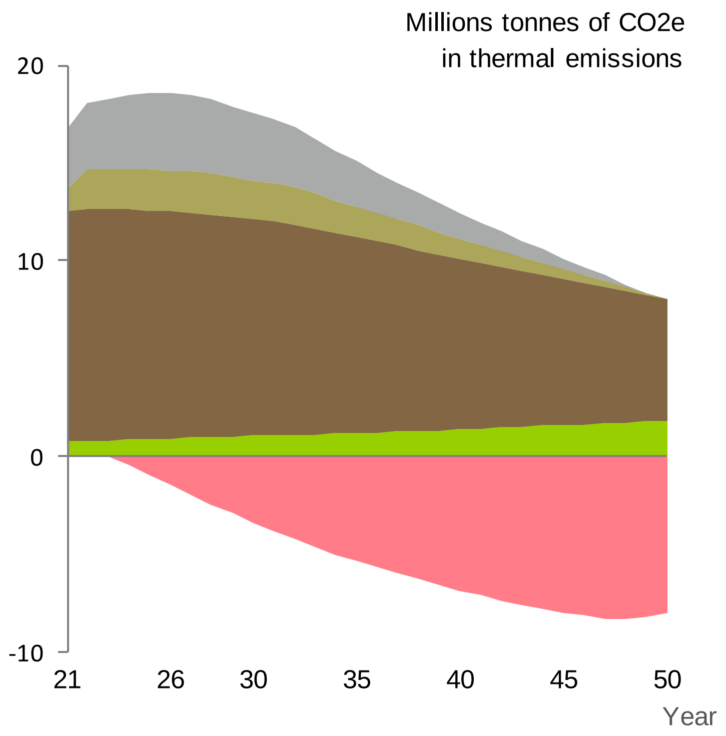
Heavy emitting coal, which is used for heat and as feedstock in the rotary kiln, can be **partially displaced with biomass**, which can compose up to 50% of the total rotary kiln mix by 2050; some European cement manufacturers are using ~60% alternative fuels in their rotary kiln mix (displacing ~40% of coal)4

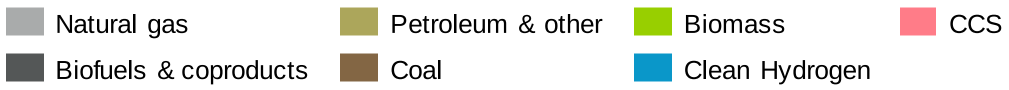
Given the inability to distinguish process and thermal emissions, it is likely that **carbon capture deployed to capture process emissions (~58% of total emissions) will also be used to capture thermal emissions (~42% of total emissions)**, until a longer-term alternative for coal-based cement production is developed

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 3. DOE Industrial Decarbonization Roadmap (2022) 4. PCA Roadmap to Carbon Neutrality (2021) Source: EIA outlook; EIA emissions intensity; BCG analysis

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