Industrial Thermal Decarbonization Package

RENEWABLE
THERMAL
COLLABORATIVE

Included in this Package

Industrial Thermal Decarbonization

Approach, Methodology, and Sources

1. Assess industrial thermal emissions and sources to prioritize efforts (EIA Outlook; EPA GHGRP Flight Database 2018)
2. Technology review of available renewable thermal fuels / technologies abatement potential and costs (BCG analysis)
3. Assess fuel supply availability for industrial heat to prioritize low carbon fuel supply for impact (DOE, EIA, NREL)
4. Deploy renewable thermal technologies and fuels to industrial sectors based on heat and process needs, costs, and fuel supply availability (BCG analysis)
5. Model thermal energy consumption and related emissions based on desired uptake, low-cost renewable alternatives, supply availability (EIA Energy Outlook 2022)

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Industrial thermal emissions and abatement options

Decarbonization pathways to net zero 2050

Decarbonization roadmaps for industry and key sectors

Supporting materials:

- *US industrial thermal emissions*
- *Renewable thermal technology prioritization*

This roadmap focuses on fuel-related emissions and a subset of decarbonization technology pillars within US industrial emissions

Emission Types

Fuel combustion related

Electricity generation

Process related

Product lifecycle

RTC roadmap focuses on thermal energy and **on-site fuel combustion related industrial emissions**

Decarbonization Technological Pillars[1]

Low-carbon fuels & energy sources

CCS[2]

Low-carbon feedstocks

Electrification

Energy storage

Energy efficiency

Similarly, **decarbonization technologies related to fuels and emissions from fuels** are considered as part of this roadmap

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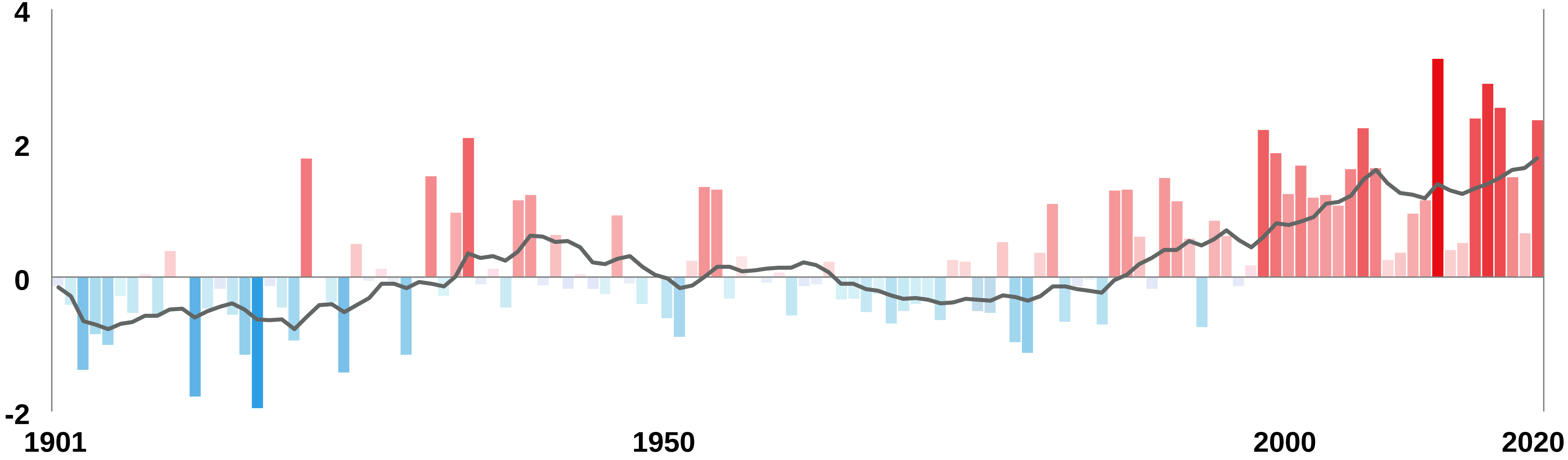
1. This roadmap focusses on growth of renewable thermal energy and related technologies; for prioritization purposes, energy efficiency has not been modeled (except for electric heat pumps and EAF); please refer to the DOE industrial decarbonization roadmap for information on energy efficiency 2. CCS is included given relevance to near- and medium-term abatement objectives; CCUS may be deemed outside of RTC near term priorities

The US is already facing the impacts of a 1.5°C world

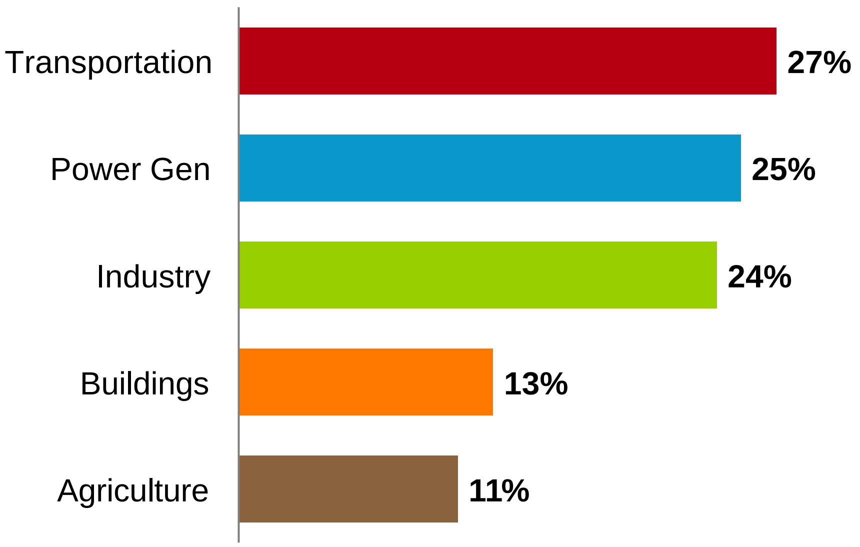
Average air temperature anomaly in the 48 contiguous states (°C)



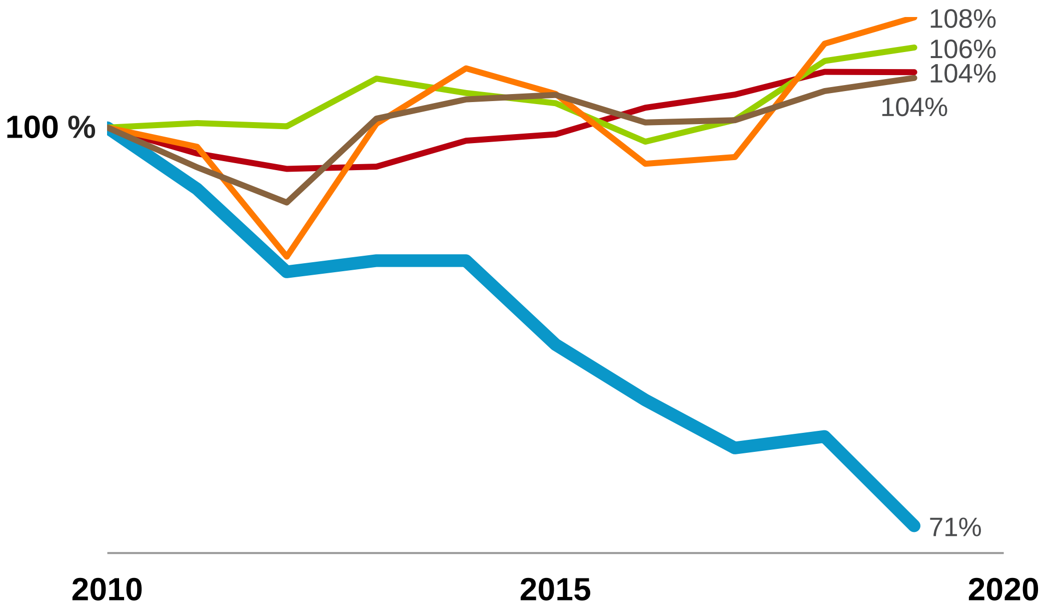
Source: USGCRP (U.S. Global Change Research Program) 2017 Climate science special report: Fourth National Climate Assessment, volume I

Heightened attention is needed around industrial emissions; only Power Gen has reduced carbon footprint

Industrial emissions represent
24% of total US emissions …



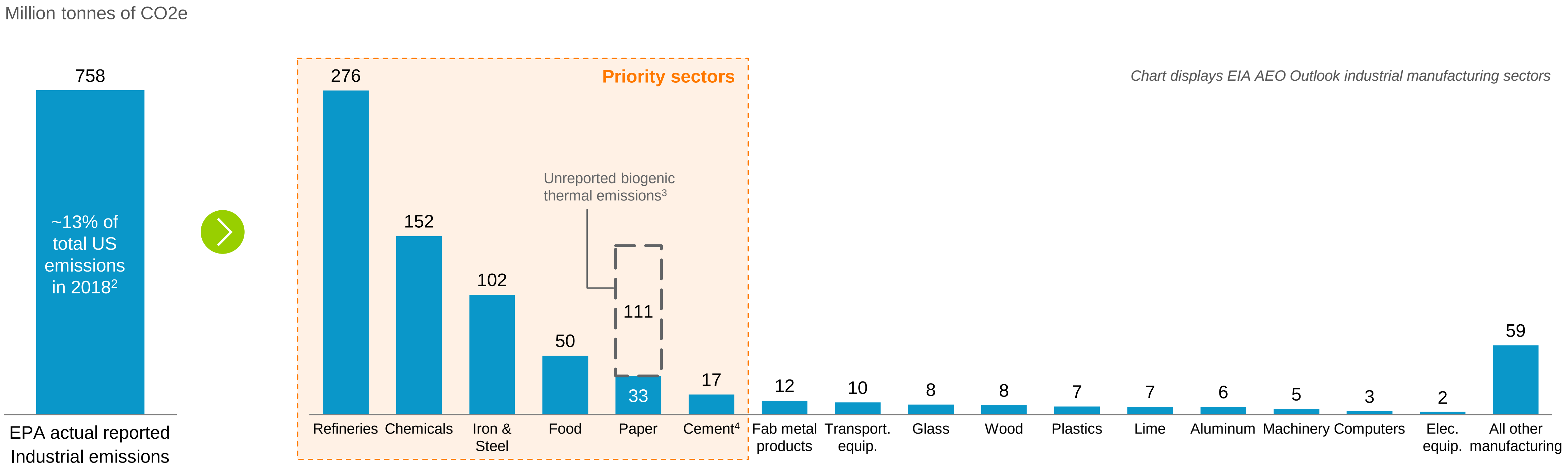
… and have been increasing since 2010;
only Power Gen has shown improvement



Source: EPA Emissions and Sinks: 1990-2020 (published 2022); displayed data is for 2020

US industrial thermal emissions[1] totaled 758 million tonnes of CO2e in 2018[2]

US industrial thermal emissions for all industrial manufacturing sectors (2018)[1]

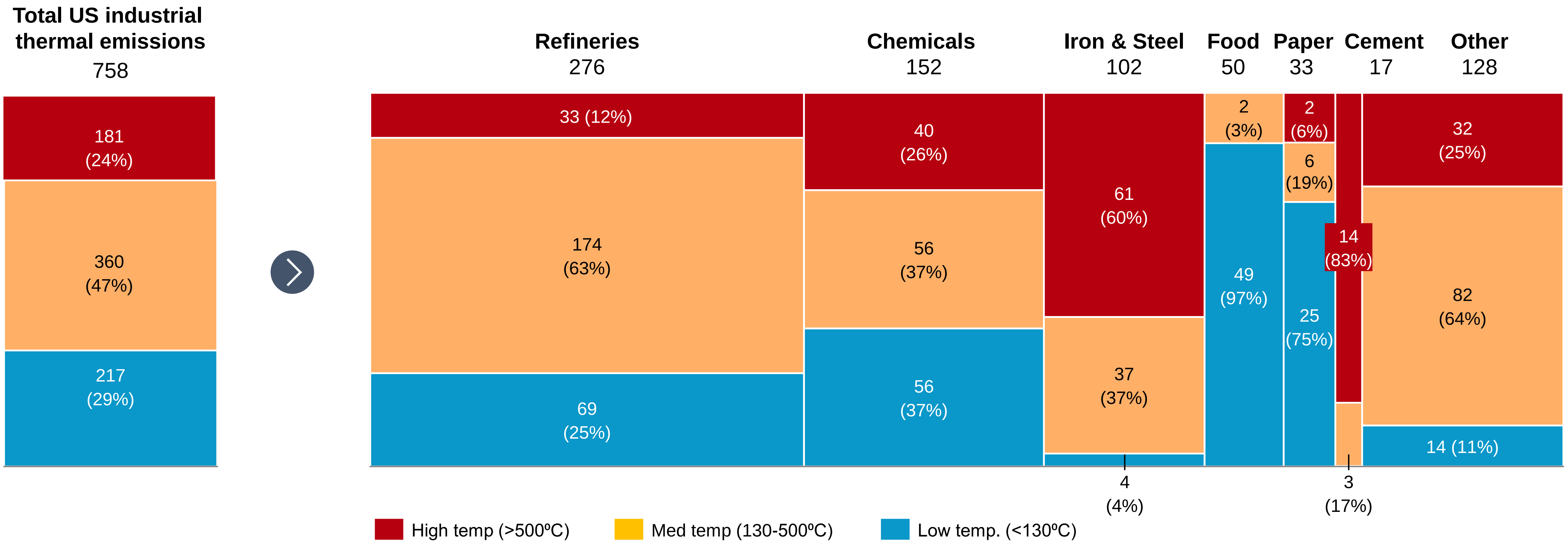


1. Including combustion of fossil fuels for machine drives.
2. Based on AEO 2019 Outlook for 2018 energy consumption by combustible fuel (excludes purchased electricity) for each sector, and EPA emissions intensity of individual fuels except for biomass, which is estimated at 15 kg CO2e/mmBtu; excludes non-manufacturing sectors of Agriculture, Construction, Mining 3. Biogenic emissions are considered 'net zero' by the EPA and are not included/reported in US industrial thermal emissions 2. Based on net emissions (including sinks) of 5,903 million tonnes of CO2e in 2018; gross emissions were 6,677 million tonnes of CO2e 4. Cement sector is estimated to represent 71.8% of the EIA Cement & Lime sector energy consumption

Source: US EIA Energy Outlook 2019 (2018 data); EPA emissions intensity by fuel type (June 2022); NREL (cement energy consumption)

Low & medium heat processes dominate industrial thermal emissions and account for ~76% of total

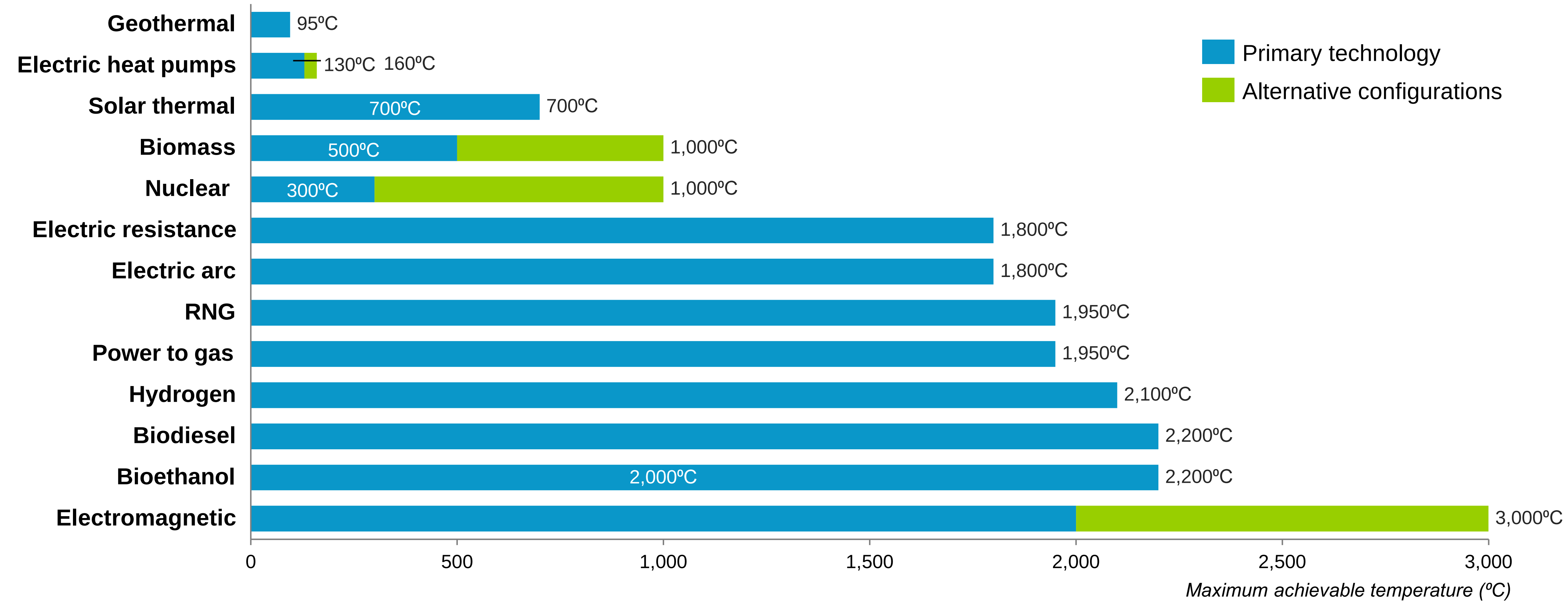
Estimated share of 2018 thermal emissions by temperature range (million tonnes of CO2e)



Notes: Chart updated September 2023 to correct computation error. Energy usage by temperature range was used as a proxy for thermal emissions by temperature range, most of industrial heat is fueled by natural gas across low, medium, and high temperature processes; certain sector emissions (e.g. Iron & Steel, Cement) may skew more towards the higher temperature range as these sectors combust fuels with higher carbon intensity for high temperature processes (e.g. coal in steel making) Source: NREL Manufacturing Thermal Energy Use in 2014 (provides thermal energy use by temperature); EIA Outlook 2019 (provides 2018 energy consumption by fuel); EPA emissions intensity by fuel.

Renewable thermal technologies are available across a range of temperatures

Available renewable thermal energy technologies and heat temperature range (ºC)



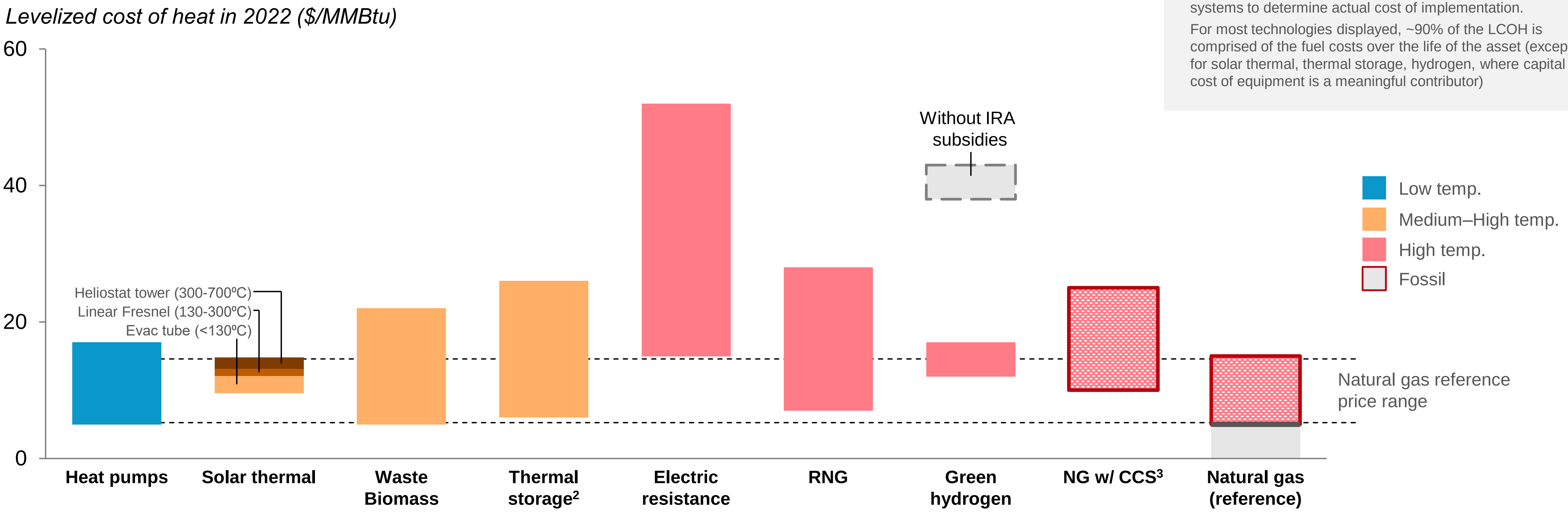
Source: DOE; research reports, papers, and studies; BCG analysis

Prioritized technologies offer competitive levelized cost of heat relative to natural gas

Note: Analysis reflects macro levelized cost of producing heat for each technology and is intended to provide overall cost of heat delivery of technologies relative to one another. Sector and process specific considerations will impact the generalized costs below; further analysis should be performed to consider industry heat application process and systems to determine actual cost of implementation.

For most technologies displayed, ~90% of the LCOH is comprised of the fuel costs over the life of the asset (except for solar thermal, thermal storage, hydrogen, where capital cost of equipment is a meaningful contributor)

Levelized cost of heat (LCOH) delivery across renewable thermal technologies[1]

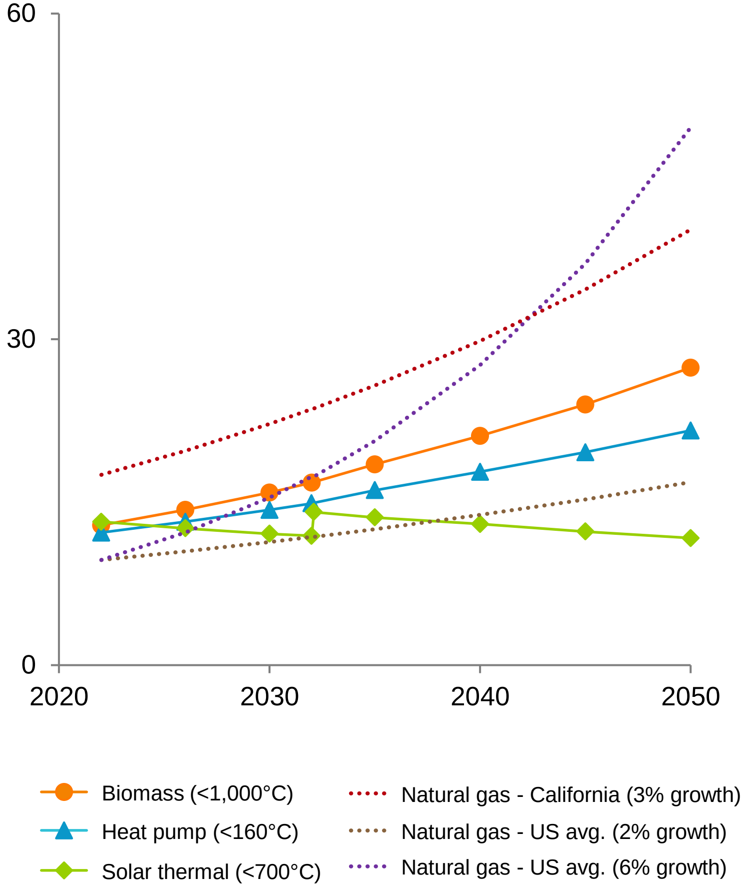


1. LCOH compares project lifetime costs against lifetime energy produced; costs include capital costs of equipment, fuel costs, and maintenance cost assumptions over the usable life of the energy asset. Electricity and natural gas pricing is based on state wholesale industrial end user electricity and natural gas prices for the past 1 year as of June 2022. Electric heat pumps, electric resistive, and natural gas heating efficiencies modeled at 300%, 99%, 75%, respectively. Includes Inflation Reduction Act incentives 2. Cost is modeled for the most economic configuration; thermal storage combined with electric resistance using inexpensive intermittent electricity and post-IRA subsidized solar, onshore wind, and offshore electricity prices without T&D costs 3. Cost of natural gas combustion with CCS; includes $85/metric ton 45Q tax credits from IRA Source: EIA; EPA; Inflation Reduction Act; BCG analysis

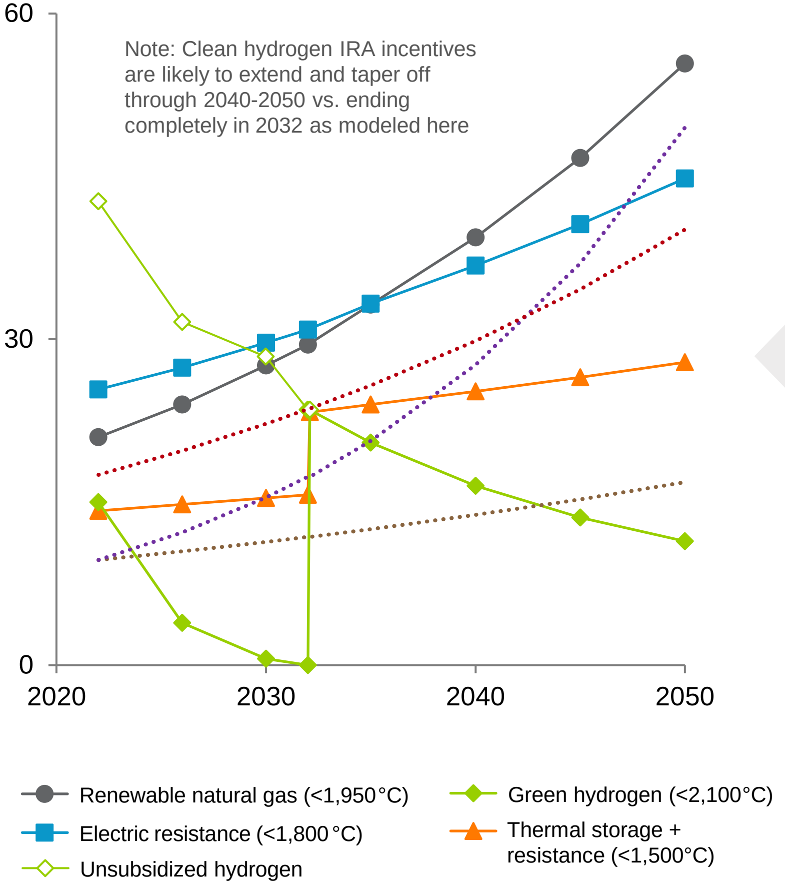
Projected LCOH

Technologies are economic v. natural gas in several scenarios; heat pumps & solar thermal for low temp, hydrogen for high temp

LCOH: Low & medium heat ($/MMBtu)[1]



LCOH: High heat ($/MMBtu)[1]



Note: Clean hydrogen IRA incentives are likely to extend and taper off through 2040-2050 vs. ending completely in 2032 as modeled here

Key assumptions

- Assumes US average retail end user industrial price for electricity and NG in 2022[1] (including T&D costs)
- Electricity end user retail price is projected to grow at 2%[2] per year. Power gen. is expected to decline, and T&D & grid interconnection costs are expected to grow as electrification penetrates US transportation, residential, commercial, industrial
- Natural gas end user price is modeled under low, medium, and high scenarios (CA pricing)
- Includes Inflation Reduction Act incentives for green hydrogen, renewable electricity, and industrial heat decarbonization under 48C[3]
- Hydrogen cost is modeled for production in hydrogen hubs using off-grid renewable electricity (excludes electricity T&D costs); industrial on-site hydrogen production with electricity pricing (including T&D) will result in higher cost
- Natural gas, electric resistance, and heat pumps modeled at 75%, 99%, 300% efficiency, respectively

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. EIA electricity nominal pricing projected to grow at 1.8% per year through 2050 3. Inflation Reduction Act section 48C offers a broad 30% ITC for industrial heat decarbonization projects that reduce emissions by 20%; funding is limited to ~$10B, after which costs for some technologies (excluding hydrogen) would revert to their pre-incentive cost (e.g. solar thermal) Source: US EIA, IRA, BCG analysis

Technologies must be strategically deployed to navigate low carbon fuel supply constraints

		Heat pumps	Solar thermal	Biomass	Thermal storage[2]	Other Electric[3]	RNG	Green hydrogen	CCS[4]	Natural gas (reference)
	Primary temp (ºC)	160	700	1,000	1,500	1,800	1,950	2,100	N/A	1,950
Food	<130ºC	✅	✅	✓	✓	✅	✓	✓	✓	✔
Refineries	<480ºC	✓		✓	✓	✓	✓	✓	✅	✔
Chemicals	<815ºC	✅		✅	✓	✅	✅	✅	✅	✔
Paper	<200ºC	✅	✓	✅	✓	✅	✓	✓	✅	✔
Cement	600-1,500ºC			✅	✓	✓	✓	✅	✅	✔
Iron & Steel	1,600-2,000ºC			✓	✓	✅	✓	✅	✅	✔
Avg US LCOH[1] ($/MMBtu)		12	13	13	14	25	21	15	15-20[2]	10

✓ Technology is applicable in the sector

✅ Technology identified as priority for the sector

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1. Levelized cost of heat in 2022 using national weighted averages for end user industrial electricity and natural gas pricing for the past 12 months as of June 2022 2. Combined with electric resistance 3. Includes electric resistive technologies, electric arc heating, and other developed electric heating technologies (e.g., electric steam boilers) 4. Using natural gas combustion as baseline fuel with emissions intensity of 53.06 kg/MMBtu; includes cost of natural gas fuel and $85/metric ton 45Q tax credits from IRA Source: EIA; EPA; BCG analysis

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Our analysis uncovered four important findings, which guided the decarbonization roadmap

Low & medium heat processes (<500ºC) dominate industrial thermal emissions, and their conversion alone to renewable energy can reduce thermal emissions by nearly 80%

Electric heat pumps can be deployed cost effectively at temperatures under ~130ºC, representing up to ~42% of industrial thermal emissions; heat pumps are expected to reach 200ºC by 2030, representing up to ~60% of industrial thermal emissions

Clean[1] hydrogen can displace high temperature fossil fuel combustion, but is supply constrained in near term; **early efforts to develop clean hydrogen are needed to ensure future supply**

Paper sector produces 100+ million tonnes of biogenic CO2e emissions[2] annually, **if captured, could offset ~15% of US industrial thermal emissions**; IRA carbon capture credits of $85/metric ton provide a cost competitive[3] pathway to capture these emissions

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1. Clean hydrogen includes green and blue hydrogen 2. Total paper sector biogenic CO2e emissions totaled 111 million tonnes in 2018 with the top 50 facilities generating ~75 million tonnes of biogenic CO2e; biogenic emissions are considered 'net zero' by the EPA and are not reported in US industrial thermal emissions 3. Cost of carbon capture on biomass ranges from $60-$120/tonne of carbon with costs expected to decline due to technology maturity; EIA estimates cost of transport and storage at $12-24/tonne of carbon; Inflation Reduction Act offers a credit of $85/tonne of carbon, which may allow a significant portion of the biogenic emissions to be captured economically

Parallel pathways to decarbonize industrial heat[1]

Electrify industry processes

- Electrify low temperature processes with cost competitive heat pumps
- Electrify remaining US steel blast furnaces with DRI-EAF2
- Electrify steam boilers & deploy other electric resistance technologies in medium-high temp. processes

Green the grid

- Enter (V)PPAs to reduce electric carbon footprint where possible
- Accelerate the transition to a carbon free electric grid to meet industrial green electricity needs

Deploy renewable fuels

- Deploy RNG as supply constraints allow
- Deploy biomass from waste feedstock; develop and deploy BECCS (Bio-energy w/ CCS) for new and existing biomass combustion
- Develop, procure, and deploy green hydrogen

Deploy renewable technologies

- Deploy solar thermal where economically viable
- Pair thermal storage with intermittent renewables; use cases likely to grow as grid mix of renewable grows
- Clean tech combinations e.g., heat pumps with geo or solar thermal

Capture & store carbon

- Deploy CCS & DAC using scale efficiencies as a short- and medium-term lever in specific sectors. Phase down CCS as industry transitions to clean processes

Energy efficiency spans across pillars[1]

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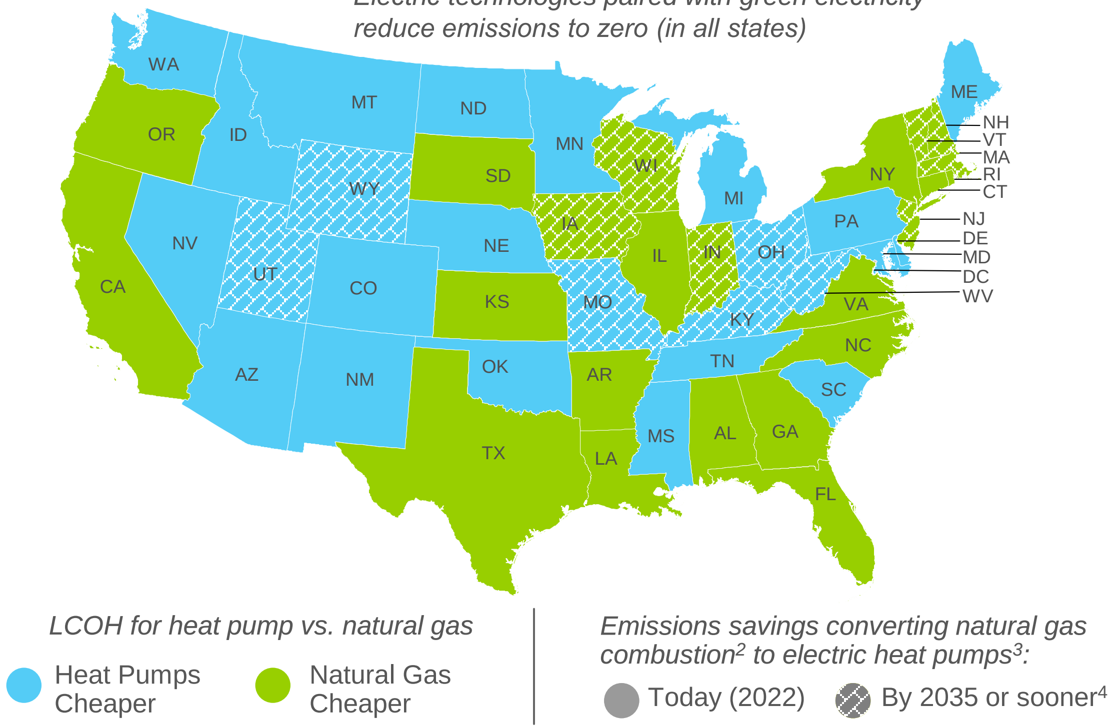
1. This roadmap focusses on growth of renewable thermal energy and related technologies; for prioritization purposes, industrial heat application process changes and energy efficiency have not been modeled (except for electric heat pumps and EAF); please refer to the DOE industrial decarbonization roadmap for information on process changes and energy efficiency 2. Direct reduced iron in an electric arc furnace with green hydrogen

Electrification is a primary decarbonization pathway in the short, medium, and long-term

Electricity offers immediate decarbonization opportunities and a sustainable net zero fuel

- Electric heat pumps can be deployed effectively today at temperatures under ~130ºC, representing ~42%[1] of industrial thermal emissions
- Heat pumps can achieve efficiencies of 300%+ (natural gas <85%) because they move heat around vs. generate heat. Heat pumps with "dirty" grid electricity can replace natural gas and reduce emissions in nearly every US state today; furthermore, total levelized cost of heat (LCOH) for heat pumps is cost competitive to natural gas today, and lower in many states
- Electric resistance, while not as efficient as heat pumps, can replace natural gas combustion to reduce emissions in ~half of US states today, using grid electricity
- Other electric heating technologies such as electric arc heating have valuable niche applications, are already deployed in the US, and are one of the primary decarbonizing levers for Iron & Steel
- Furthermore, electric heat pumps are expected to achieve max temp. of ~200ºC by 2030+ and may become applicable for up to ~60%[1] of industrial thermal energy consumption occurring under ~200ºC

Heat pumps are cost competitive & reduce emissions across the US, even with "dirty" grid electricity



Electric technologies paired with green electricity reduce emissions to zero (in all states)

LCOH for heat pump vs. natural gas

● Heat Pumps Cheaper

● Natural Gas Cheaper

Emissions savings converting natural gas combustion[2] to electric heat pumps[3]:

● Today (2022)

▨ By 2035 or sooner[4]

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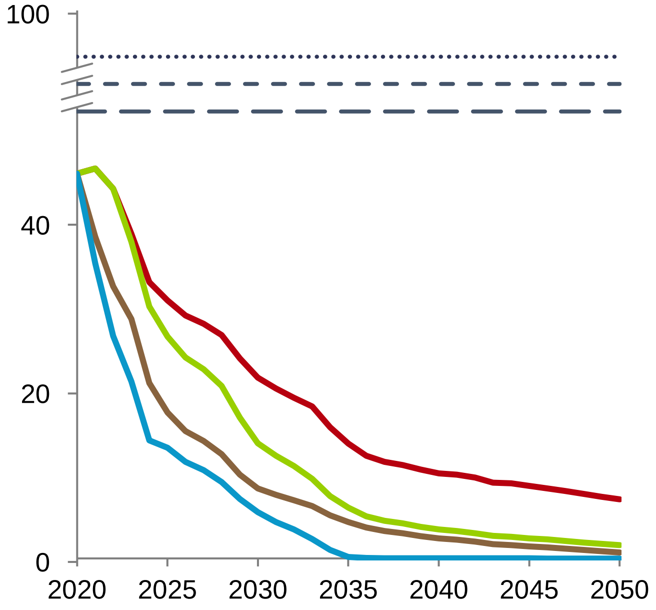
1. NREL Manufacturing Thermal Energy Use (2014) 2. Calculated using 85% efficiency for natural gas boiler; 3. Calculated using a conservative COP of 3; COP can increase if a waste heat source is available 4. IN, WV electric grid offer abatement by 2035, UT by 2030, WY, MO, KY, OH by 2026 Source: US EIA; State Renewable Portfolio Standards; IEA ETSAP Industrial Combustion Boilers Fact Sheet; BCG analysis

Grid decarbonization will unlock even more abatement opportunities and enable a NZ 2050

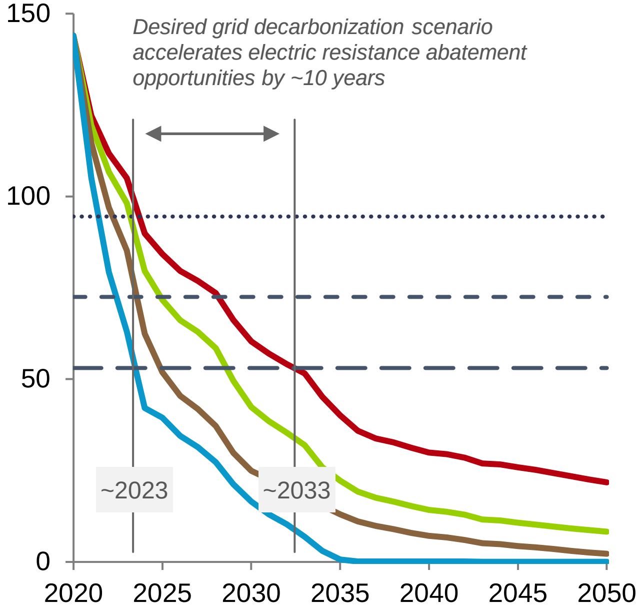
Heat pumps with grid electricity reduce emissions immediately

Electric heat pump emissions intensity v. fossil fuels (Kg CO2e/mmBtu)



Elec. resistance with grid electricity offers abatement in a few years

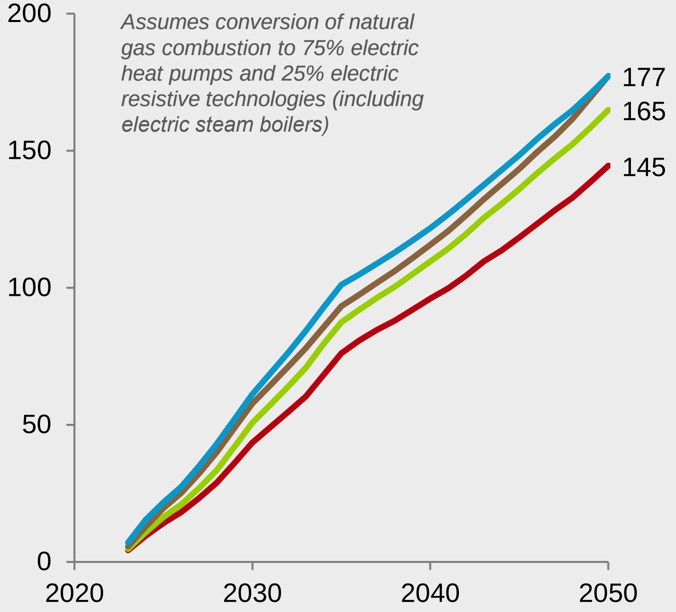
Electric resistance emissions intensity v. fossil fuels (Kg CO2e/mmBtu)



Desired grid decarbonization scenario accelerates electric resistance abatement opportunities by ~10 years

"Dirty" grid electricity reduces emissions vs. natural gas under all grid scenarios

Emissions savings for NG combustion that is switched to electricity (million tonnes of CO2e/year)



Assumes conversion of natural gas combustion to 75% electric heat pumps and 25% electric resistive technologies (including electric steam boilers)

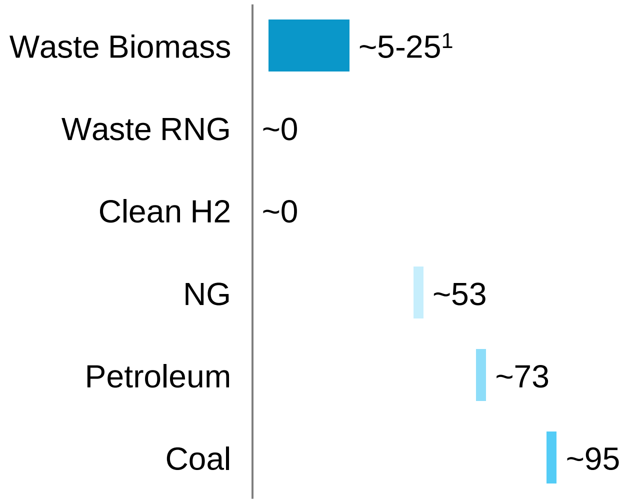
- Low grid decarbonization
- Expected grid decarbonization
- Desired grid decarbonization
- Most ambitious grid decarbonization
- Natural Gas
- Petroleum
- Coal

Notes: Low grid decarbonization assumes ~56%-80% renewables by 2030-2050, expected grid decarbonization assumes ~65%-92% renewables by 2030-2050, desired grid decarbonization assumes ~80%-100% renewables by 2030-2050, most ambitious grid decarbonization assumes ~100% renewables by 2035; Analysis assumes efficiencies of 75%, 99%, 300% for natural gas combustion, electric heat pumps, and electric resistance Source: US EIA; DOE; State Renewable Portfolio Standards; BCG analysis

Hydrogen & RNG are supply constrained, allowing biomass to also play a role as a combustible fuel

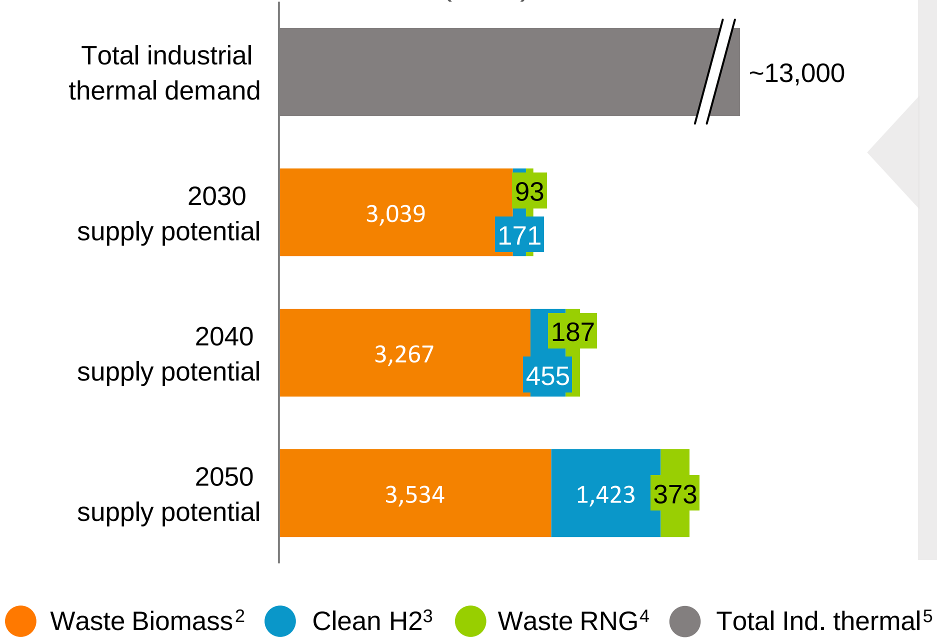
RNG & clean H2 are preferred over biomass but …

Emissions intensity (kg CO2e / mmBtu)



… RNG & clean H2 are supply constrained, which means …

Low carbon fuel supply potential for industrial heat (TBtu)



… all 3 fuels likely needed to decarbonize industrial heat

- RNG and clean hydrogen are preferrable over biomass as long-term sustainable NZ fuels
- However, biomass can play a role as a bridge to a net zero future, while RNG and clean hydrogen production supply constraints are alleviated
- Clean hydrogen has significant potential as a long-term sustainable fuel due to declining cost of hydrogen production and few feedstock constraints

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1. Biomass Thermal Energy Council wood chips and pellets 2. Biomass long term supply potential excluding energy crops, based on DOE 2016 Billion Ton Report; 2021 US biomass usage was 4,835 TBtu of which 2,313 TBtu was used by industry (EIA) 3. Clean hydrogen includes blue and green hydrogen; clean hydrogen supply based on DOE US clean hydrogen production goals, which earmark industrial heat as one of three priorities; analysis assumes 15%, 20%, and 25% of total US clean hydrogen supply is available for industrial heat in 2030, 2040, 2050 4. BCG analysis; includes landfill and waste RNG; excludes lignocellulosic RNG; assumes all commercial and industrial RNG available is allocated to industrial heat 5. Based on 2021 energy consumption per EIA 2022 Outlook for all industrial manufacturing sectors Source: DOE, NREL, EIA

Carbon capture, thermal storage, and other hybrids will play a role in the journey to net zero

Strategically deploy carbon capture & prioritize low carbon fuels for impact

- Deploy CCS in refineries and other sectors where CCS will likely be deployed to capture process emissions
- Refineries, the highest emitting sector for industrial thermal emissions, generate thermal emissions from burning natural gas (~1/3rd share) and refinery byproducts (~2/3rd share); Refineries are expected to continue combusting refinery byproducts particularly when alternatives include flaring or sequestering the gas; CCS is likely the primary decarbonizing pathway for refineries
- Iron & Steel and Cement create significant process emissions and are expected to deploy CCS as near term decarbonization pathways, as they source cleaner feedstocks and update manufacturing processes
- Strategic deployment of CCS enables near term emission abatement goals, and reserves and prioritizes low carbon fuels for higher impact uses in a supply constrained environment
- The levelized cost of heat for clean hydrogen (~\$15/mmBtu[2]) is expected to be lower than the cost of CCS paired with natural gas combustion (~\$15-20/mmBtu[2]); as supply constraints ease, clean hydrogen is likely preferrable to CCS

Deploy hybrid technology configurations to maximize impact of renewables

Thermal storage & Intermittent renewables

- Thermal storage can resolve renewable intermittency and expand process heating potential
- Storage can expand solar thermal potential beyond limited hours of high solar irradiation by ~28%[1] and reduce LCOH by ~\$5/mmBtu[2]
- Can be deployed alongside wind & solar electricity, particularly when cheap electricity can be procured

Upgrading low temperature heat

- Geothermal and solar thermal technologies can be paired with electric heat pumps to lift low temperature heat
- Electric heat pumps can be deployed with combustion (e.g., hydrogen, RNG, biomass) to upgrade and re-use waste heat for low temperature applications; electric heat pump LCOH declines with higher input heat sources

Renewable fuel combustion & CCS

- Bio energy (waste biomass or RNG combustion) plus CCS i.e. BECCS, offers potential for negative emissions and/or carbon credits
- The paper sector is a primary user of biomass in industry, and generated 100mmMT+ CO2e in 2018 from biogenic emissions[3] (~3x the reported paper sector thermal emissions) - offering significant opportunity for negative emissions

1. NREL 2. BCG analysis 3. EPA GHGRP 2018

Contents

Supporting materials:

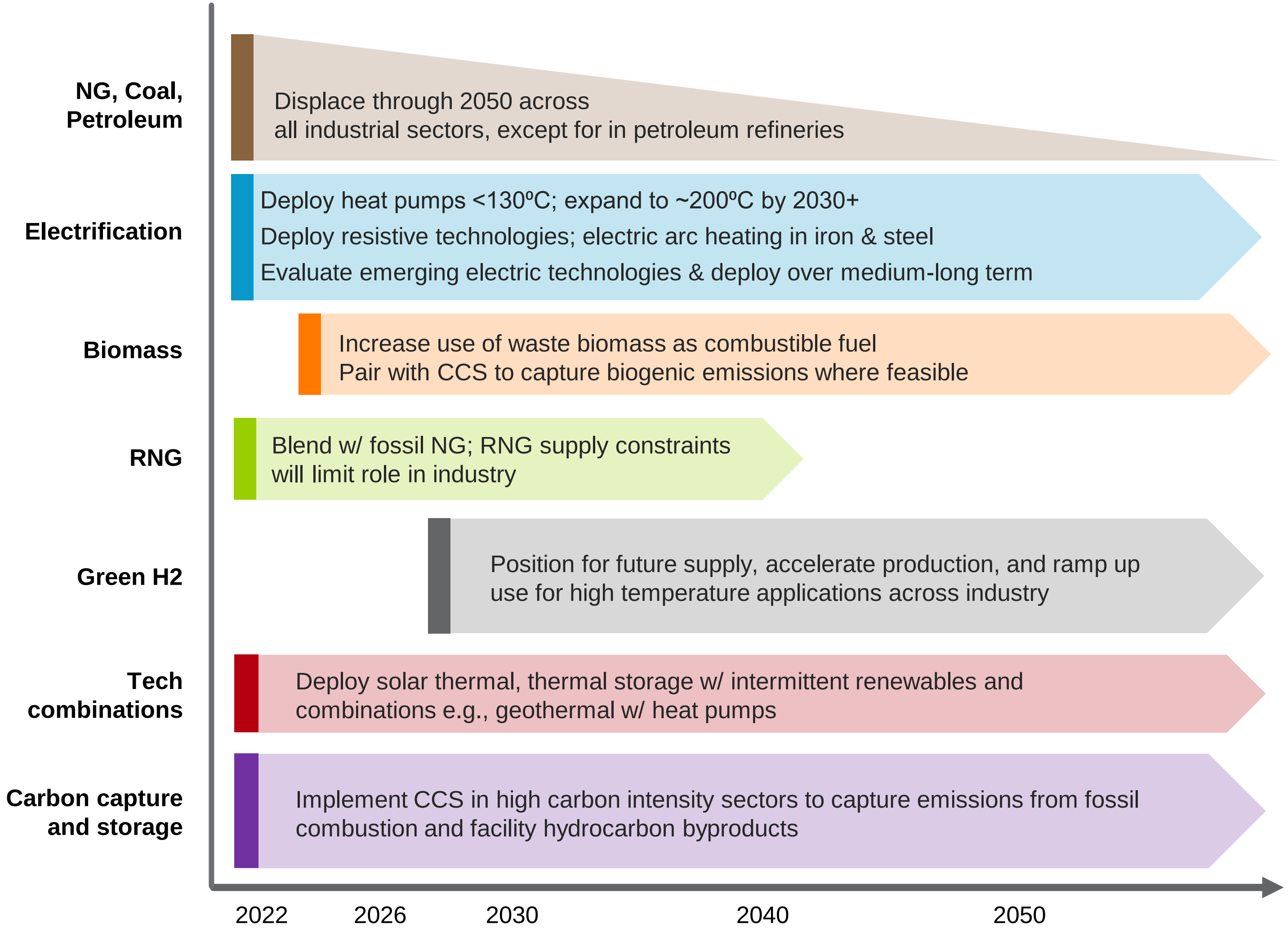
- *US industrial thermal emissions*
- *Renewable thermal technology prioritization*

Priority actions will need attention across multiple fronts

- ✓ Displace virtually all fossil combustion across industrial sectors except refineries
- ✓ Realize electrification opportunities across industry & leverage the decarbonizing grid
- ✓ Activate untapped biomass; pair with subsidized CCS to 'inset' emissions
- ✓ Accelerate development, production and use of green H2 across industry
- ✓ Investigate and deploy clean technologies in economic use cases
- ✓ Capture CO2 in carbon intense sectors until they transition to clean processes

The full suite of abatement levers will be needed to achieve short- and long-term goals

Thermal energy & technology actions across industry



NG, Coal, Petroleum

Displace through 2050 across
all industrial sectors, except for in petroleum refineries

Electrification

Deploy heat pumps <130ºC; expand to ~200ºC by 2030+
Deploy resistive technologies; electric arc heating in iron & steel
Evaluate emerging electric technologies & deploy over medium-long term

Biomass

Increase use of waste biomass as combustible fuel
Pair with CCS to capture biogenic emissions where feasible

RNG

Blend w/ fossil NG; RNG supply constraints
will limit role in industry

Green H2

Position for future supply, accelerate production, and ramp up
use for high temperature applications across industry

Tech combinations

Deploy solar thermal, thermal storage w/ intermittent renewables and
combinations e.g., geothermal w/ heat pumps

Carbon capture and storage

Implement CCS in high carbon intensity sectors to capture emissions from fossil
combustion and facility hydrocarbon byproducts

Decarbonization Roadmap

Refineries*, Chemicals, Iron & Steel, Cement, Food, Paper

**For consistency across sectors, EIA energy consumption forecast for refineries is used below; however, refinery energy consumption is likely to decline in the 2030-2050 period as fossil fuel usage is reduced globally. Accordingly, overall thermal energy consumption, thermal emissions, and related carbon capture needs are expected to be lower than projected below (using EIA energy forecast)*

Decarbonization pathways

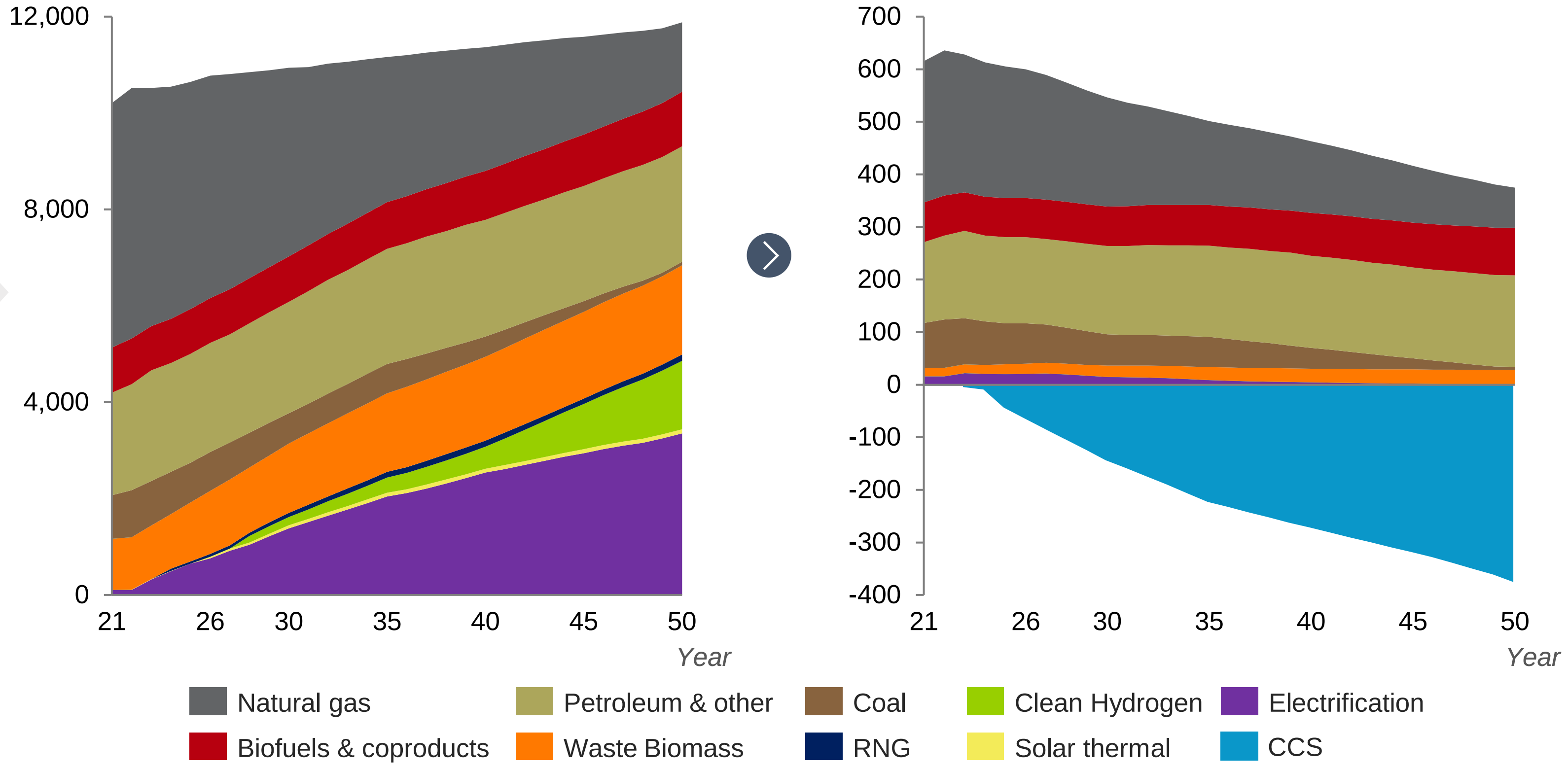
- Phase out fossil natural gas, coal, and petroleum in all sectors except for Refineries
- Electrify low and medium temperature processes across all sectors, and on an accelerated timeline in the Food, Paper, and other sectors where low temperature processes dominate
- Deploy and increase use of waste biomass in Chemicals and Paper, respectively. Implement CCS to capture thermal emissions, and biogenic emissions in Paper sector where there is opportunity to generate negative emissions annually
- Prioritize and deploy green hydrogen for high heat applications in Chemicals, Iron & Steel, Cement
- Accelerate electric grid decarbonization to ~80% renewables by 2030 and ~100% by 2050 to meet full decarbonization goals6
- Deploy CCS as the primary decarbonizing lever for refineries, where majority of industrial heat is generated from combustion of refinery byproducts; refineries are the only sector projected to use fossil fuels by 2050

Thermal energy consumption[1]

Tbtu of thermal energy

Thermal emissions[2]

Millions tonnes of CO2e in thermal emissions



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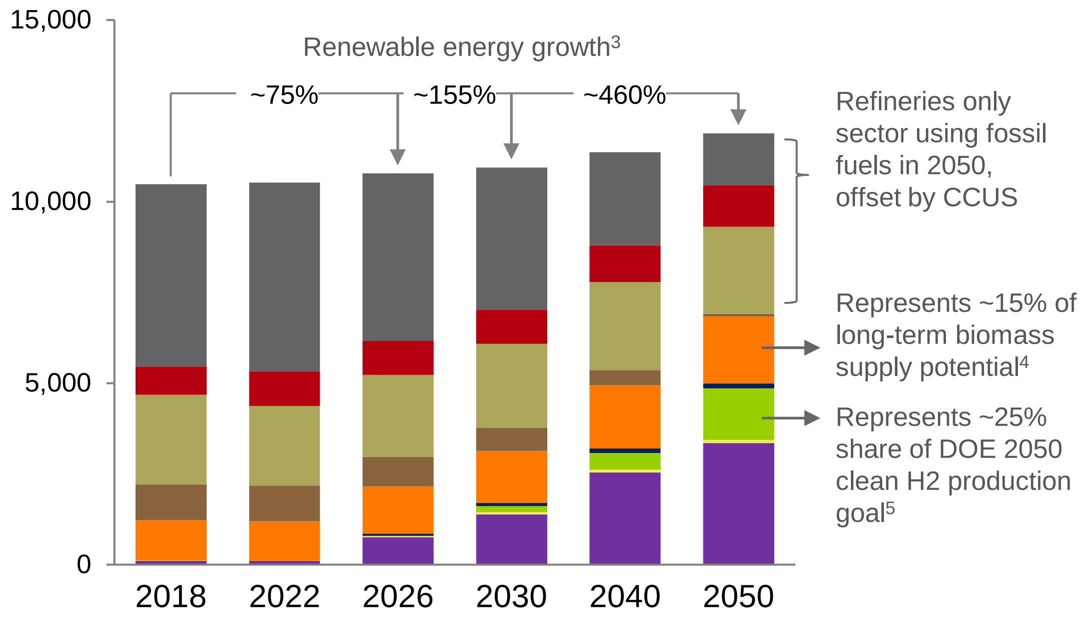
1. Total thermal energy consumption based on EIA 2022 Outlook; forecasted energy mix per BCG analysis 2. Thermal emissions calculated based on emissions intensity of individual fuels; RNG and clean hydrogen assumed to be net zero fuels, biomass assumed to have an emissions intensity of 15 kg CO2e per mmBtu, electricity based on forecasted US electric grid emissions intensity assuming 80% renewables by 2030 3. Renewable energy includes biomass, RNG, hydrogen and electrification (with a decarbonizing grid) 4. Biomass supply potential per DOE and EIA 5. DOE target of 50 million tonnes of clean hydrogen by 2050 translates to 5,690 Tbtu 6. Assumes insufficient net new (V)PPA green electricity supply to meet projected demand for industrial electrification Source: EIA outlook; EIA emissions intensity; BCG analysis

Strategic deployment of clean fuels & abatement technologies will enable emission reduction goals for 2026 and 2030

Thermal energy consumption[1]

TBtu of thermal energy



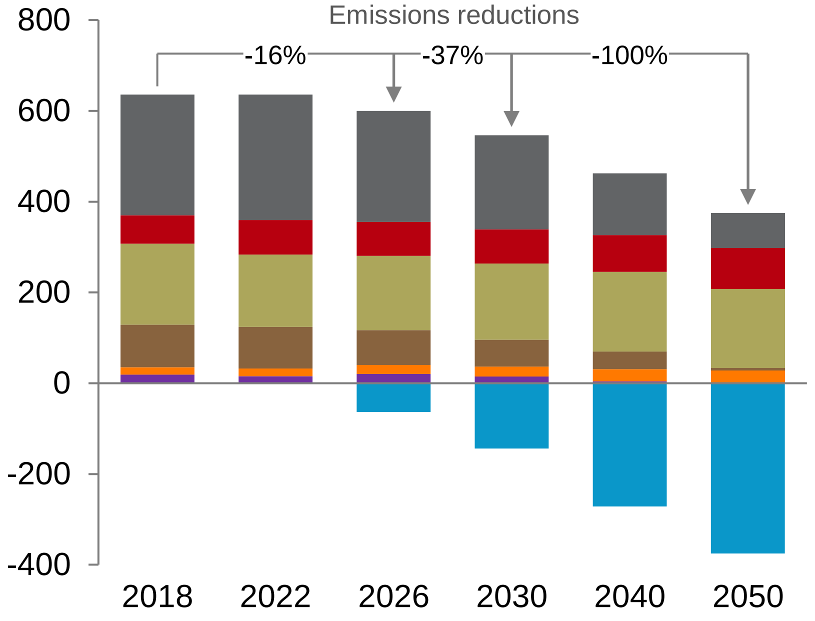
Refineries only sector using fossil fuels in 2050, offset by CCUS

Represents ~15% of long-term biomass supply potential[4]

Represents ~25% share of DOE 2050 clean H2 production goal[5]

Thermal emissions[2]

Million tonnes of CO2e thermal emissions



⬛ Natural gas 🟥 Biofuels & coproducts 🟫 Petroleum & other 🟫 Coal 🟧 Waste Biomass 🟦 RNG 🟩 Clean Hydrogen 🟨 Solar thermal 🟪 Electrification 🟦 CCS

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1. Total thermal energy consumption based on EIA 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 based on forecasted US electric grid emissions intensity assuming 80% and 100% renewables by 2030 and 2050 3. Renewable energy includes biomass, RNG, hydrogen and electrification 4. Biomass supply potential per DOE and EIA 5. DOE target of 50 mmT of clean hydrogen by 2050 translates to 5,690 TBtu Source: EIA outlook; EIA emissions intensity; BCG analysis

Food

Thermal Energy Decarbonization

Decarbonization pathways

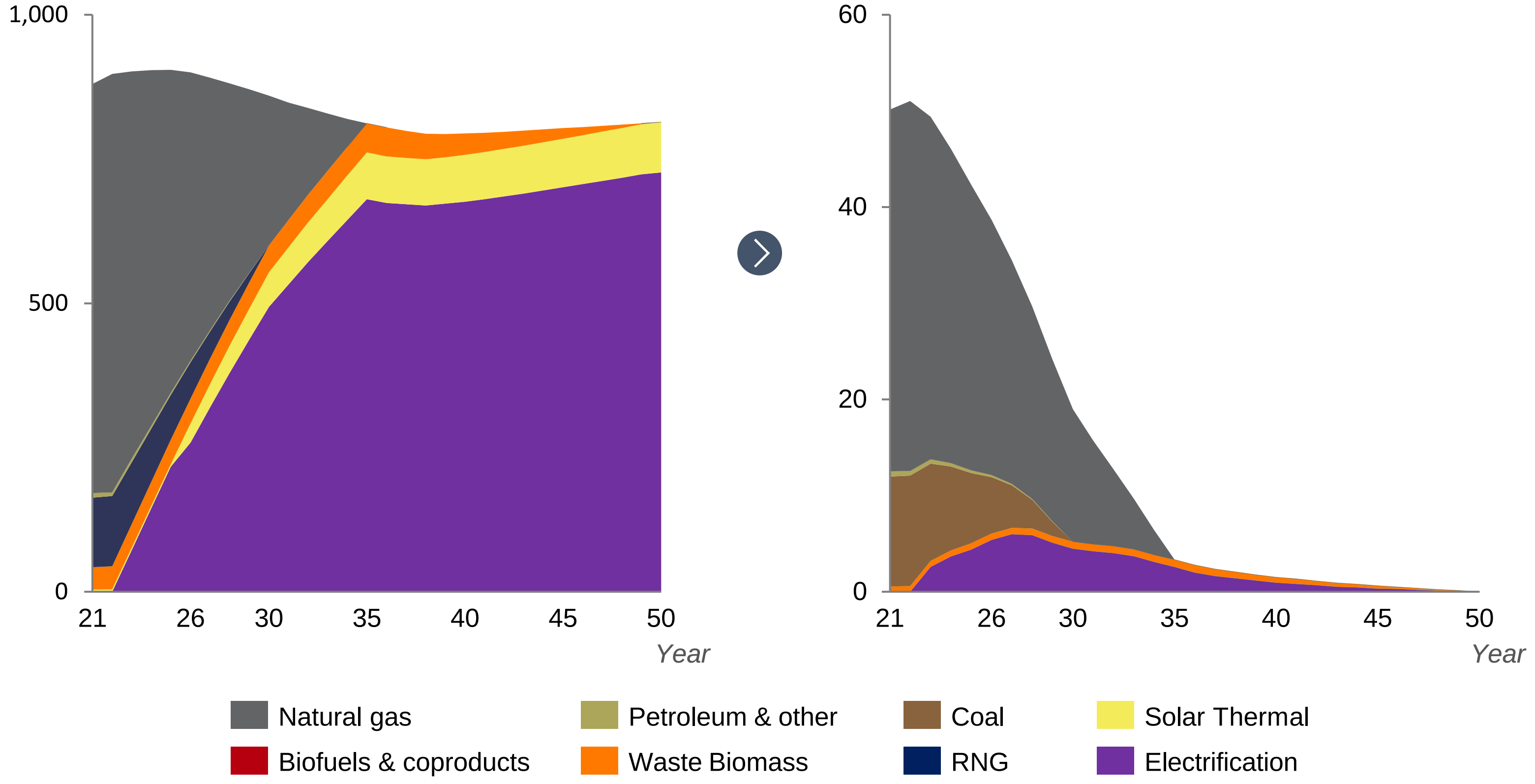
- 97% of industrial heat needs are for applications in the low temperature range (<130ºC), which can be decarbonized on an accelerated timeline with electrification and heat pumps. Natural gas, which combusts at ~1,850ºC is not required for most heat needs in the sector
- Use of fossil coal and petroleum is phased out by 2030, and natural gas phased out by 2035 - replaced with electrification
- Solar thermal energy with battery storage should also be considered, particularly in the US Southwest, and/or when electric heat pumps have a higher cost to generate heat than fossil natural gas (e.g. California)

Thermal energy consumption[1]

Tbtu of thermal energy

Thermal emissions[2]

Millions tonnes of CO2e in thermal emissions



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 assuming 80% and 100% renewables by 2030 and 2050 Source: EIA outlook; EIA emissions intensity; BCG analysis

Paper

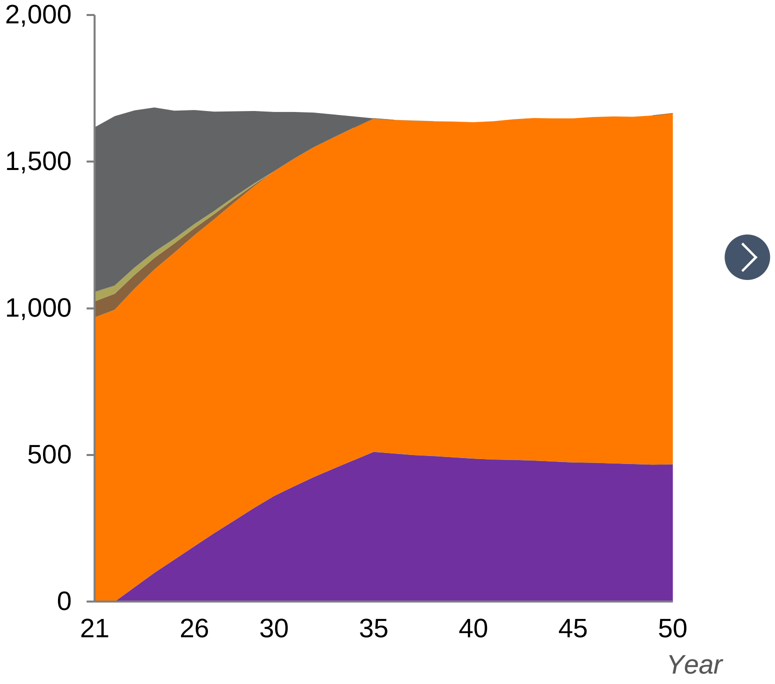
Thermal Energy Decarbonization

Decarbonization pathways

- 94% of industrial heat is in low (75%) and medium (19%) temperature ranges, which can be decarbonized on an accelerated timeline with electrification and heat pumps
- Use of fossil coal and petroleum is phased out by 2030, and natural gas phased out by 2035 – replaced primarily by electrification
- Woody biomass represents majority of current energy consumption; increased efficiency in use of biomass is recommended to reduce released carbon from waste
- The sector generated 111 million tonnes of biogenic CO2e3,4 in 2018 primarily due to combustion; while these emissions are unreported, there is an opportunity for the sector to capture this carbon, equating to a ~15% reduction in total US industrial thermal emissions
- Cost of carbon capture on biomass ranges from \$60-\$120/tonne of carbon with cost reductions expected due to technology maturity; EIA estimates cost of transport and storage at \$12-24/tonne of carbon. The Inflation Reduction Act offers a credit of \$85/tonne of carbon, which may allow a significant portion of the biogenic emissions to be captured economically over the short and medium term (with increasing economic viability over time)

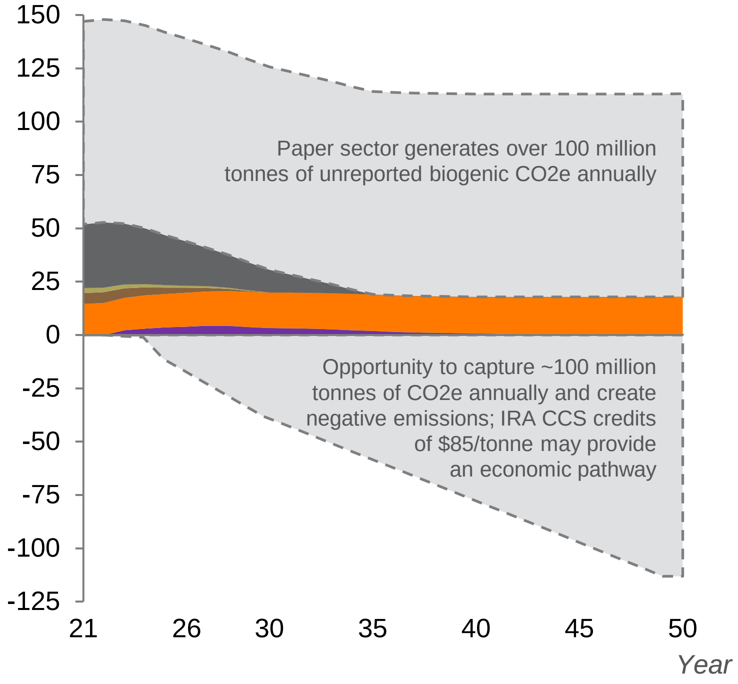
Thermal energy consumption[1]

Tbtu of thermal energy



Thermal emissions[2]

Millions tonnes of CO2e in thermal emissions



Paper sector generates over 100 million tonnes of unreported biogenic CO2e annually

Opportunity to capture ~100 million tonnes of CO2e annually and create negative emissions; IRA CCS credits of \$85/tonne may provide an economic pathway

■ Natural gas ■ Petroleum & other ■ Coal ■ Electrification

■ Biofuels & coproducts ■ Waste Biomass ■ Clean Hydrogen ■ Biogenic CO2e & CCS

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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 assuming 80% and 100% renewables by 2030 and 2050 3. Biogenic emissions are not included in EPA GHGRP stationary combustion emissions since EPA accounts for these fuels as net zero 4. Biogenic combustion is unlikely net zero; the US has lost tree cover annually since 2000; 16% total loss from 2000-2021 equating to 17.4Gt of CO2e Source: EIA outlook; EIA emissions intensity; Global Forest Watch; USDA; industry reports; BCG analysis

Chemicals

Thermal Energy Decarbonization

Decarbonization pathways

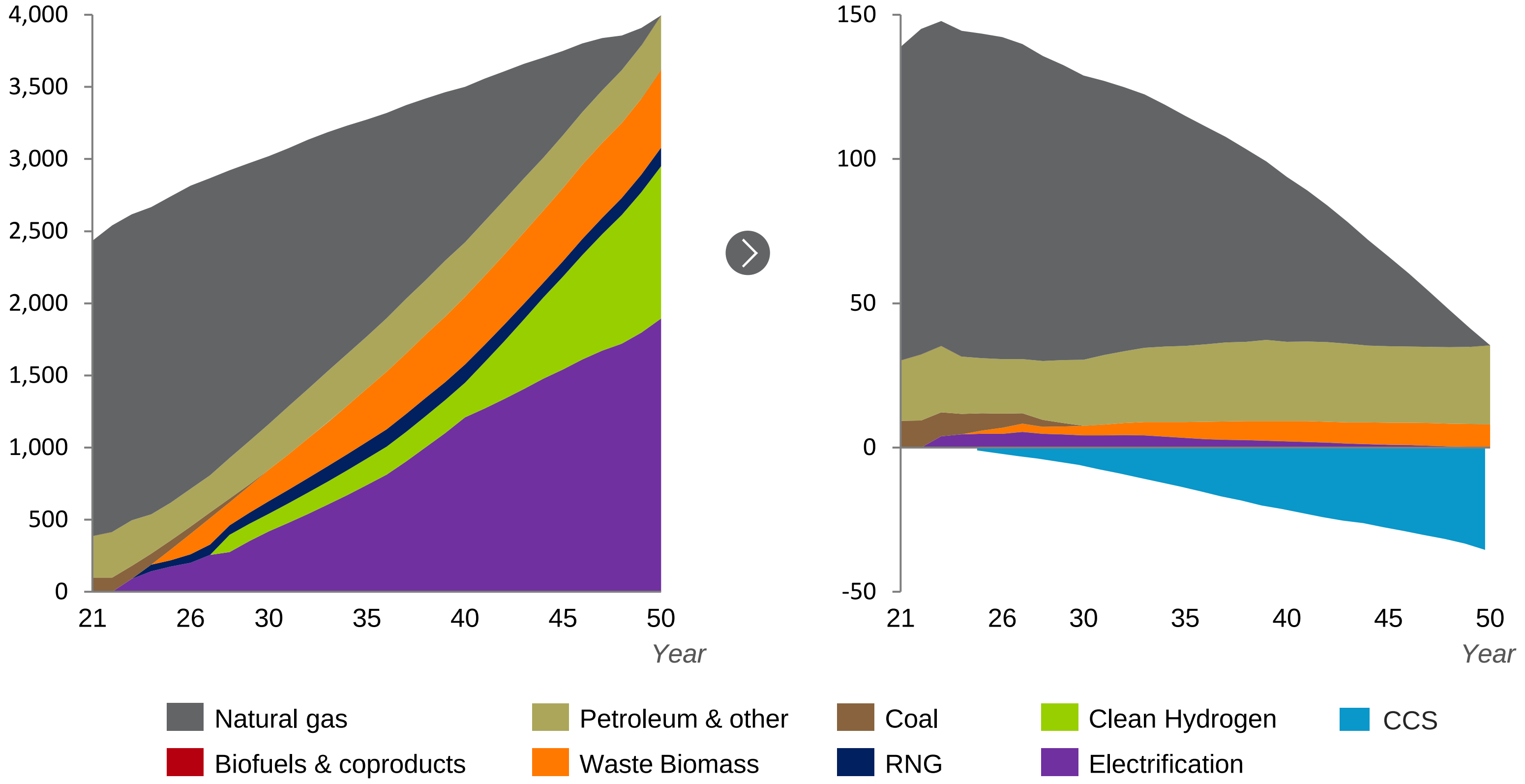
- Use of fossil natural gas is eliminated through 2050
- RNG and biomass are deployed as immediate solutions for medium and high heat applications; Biomass use continues to grow over the forecast period (RNG use is not expected to scale due to RNG supply constraints)
- Electrification of low and medium temperature applications is deployed beginning immediately; electric grid emissions intensity is lower than fossil NG for heat pumps in nearly all states today; can be deployed against <130ºC processes representing ~37% of total thermal emissions in the sector. As heat pumps improve to ~200ºC, higher heat applications can be electrified (~X% of total thermal emissions were generated <200ºC in 2018)
- CCS is expected to be deployed in the Chemicals sector to abate process emissions, which outsize thermal emissions for this sector. CCS deployments can be leveraged to abate the thermal emissions from waste products (included under petroleum & other liquids) and biomass that is combusted for heat

Thermal energy consumption[1]

Tbtu of thermal energy

Thermal emissions[2]

Millions tonnes of CO2e in thermal emissions



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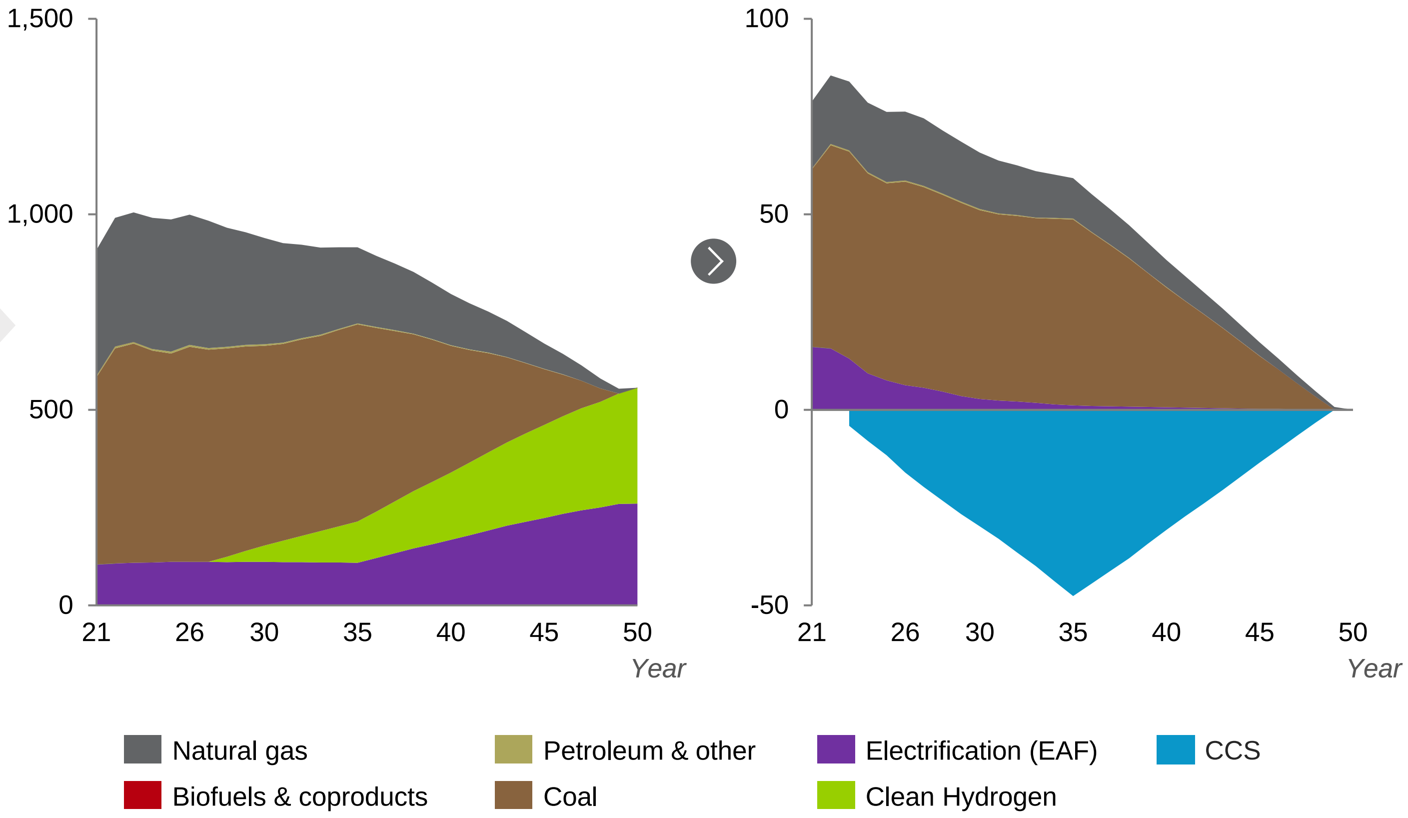
1. Total thermal energy consumption based on EIA 2022 Outlook; forecasted energy mix per BCG analysis 2. Thermal emissions calculated based on emissions intensity of individual fuels; RNG and clean hydrogen assumed to be net zero fuels, biomass assumed to have an emissions intensity of 15 kg CO2e per 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

Iron and Steel

Thermal Energy Decarbonization

Decarbonization pathways

- Primary decarbonizing pathway is transitioning away from blast furnaces (BF) and basic oxygen furnaces (BOF), which use coal, to electrified processes – producing direct reduced iron (DRI) with electricity & clean hydrogen (replaces BF) and using an electric arc furnace (EAF; replaced BOF). This process largely eliminates use of coal. DRI-EAF with green hydrogen is less energy intensive than BF-BOF and total thermal energy consumption is expected to decline as sector transitions
- More than 2/3rds of US steel facilities today use EAFs, and only ~10 facilities remain operating ~14 total blast furnaces - these facilities generated 77% of total thermal emissions for the sector in 2018
- Data suggests current stock of BF-BOFs will require upgrades from 2023-2036 period, however, due to various sector specific factors including insufficient DRI supply to produce high quality steel, the remaining BF-BOFs are not expected to convert to DRI-EAF w/ green hydrogen in the short and medium term. The decarbonization pathway model delays converting BF-BOFs to 2036 and converts all ~14 BF-BOFs by 2050.
- In the interim period, the sector should deploy CCS to capture emissions while the transition to DRI-EAF w/ green hydrogen occurs, upon which CCS can be phased out
- This sector also combusts natural gas for heat in upstream and downstream heat applications (e.g. hot rolling); use of fossil combustion can be displaced through 2050 with green hydrogen



Thermal energy consumption[1]

Tbtu of thermal energy

Thermal emissions[2]

Millions tonnes of CO2e in thermal emissions

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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 outlook; EIA emissions intensity; BCG analysis

Cement

Thermal Energy Decarbonization

Decarbonization pathways

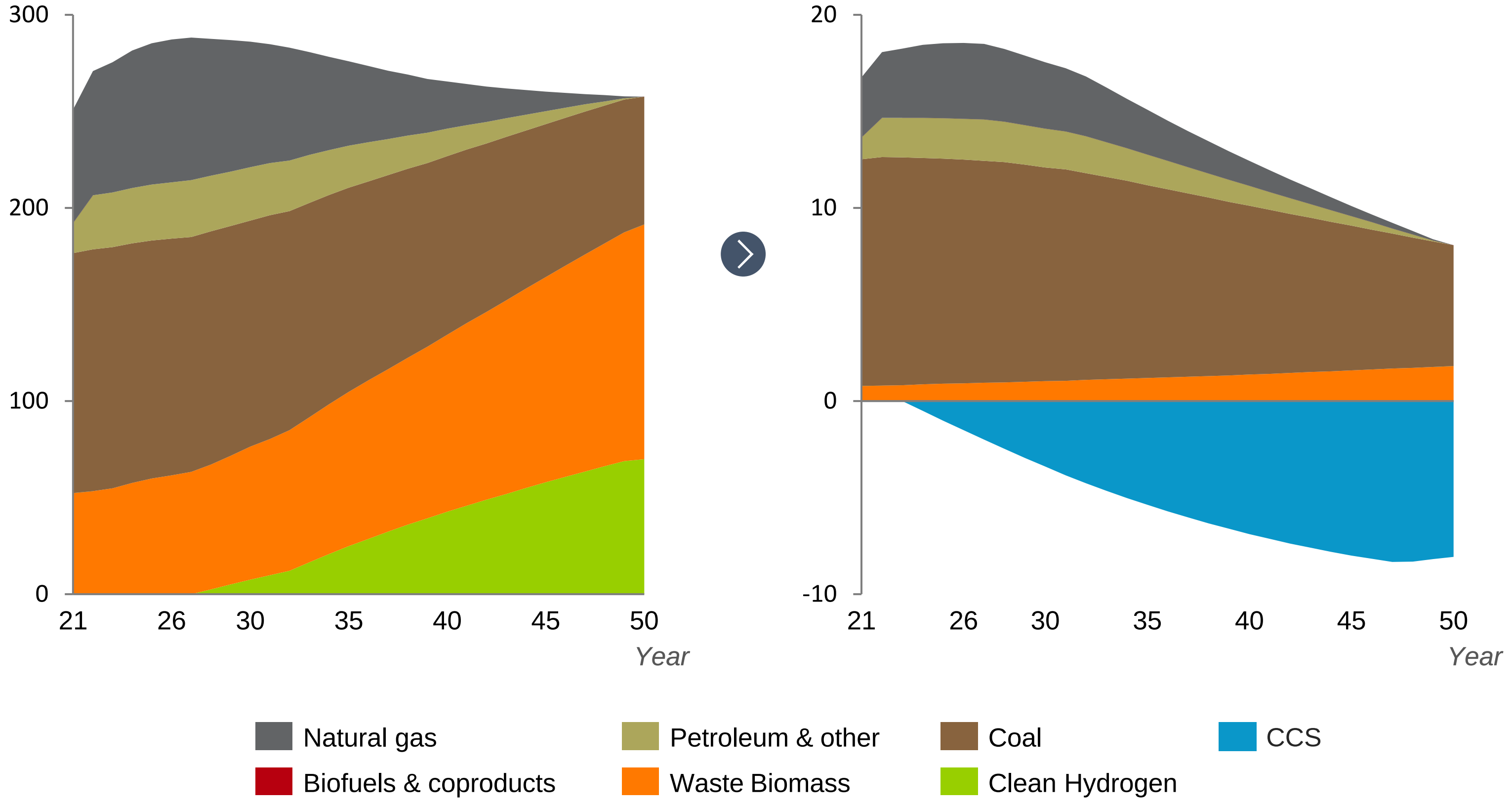
- The Cement sector creates more process emissions than thermal emissions, and both emissions are typically emitted in the same air stream. As a result, it is difficult to distinguish between process and thermal emissions and the EPA GHGRP flight database does not identify meaningful thermal emissions. 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]

Tbtu of thermal energy

Thermal emissions[2]

Millions tonnes of CO2e in thermal emissions



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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

Refineries*

Thermal Energy Decarbonization

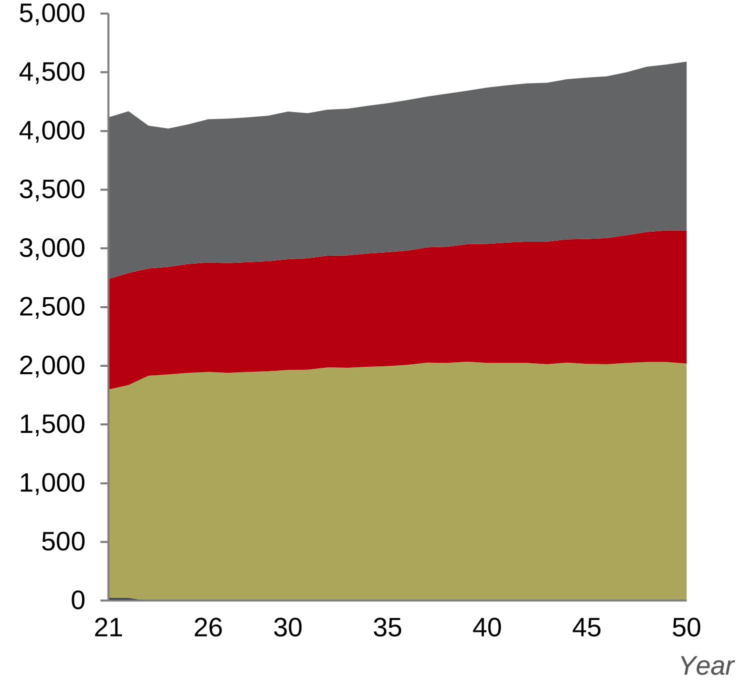
**For consistency across sectors, EIA energy consumption forecast for refineries is used below; however, refinery energy consumption is likely to decline in the 2030-2050 period as fossil fuel usage is reduced globally. Accordingly, overall thermal energy consumption, thermal emissions, and related carbon capture needs are expected to be lower than projected below (using EIA energy forecast)*

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

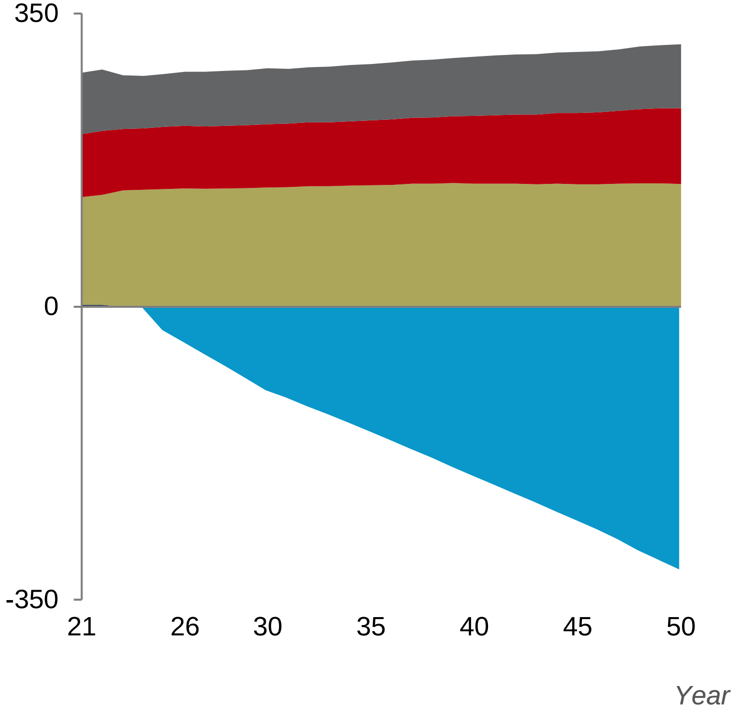
Thermal energy consumption[1]

Tbtu of thermal energy



Thermal emissions[2]

Millions tonnes of CO2e in thermal emissions



⬛ Natural gas 🟥 Biofuels & coproducts 🟨 Petroleum & other 🟫 Coal 🟦 CCS

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 outlook; EIA emissions intensity; BCG analysis

Appendix: Supporting Materials

US Industrial Thermal Energy Needs & Emissions

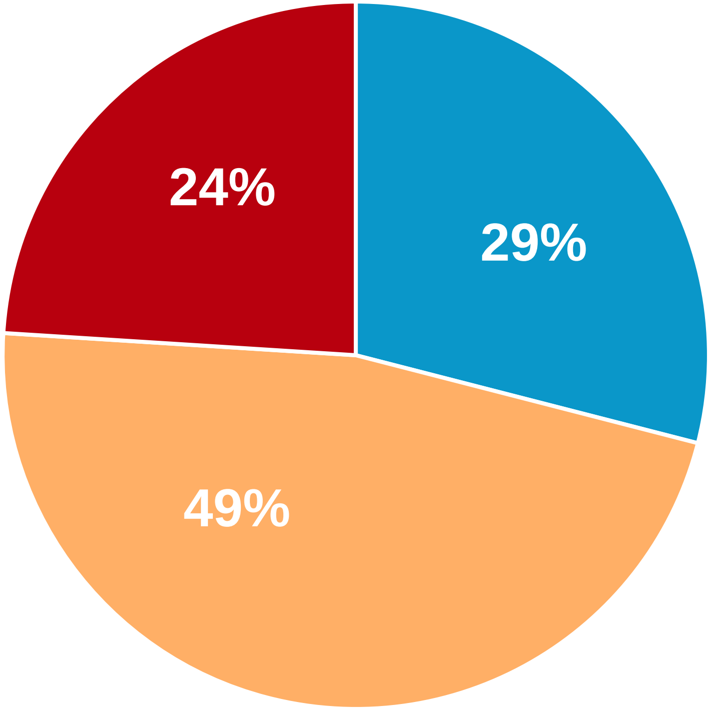
US industrial thermal energy use

76% of industrial heat is needed for low & medium heat applications (<500ºC); only 24% is needed for high heat (>500ºC)

Industrial thermal energy consumption by heat temperature range

High heat processes (24% of thermal energy use) are often bespoke applications, with fewer economic cases for conversion to available renewable thermal energy

Upcoming clean Hydrogen supply (post IRA incentives) will offer cost competitive renewable thermal energy for **high heat**



Electric heat pumps are effective **under ~130ºC** and can target ~29% of industrial thermal energy use

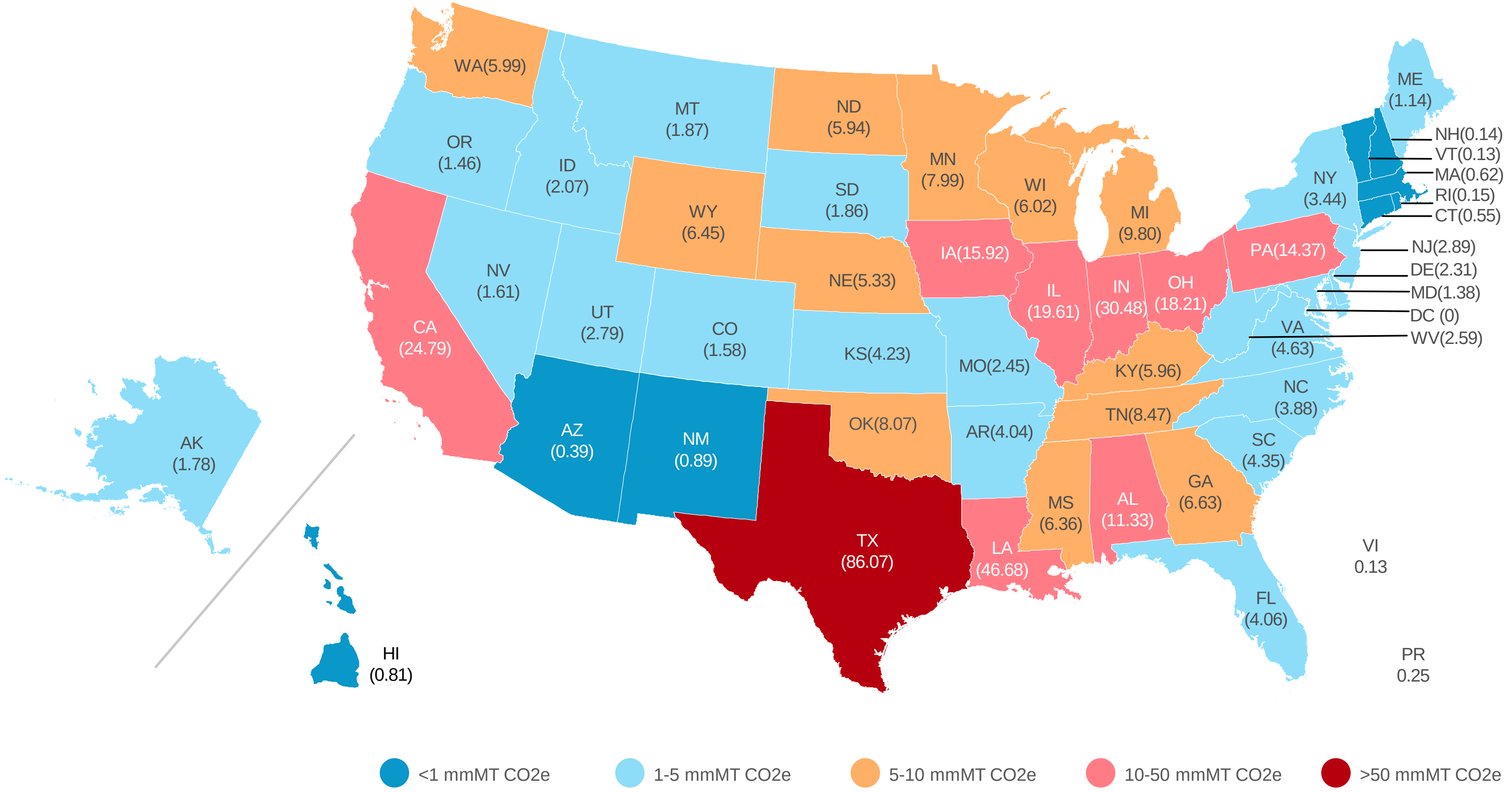
Low and **medium** heat applications are easier to convert to renewable thermal energy and abate emissions

● Low-temperature range (<130ºC) ● Mid-temperature range (130-500ºC) ● High-temperature range (>500ºC)

Note: Cumulative thermal energy only for manufacturing industries, excludes energy use from oil and gas extraction, mining, and waste facilities Source: NREL Manufacturing Thermal Energy Use in 2014

US industrial thermal emissions

Thermal emissions are concentrated in the Gulf Coast, the Midwest, & California



US thermal emissions footprint is driven by the geographic concentration of industrial activity for key sectors:

- Refineries
- Chemicals
- Iron & Steel
- Paper
- Food
- Cement

Source: US EPA GHG Inventory Flight Database 2018; captures large emitter emitting >25K tonnes of CO2e per year

Most industrial sector applications occur at low & medium heat temperatures

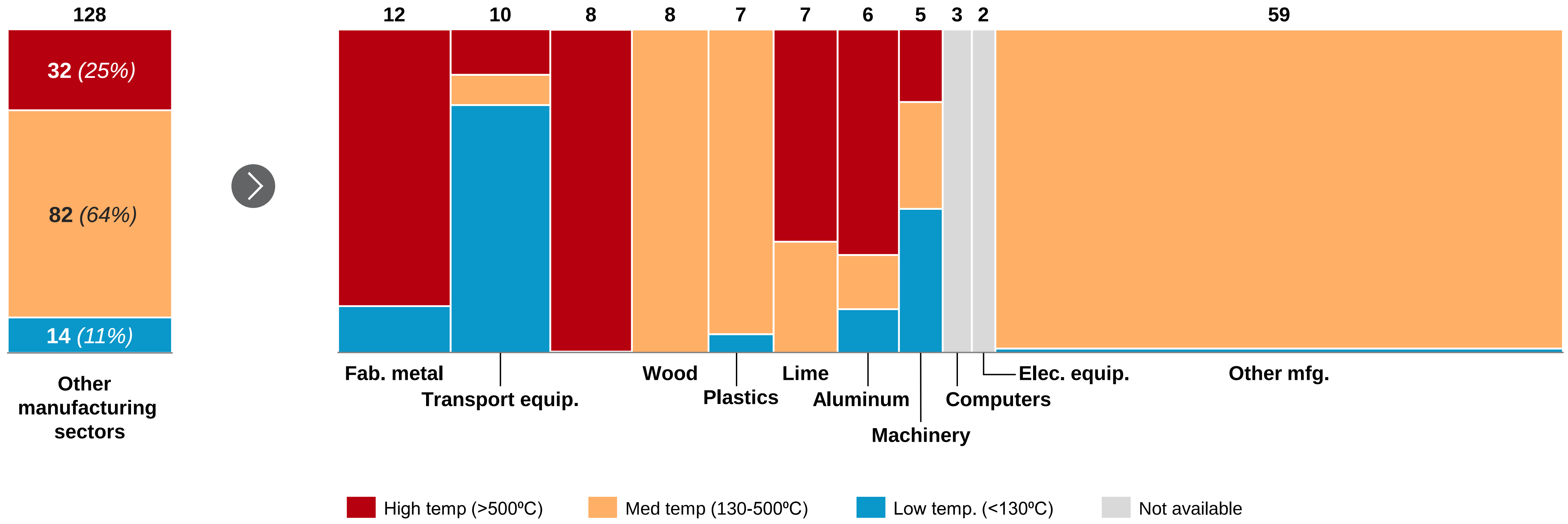
	2018 Emissions (Million Tonnes of CO2e)	Heat Processes Applications
Sector		🔵 Low heat *<130℃* 🟠 Medium heat *130℃ - 2000℃* 🔴 High heat *>2000℃*
Petroleum	276	🟧 Reactors (260-480ºC) 🟧 Distillation (150-370ºC)
Chemicals	152	🟥 Reactors (500-900ºC) 🟧 Distillation (100-300ºC) 🟧 Drying (150-200ºC)
Iron & Steel	102	🟥 Pelletizing (1000-1200 ºC) 🟥 Hot rolling; steel (1000-1300 ºC) 🟥 Blast Furnace; Iron (2200-2300ºC) 🟥 Basic Oxygen Furnace; Steel (1600ºC) 🟥 Electric Arc Furnace; Steel (1800ºC)
Food	50	🟧 Cooking (95-200ºC) 🟦 Sterilizing (110-120ºC) 🟦 Drying (30-90ºC) 🟦 Pasteurizing (60-140ºC) 🟦 Washing (60-90ºC)
Paper	33	🟧 Wood Processing (200ºC) 🟦 Drying (70-150ºC) 🟧 Chemical Prep. (60-200ºC) 🟦 Stock Steaming Prep. (60-150ºC) 🟦 Stock Steaming Prep. (60-150ºC) 🟥 Re-causticizing(800-1200ºC)
Cement	17	🟥 Precalciner (1600ºC) 🟥 Kiln Combustion(1200-1500ºC)

Source: DOE; research reports, papers, and studies; BCG analysis

Other Manufacturing Sectors

Estimated Thermal Emissions by Temperature

Estimated share of 2018 thermal emissions by temperature range (Million Tonnes of CO2e)



Notes: Energy usage by temperature range was used as a proxy for thermal emissions by temperature range, most of industrial heat is fueled by natural gas across low, medium, and high temperature processes; certain sector emissions (e.g. Iron & Steel, Cement) may skew more towards the higher temperature range as these sectors combust fuels with higher carbon intensity (e.g. coal) Source: NREL Manufacturing Thermal Energy Use in 2014 (provides thermal energy use by temperature); EIA Outlook 2019 (provides 2018 energy consumption by fuel); EPA emissions intensity by fuel

Appendix: Supporting Materials

Renewable Thermal Technology Prioritization

Priority technologies have significant abatement potential / Hydrogen & RNG are versatile fuels with the highest emissions abatement potential

	Max Temp.	Applicability to Heat Processes			Abatement Potential
Renewable Thermal Technology	ºC	*Low temp (42%)*	*Med temp (36%)*	*High temp (22%)*	
Geothermal	95	☑			Low
Electric heat pump	160	✅	☑	☑	Medium
Nuclear[1]	300+		☑		Low
Waste Biomass	500	✅	✅	☑	Medium-High
Solar thermal	700	✅	✅	☑	Medium-High
Electric resistance	1,800	✅	✅	☑	Medium-High
Electric arc heating[2]	1,800			☑	Low
Power to gas[3]	1,950	✅	✅	✅	High
Renewable natural gas	1,950	✅	✅	✅	High
Electromagnetic heating[2]	2,000			☑	Low
Clean hydrogen	2,100	✅	✅	✅	High
Biodiesel	2,200	☑	☑	✅	Low
Bioethanol	2,200	☑	☑	✅	Low
Thermal energy storage[4]	1,500	✅	✅	☑	Medium-High
CCS	-	☑	✅	✅	Medium-High

✅ High applicability ☑ Moderate applicability

- RNG and hydrogen can serve nearly all industrial heat applications, and can largely be deployed within current natural gas infrastructure
- Electric heat pumps can serve low temperature applications representing 42% of thermal energy use
- Waste biomass and solar thermal technologies can serve low and medium heat processes
- Electric arc and magnetic heating serve niche high heat applications
- CCS requires scale and is effective in ~high heat applications with higher CO2e concentration in the emissions stream

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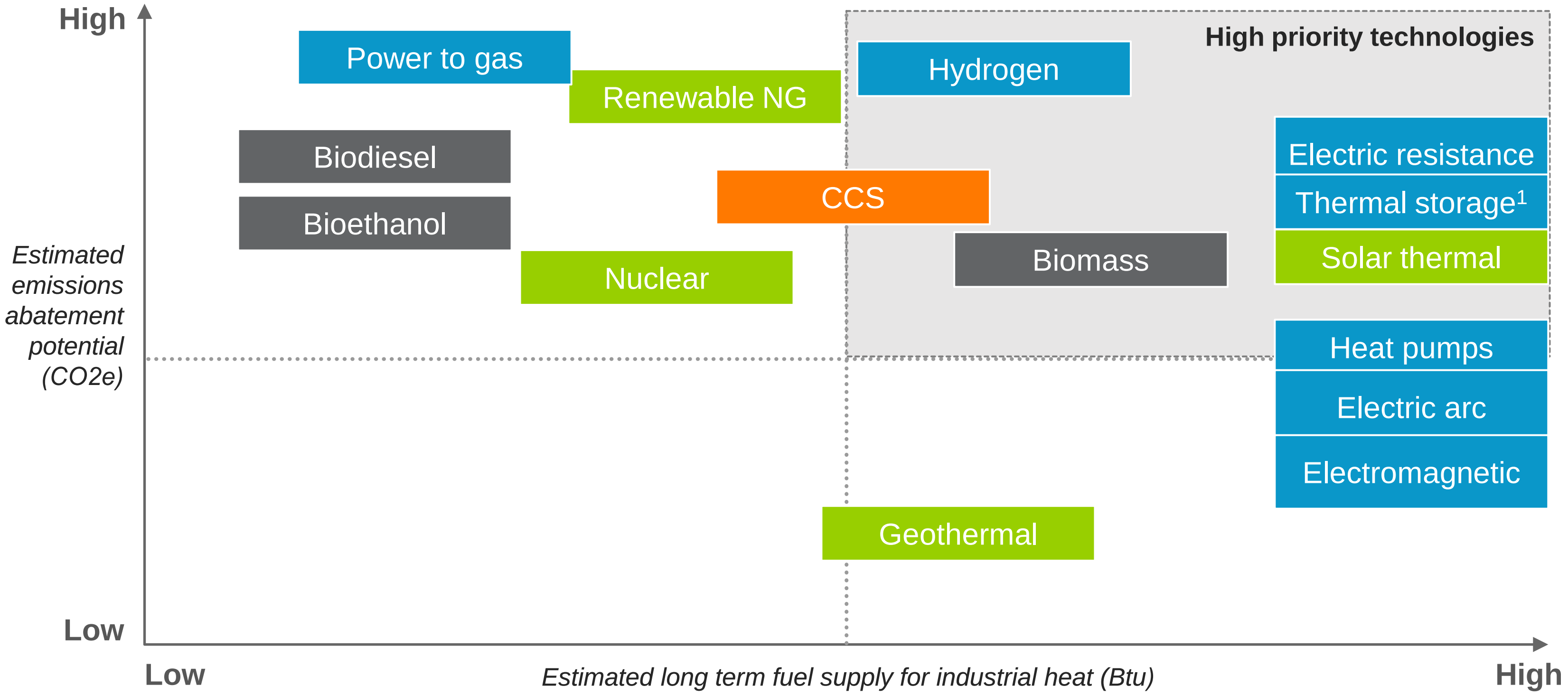
1. Nuclear heating has limited near and medium-term potential due to proximity requirements of nuclear facilities to industrial facilities for heat transfer purposes 2. Niche high heat applications 3. Green hydrogen, considered a power to gas technology, is listed separately; 4. Combined with electric resistance heating Source: DOE; research reports, papers, and studies; BCG analysis

Availability of fuel supply for industrial heat use is another key driver in identifying the highest priority technologies

Decarbonization technologies: Emissions abatement potential vs. fuel availability for industrial heat



Long term emissions intensity

- 🟩 Net zero / near net zero
- 🟦 Net zero with decarbonized grid
- ⬛ Unlikely to be net zero
- 🟧 Carbon capture

- Electrification and Solar technologies offer unconstrained fuel supply and long-term sustainable NZ fuel potential (with grid decarbonization)
- RNG & hydrogen can serve nearly all industrial heat applications and offer sustainable NZ fuel potential, however, both fuels are supply constrained
- Biomass offers lower emissions than NG but is unlikely to be a sustainable NZ fuel, and must be paired with CCS to attain net zero

1. Combined with electric resistance heating Source: DOE; research reports, papers, and studies; BCG analysis

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Cement

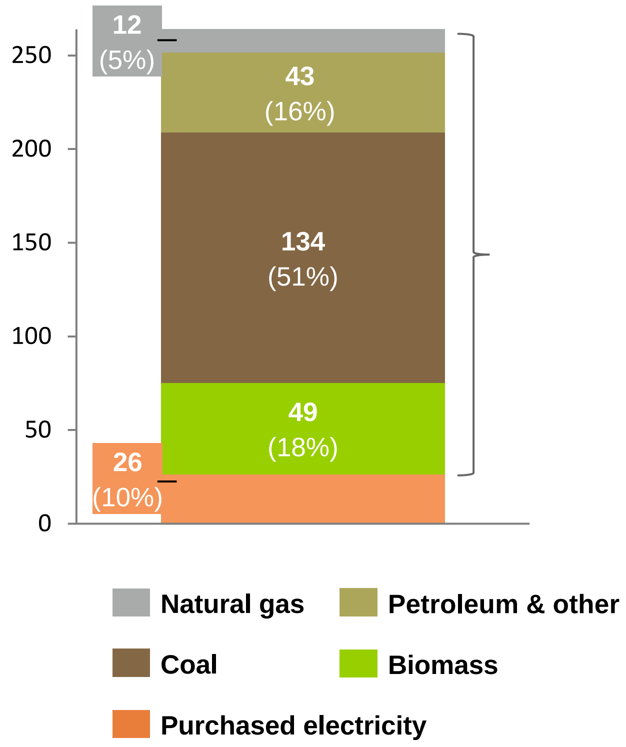
Sector Perspectives

RENEWABLE
THERMAL
COLLABORATIVE

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

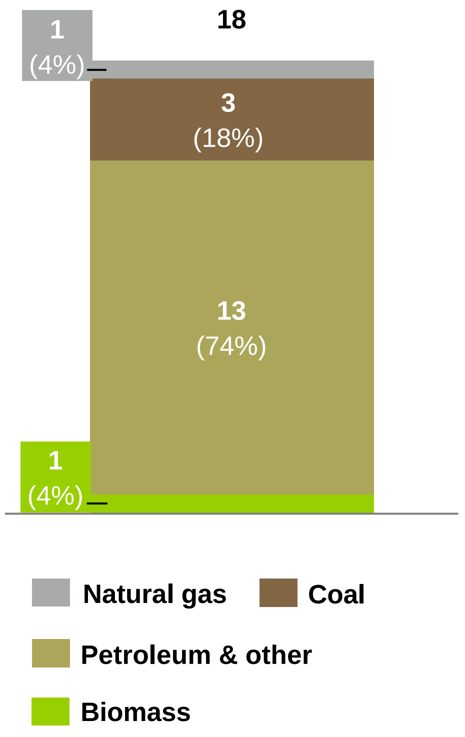
Total energy consumption (2018)[1]

Trillion Btu



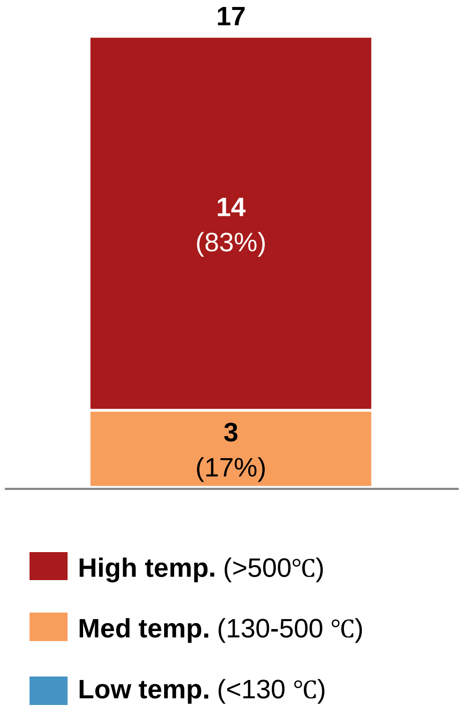
Thermal emissions (2018)[2]

Million Tonnes of CO2e



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

Million Tonnes of CO2e

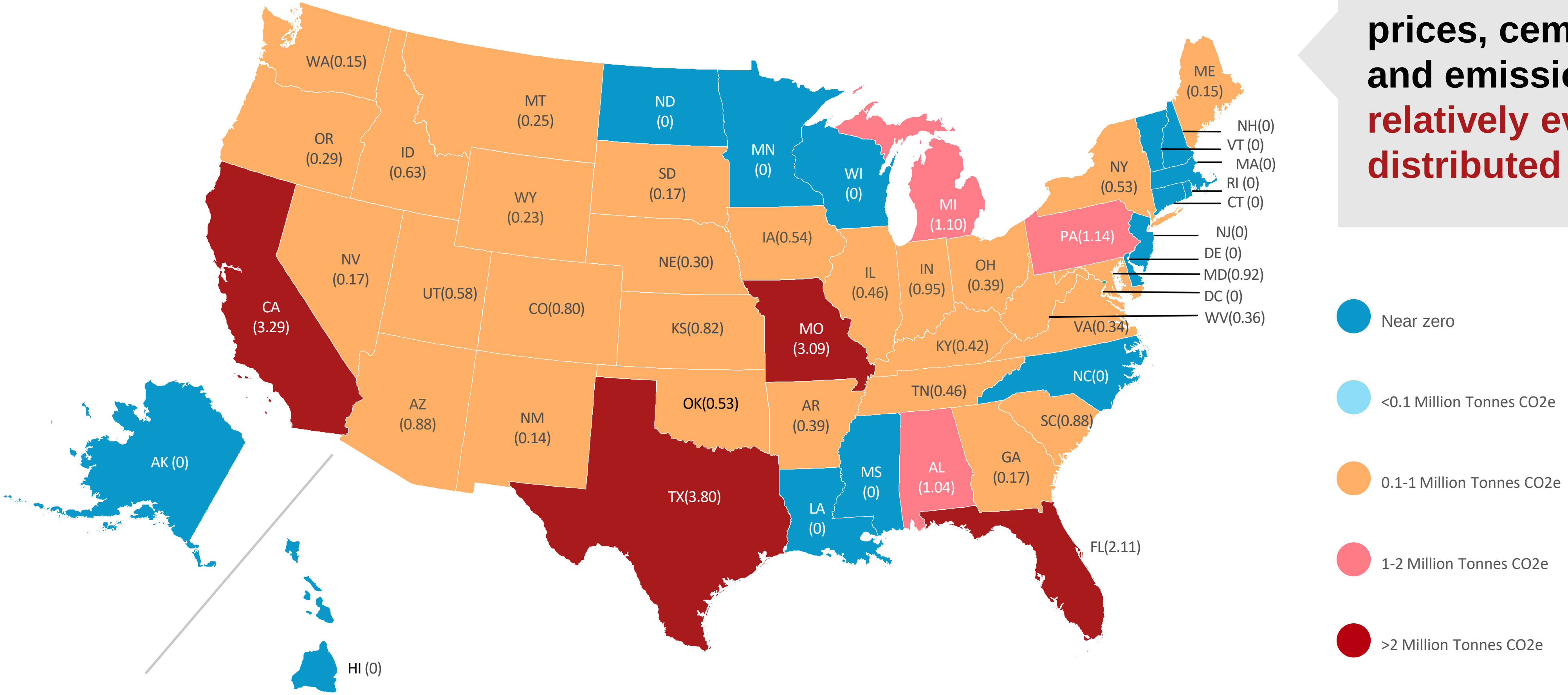


[1] EIA Annual Energy Outlook 2019 [2] Based on AEO 2019 Outlook for 2018 energy consumption by combustible fuel (excludes purchased electricity) and EPA emissions intensity of individual fuels; RNG and green hydrogen are considered net zero, biomass is estimated at 15 kg CO2e/mmBtu [3] Calculated using 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 CO2e/year

Key thermal applications in cement manufacturing occur at high temperatures

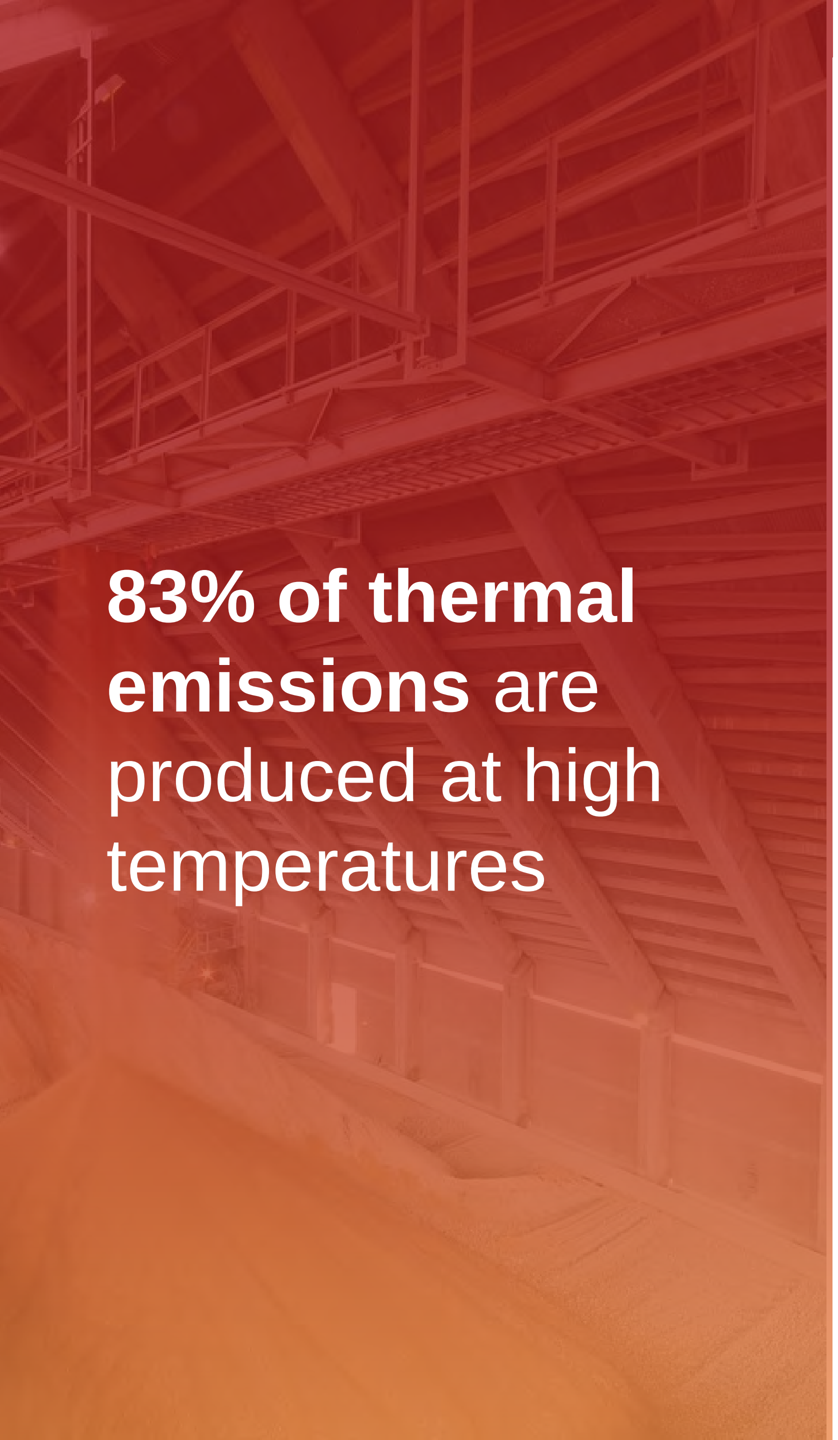
Pre-Calciners | ~600-700 ºC

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) the rawmix, which reduces the heat load of the rotary kiln.

Rotary Kilns | ~1200-1500 ºC

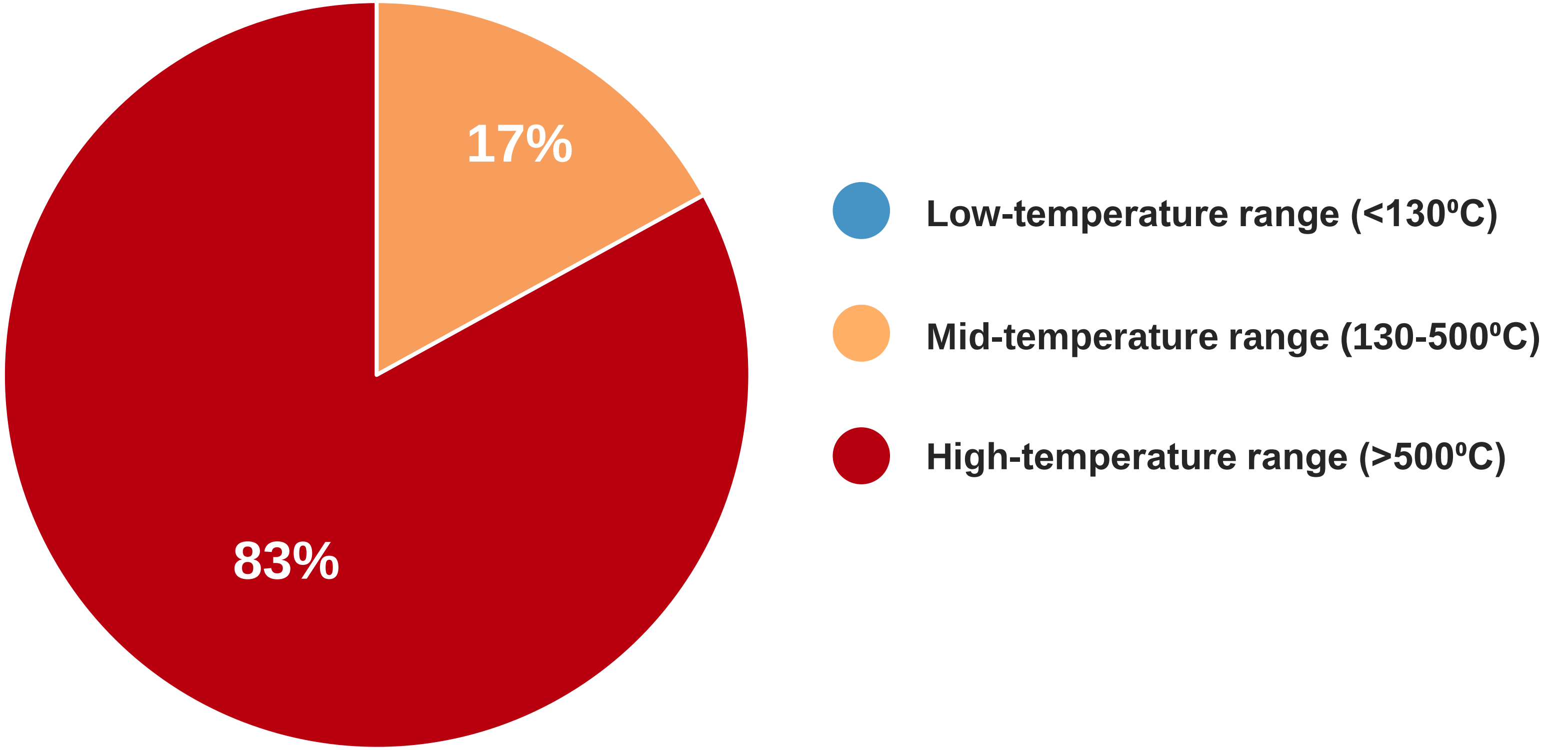
Once raw materials such as limestone and clay are grinded into a fine powder called raw meal, it is heated in a cement **kiln** to form clinker, which are round lumps or nodules. The clinker is then ground to a powder and mixed with gypsum to create cement.

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]



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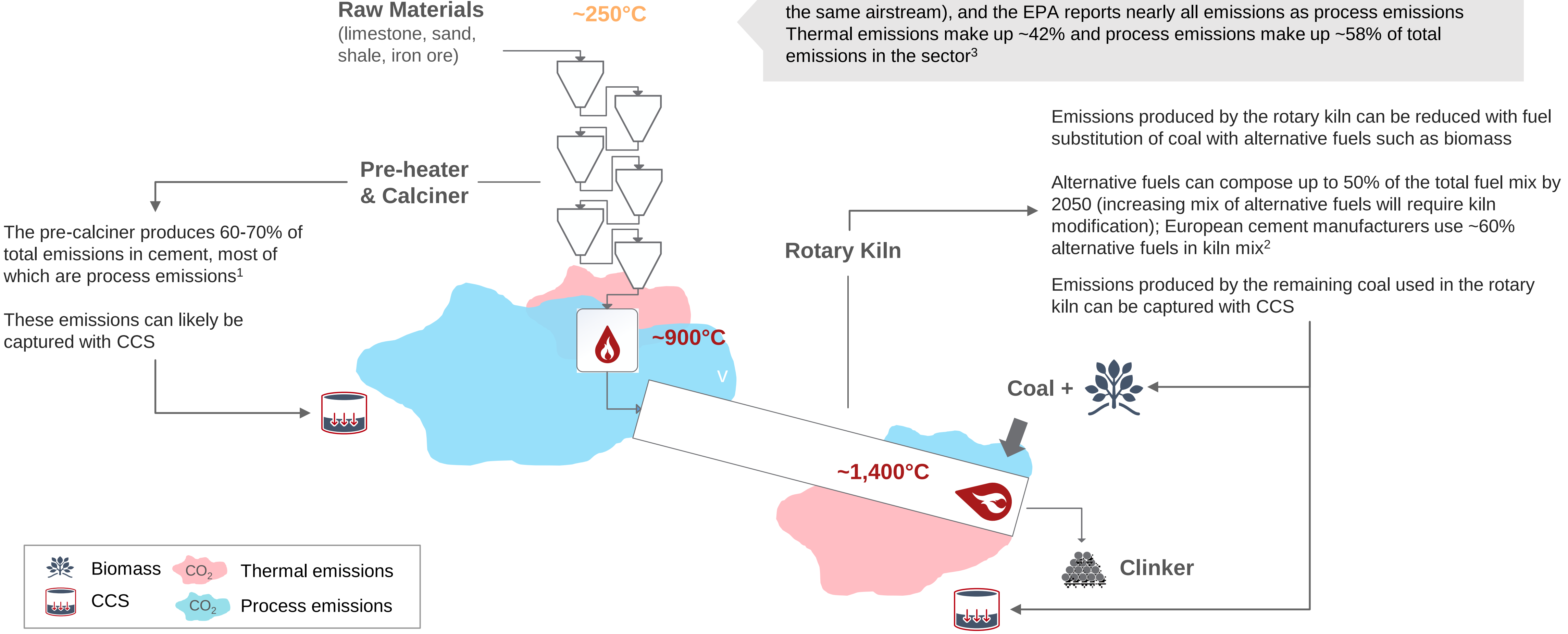
[1] Calculated using the NREL MECS survey data for thermal energy use (2014)

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]

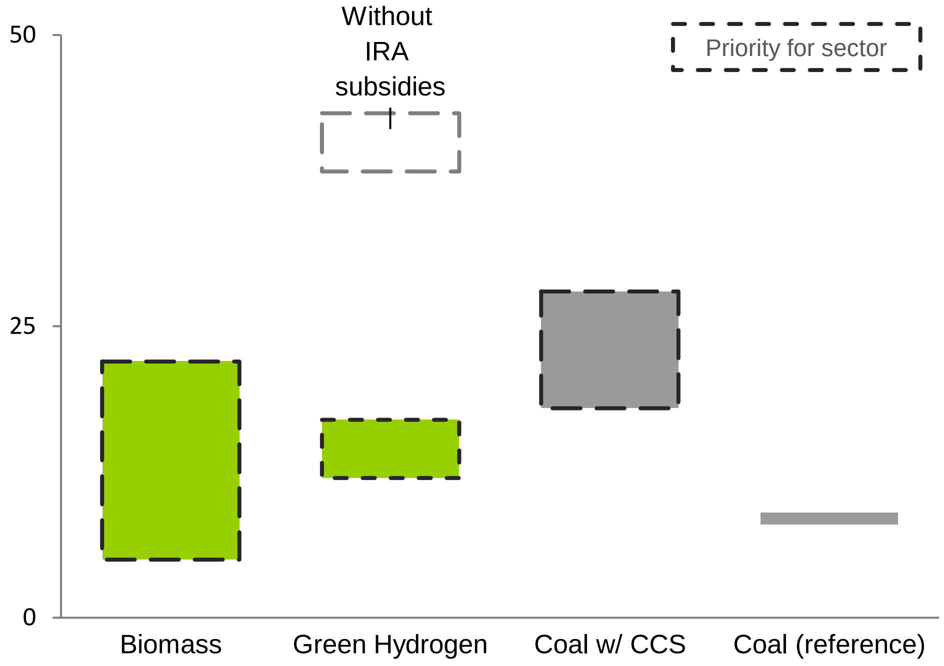
Emissions produced by the remaining coal used in the rotary kiln can be captured with CCS

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

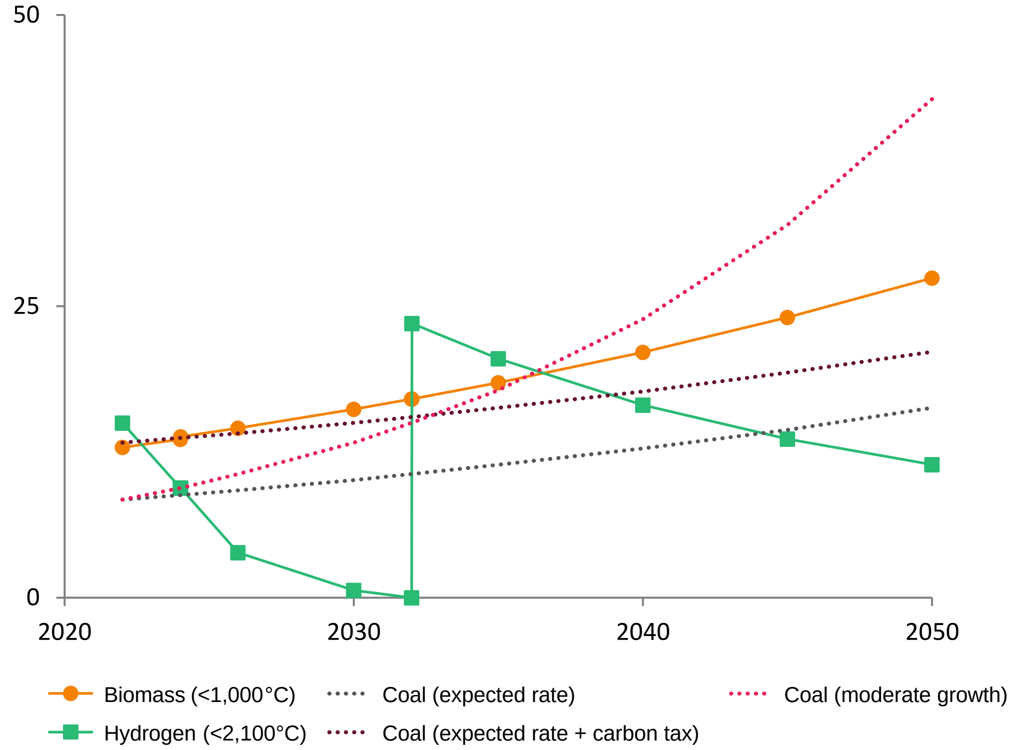
2022 LCOH for relevant technologies[1]

($/MMBtu)



Projected LCOH for relevant technologies[1]

Average US LCOH ($/MMBtu)



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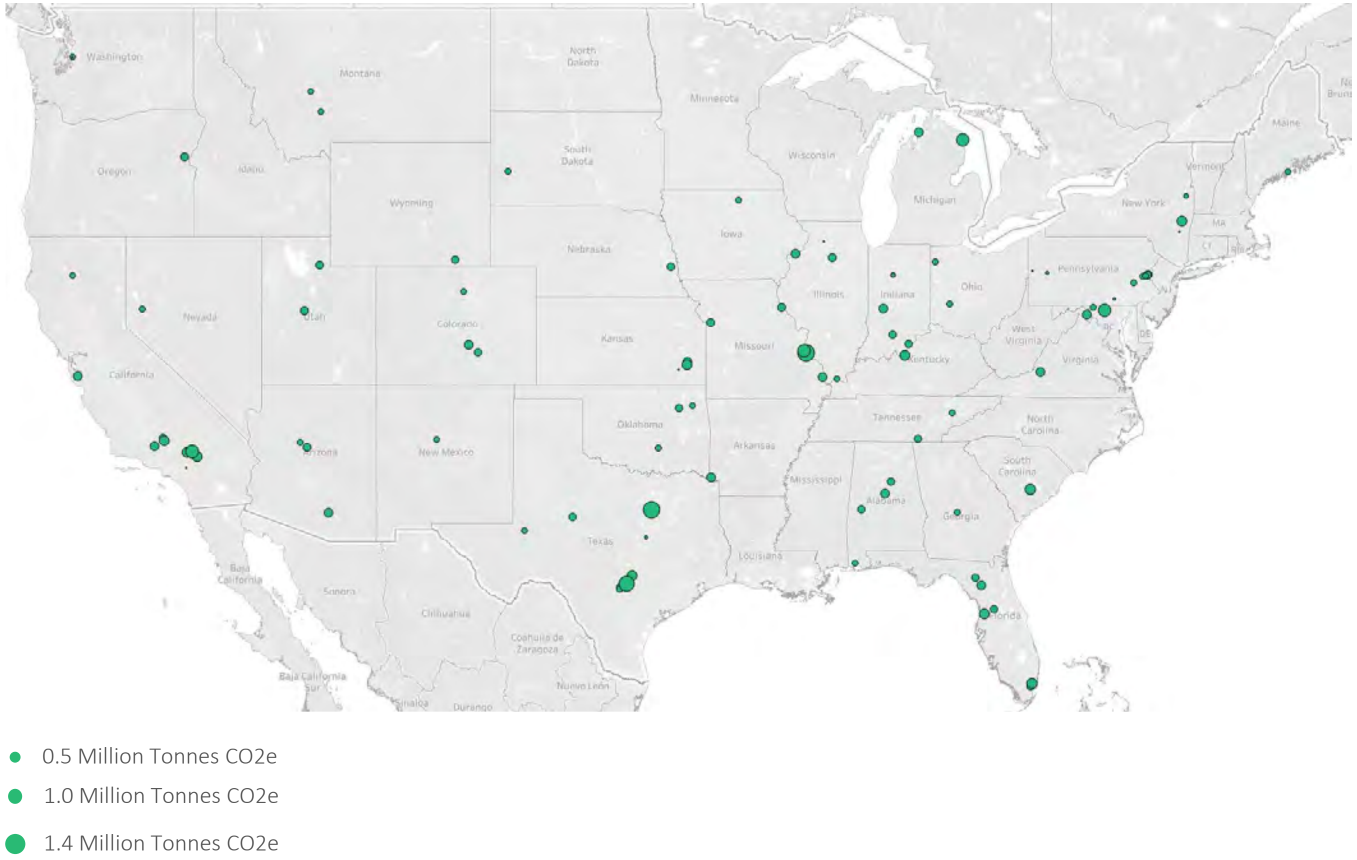
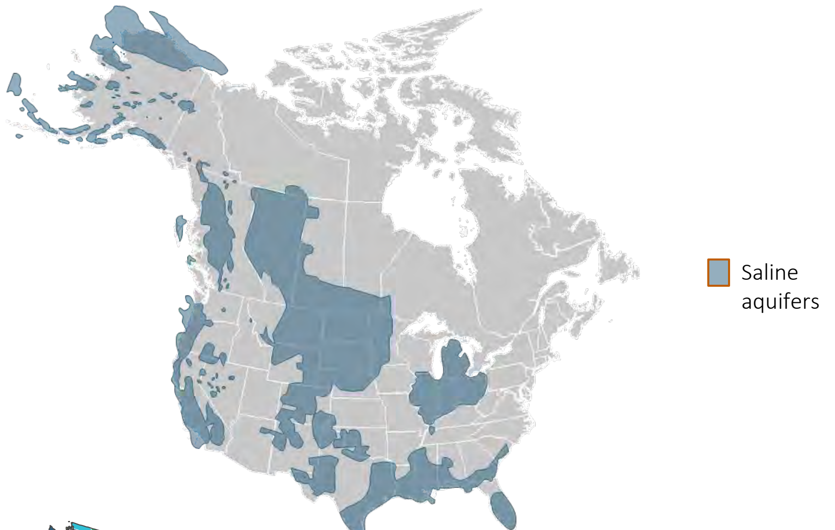
1. LCOH compares project lifetime costs against lifetime energy produced; costs include capital expense of equipment, fuel costs, and maintenance expense assumptions over the usable life of the energy asset. Electricity and natural gas pricing is based on national weighted average wholesale industrial 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

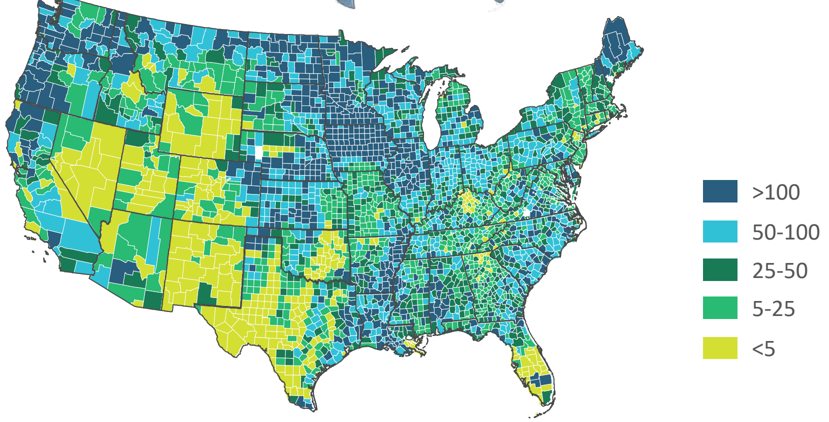
US Cement thermal emissions by zip code[1]



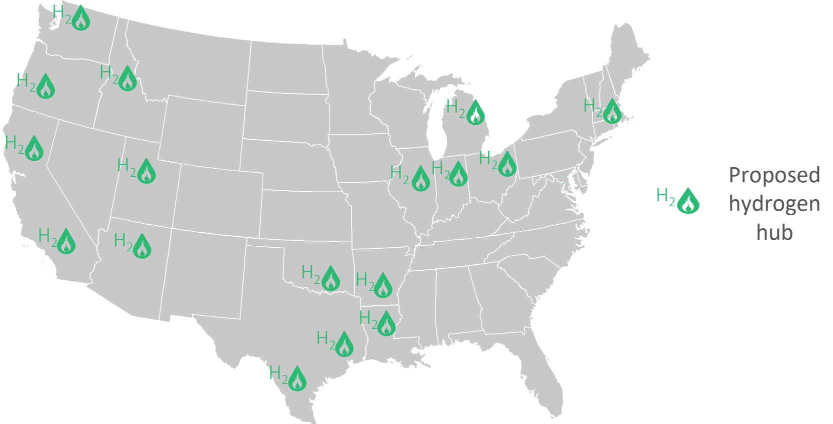
Carbon sequestration availability[2]



Biomass supply[3]



Proposed hydrogen hubs[4]



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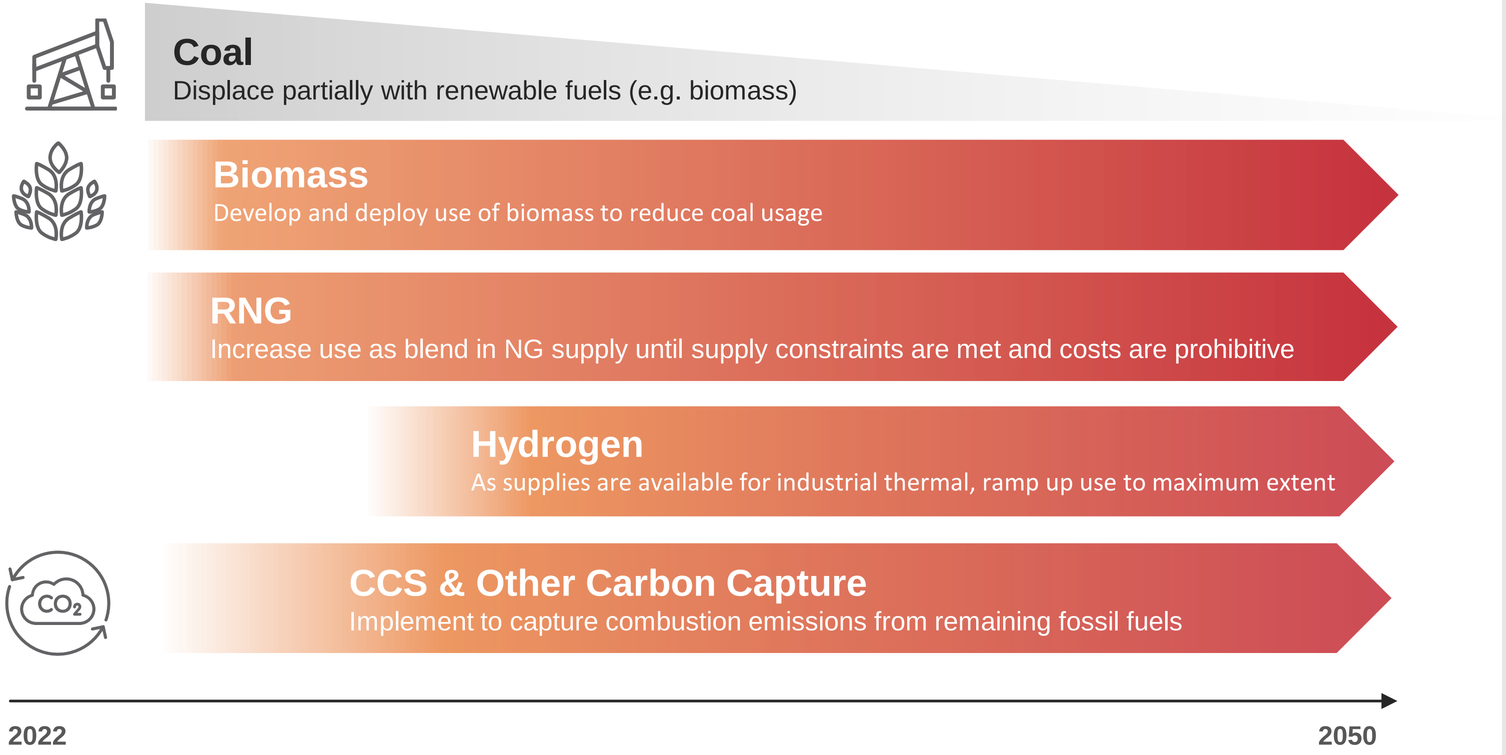
1. EPA GHGRP Inventory FLIGHT Database (2018); captures actual onsite reported emissions for large emitters emitting >25K tonnes of CO2e per year 2. USGS, NETL NATCAB 3. NREL Biofuels Atlas 4. CSIS (2022)

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

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

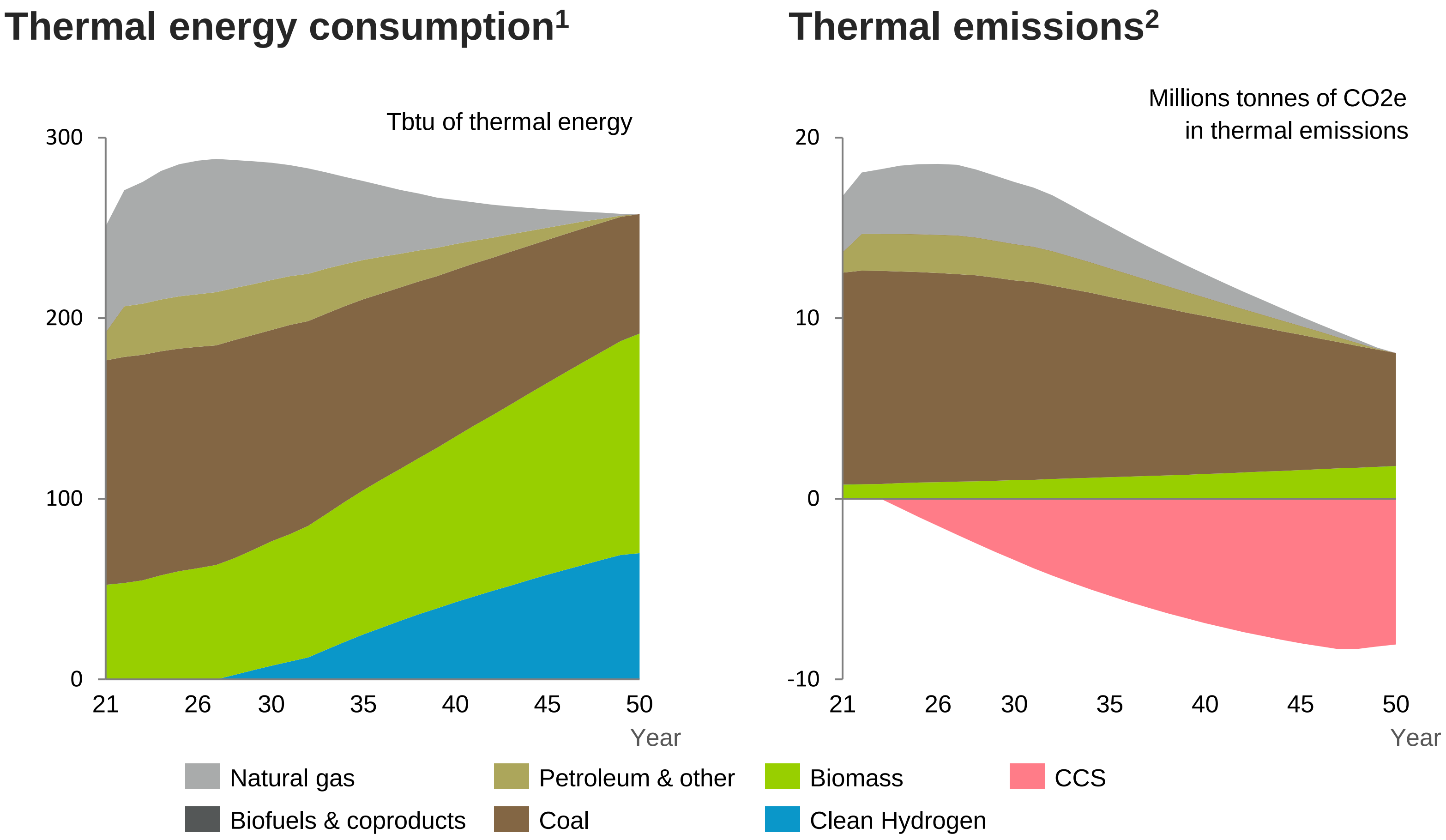
Thermal decarbonization pathways

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]

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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

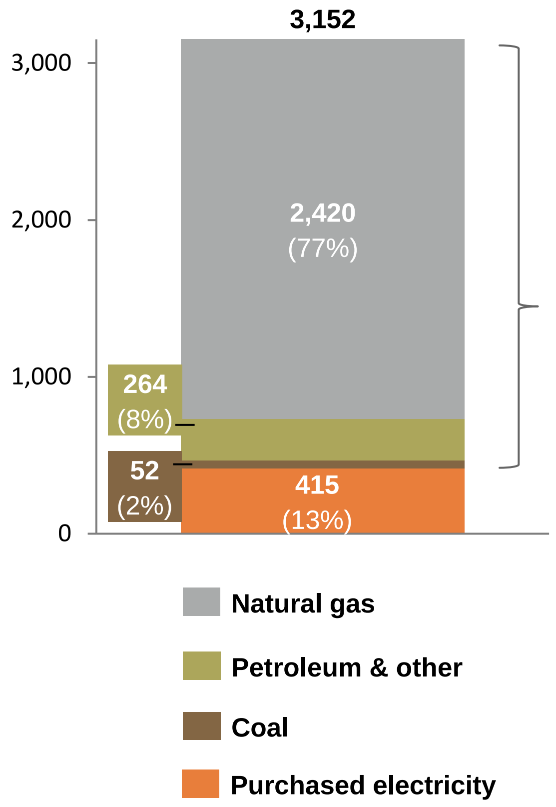
Chemicals

Sector Perspectives

77% of energy consumption is driven by natural gas and 74% of thermal emissions are produced at low and medium temperatures

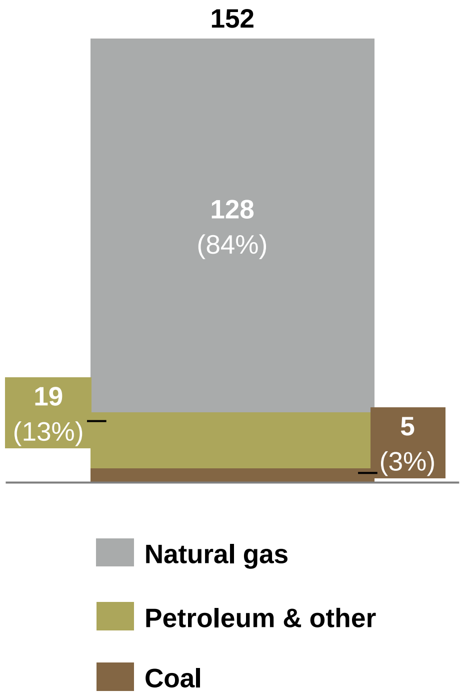
Total energy consumption (2018)[1]

Trillion Btu



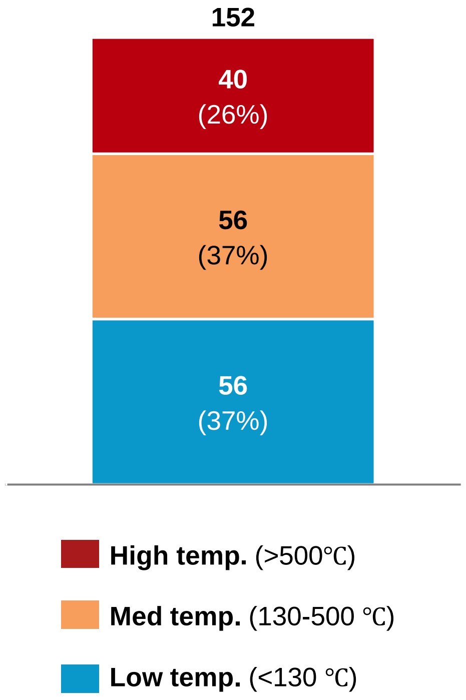
Thermal emissions (2018)[2]

Million Tonnes of CO2e



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

Million Tonnes of CO2e



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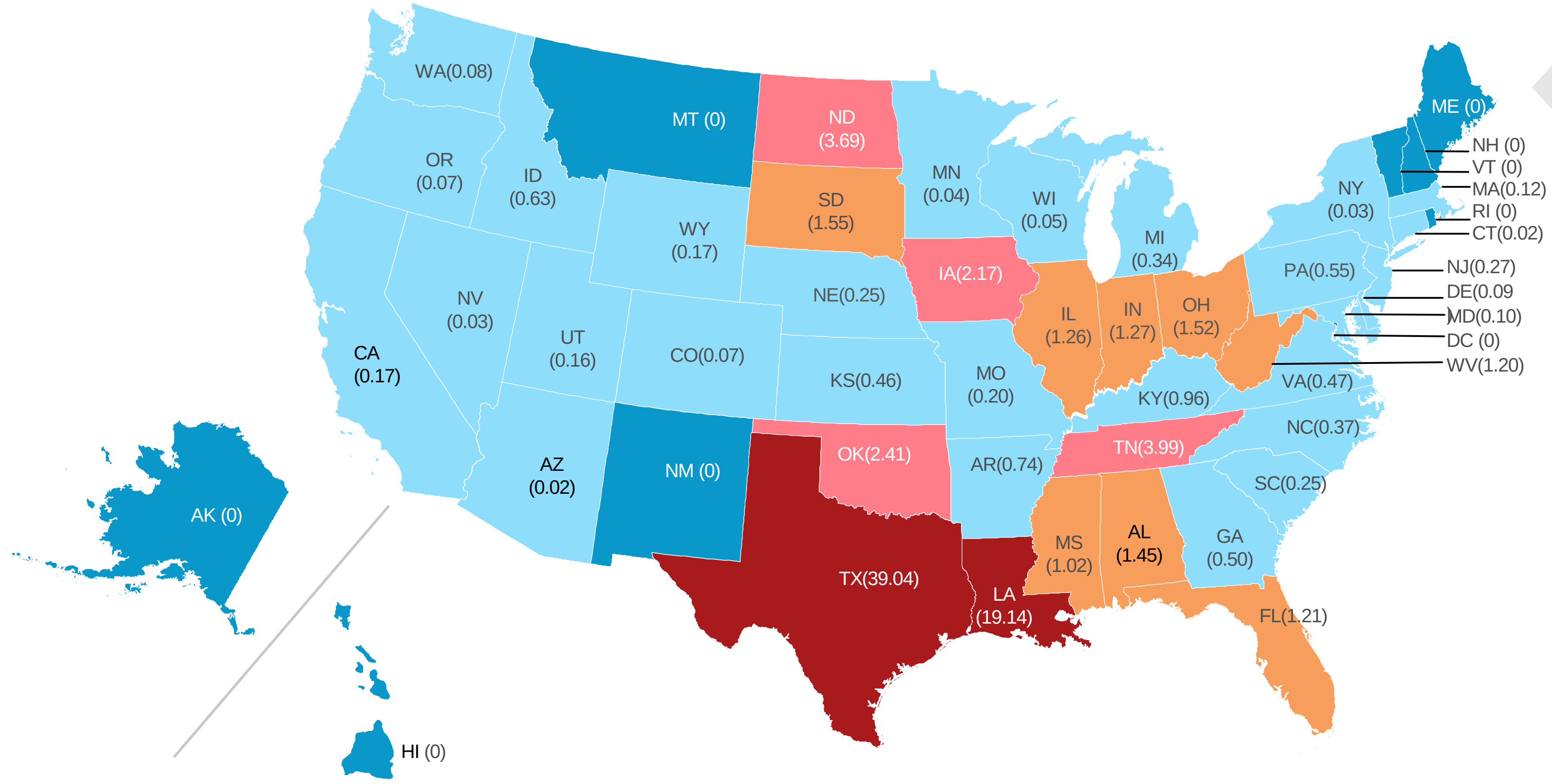
1. EIA Annual Energy Outlook 2019 2. Based on AEO 2019 Outlook for 2018 energy consumption by combustible fuel (excludes purchased electricity) and EPA emissions intensity of individual fuels; RNG and green hydrogen are considered net zero, biomass is estimated at 15 kg CO2e/mmBtu 3. Calculated using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

Thermal emissions are concentrated along the Gulf Coast (where refineries are also concentrated)

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



Chemical manufacturing plants are concentrated along the Gulf Coast and the Mississippi river

● Near zero

● <1 Million Tonnes CO2e

● 1-2 Million Tonnes CO2e

● 2-10 Million Tonnes CO2e

● >10 Million Tonnes CO2e

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

~51% of thermal energy consumption occurs in the distillation and drying temperature ranges; ~26% occurs in the reactor temperature range

Drying | ~150-200 ºC

Drying is used to stabilize solid materials, preventing ice formation, removing unnecessary liquid volume, removing toxic residuals, or creating solid textures. Various dryers are used to remove water from liquids, solids, and gases.

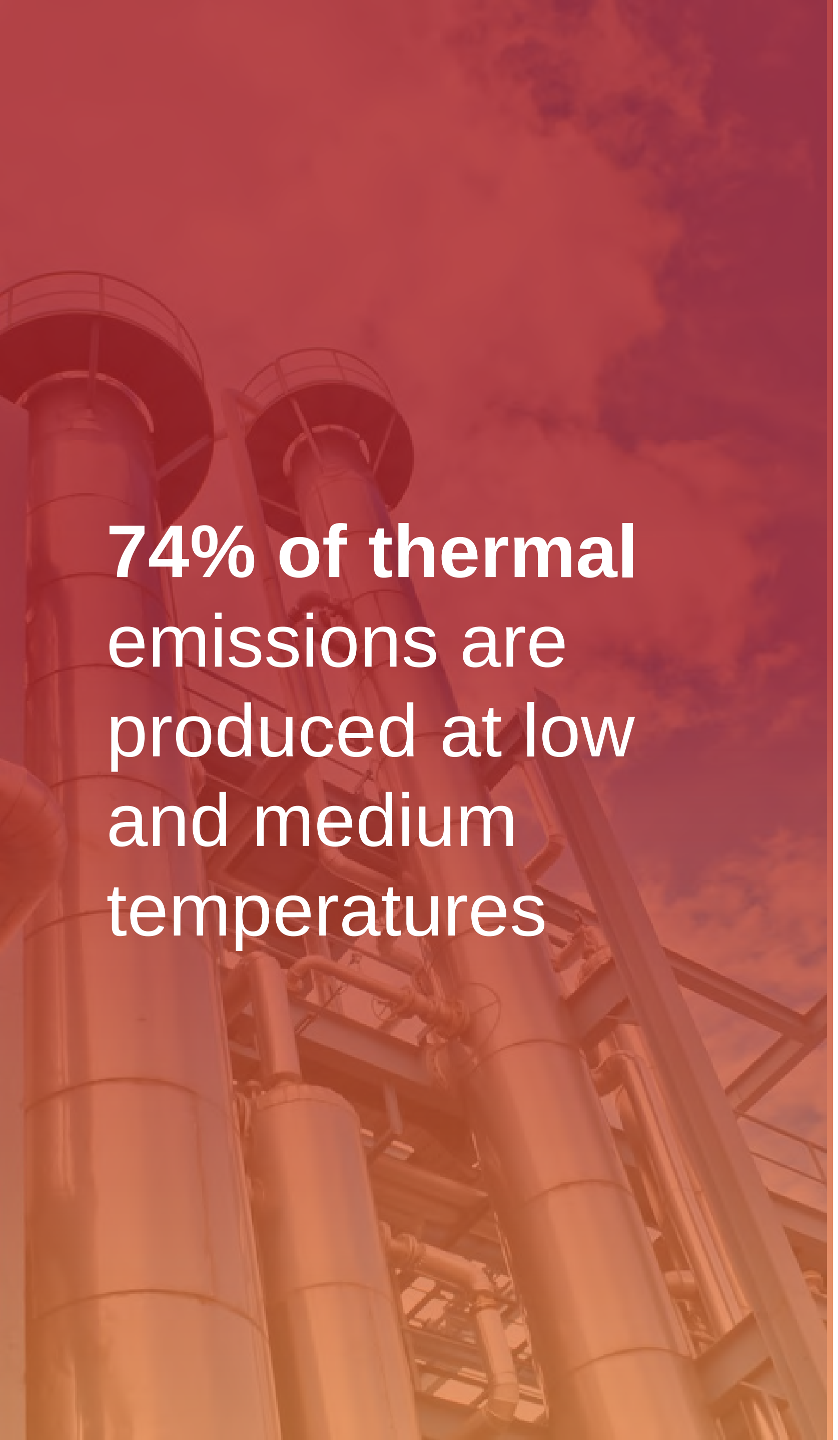
Distillation | ~100-300 ºC

The **distillation** process separates components of the mixture after the chemical reaction. Heat is applied to separate the various components of the mixture through liquid and vapor phase changes.

Reactors | ~500-900 ºC

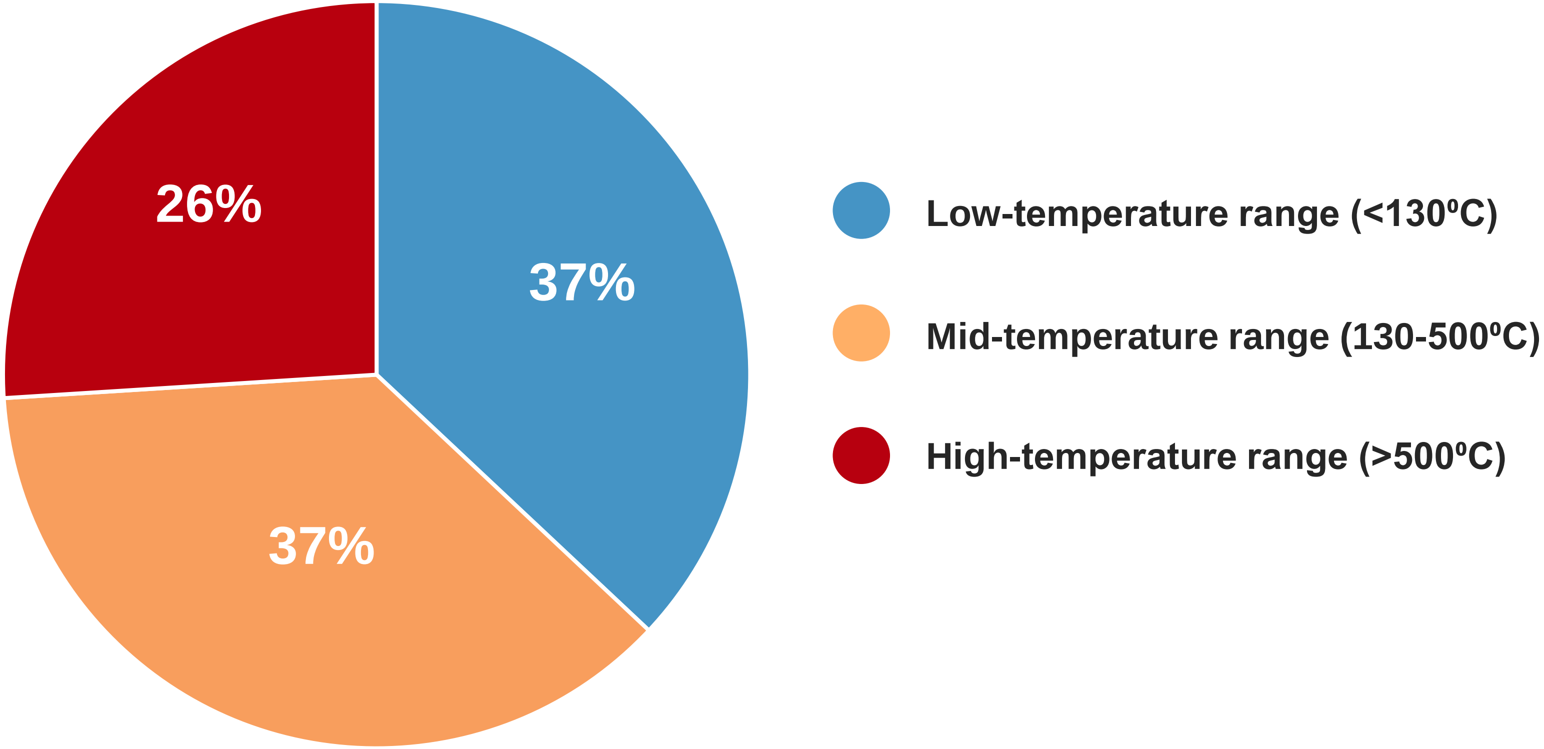
Chemical products are produced using **reactors** (e.g. steam crackers), which mix reactants using agitation, temperature changes, and pressure changes. Reactors can operate in batches or continuously and can be exothermic or endothermic.

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



74% of thermal emissions are produced at low and medium temperatures

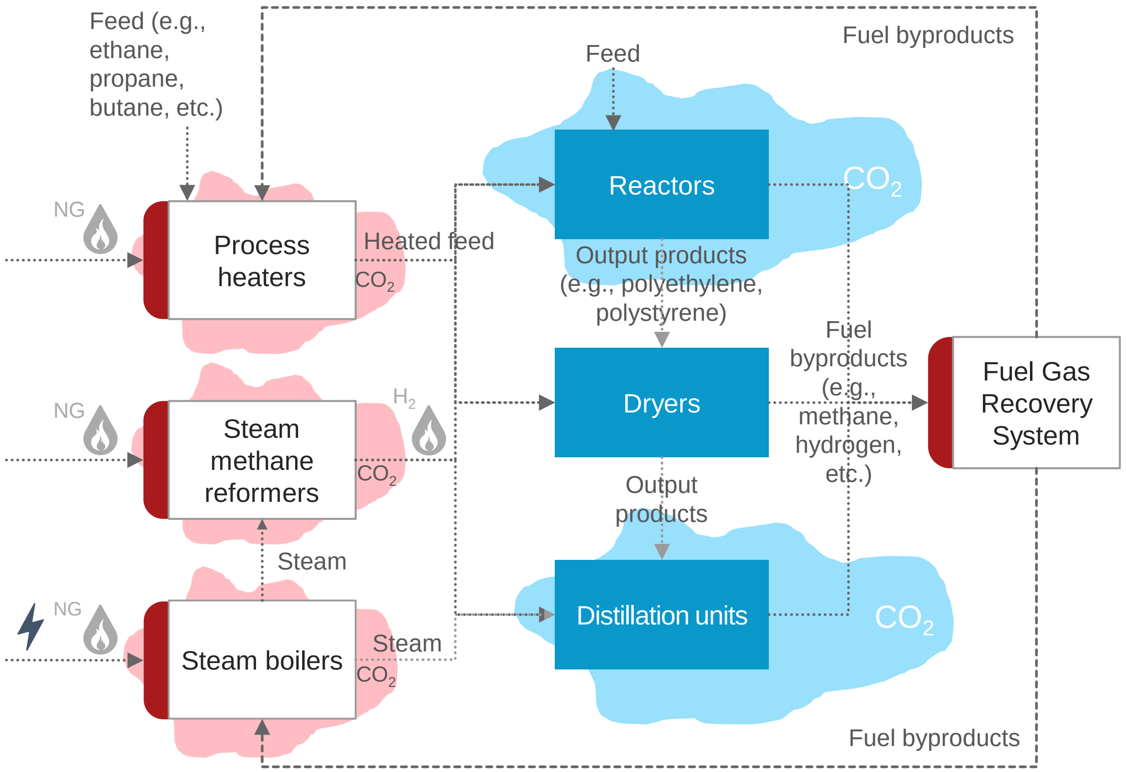
Thermal energy consumption (TBtu) by heat temperature range (ºC)[1]



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

Plants typically use natural gas to generate steam heat, which is distributed through steam networks to thermal applications

Typical chemical plant processes today



Feed (e.g., ethane, propane, butane, etc.)

Fuel byproducts

Feed

NG

Process heaters

Heated feed

CO_2

Reactors

CO_2

Output products (e.g., polyethylene, polystyrene)

NG

Steam methane reformers

H_2

CO_2

Dryers

Fuel byproducts (e.g., methane, hydrogen, etc.)

Fuel Gas Recovery System

Output products

Steam

NG

Steam boilers

Steam

CO_2

Distillation units

CO_2

Fuel byproducts

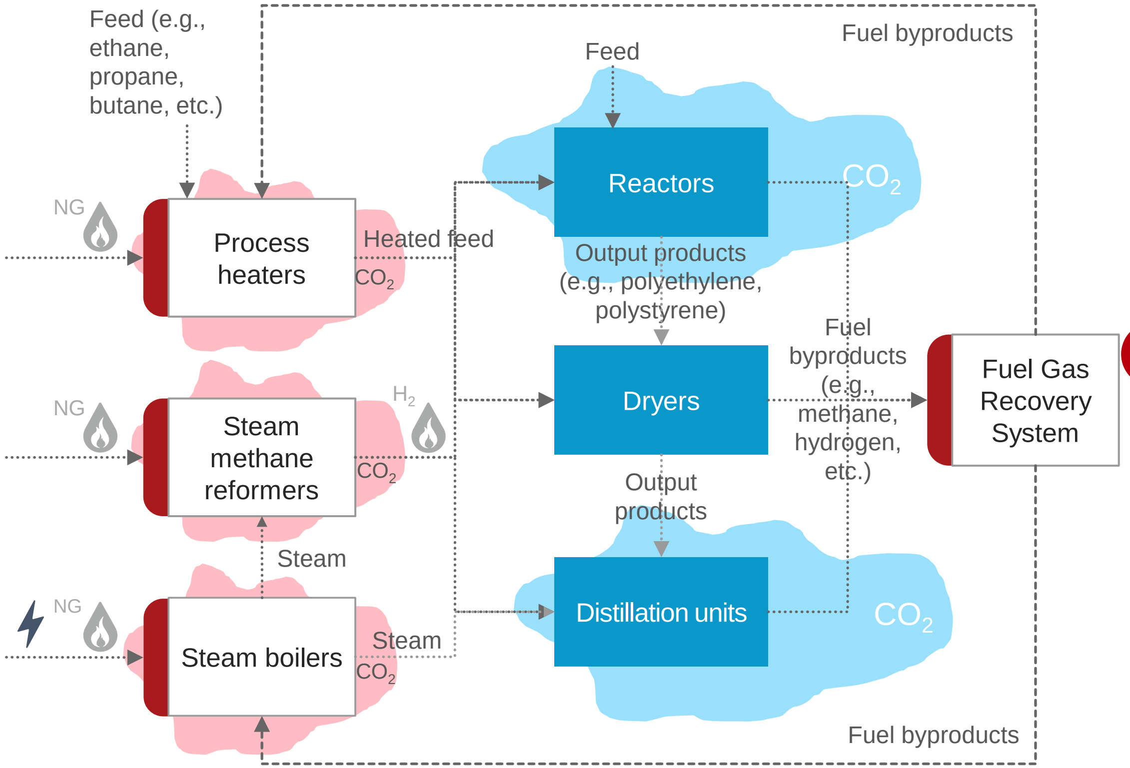
- Chemical facilities typically use process heaters and steam boilers that burn natural gas to create steam heat, which is moved around the facility through a steam network system distributing heated steam to thermal applications
- Natural gas is also used in steam methane reformers to produce hydrogen, which is used as a feedstock in thermal applications
- Process heaters, steam boilers, and steam methane reformers (SMR) release CO2e thermal emissions representing ~45% of total onsite emissions
- The heat applications (e.g. reactors, distillation units) release CO2e process emissions representing ~55% of total onsite emissions
- Facilities can electrify steam boilers and switch to low carbon fuels for process heaters and steam methane reformers

🟥 Heat generating equipment 🟦 Thermal application NG RNG H_2 Fuel source CO_2 Thermal emissions CO_2 Process emissions

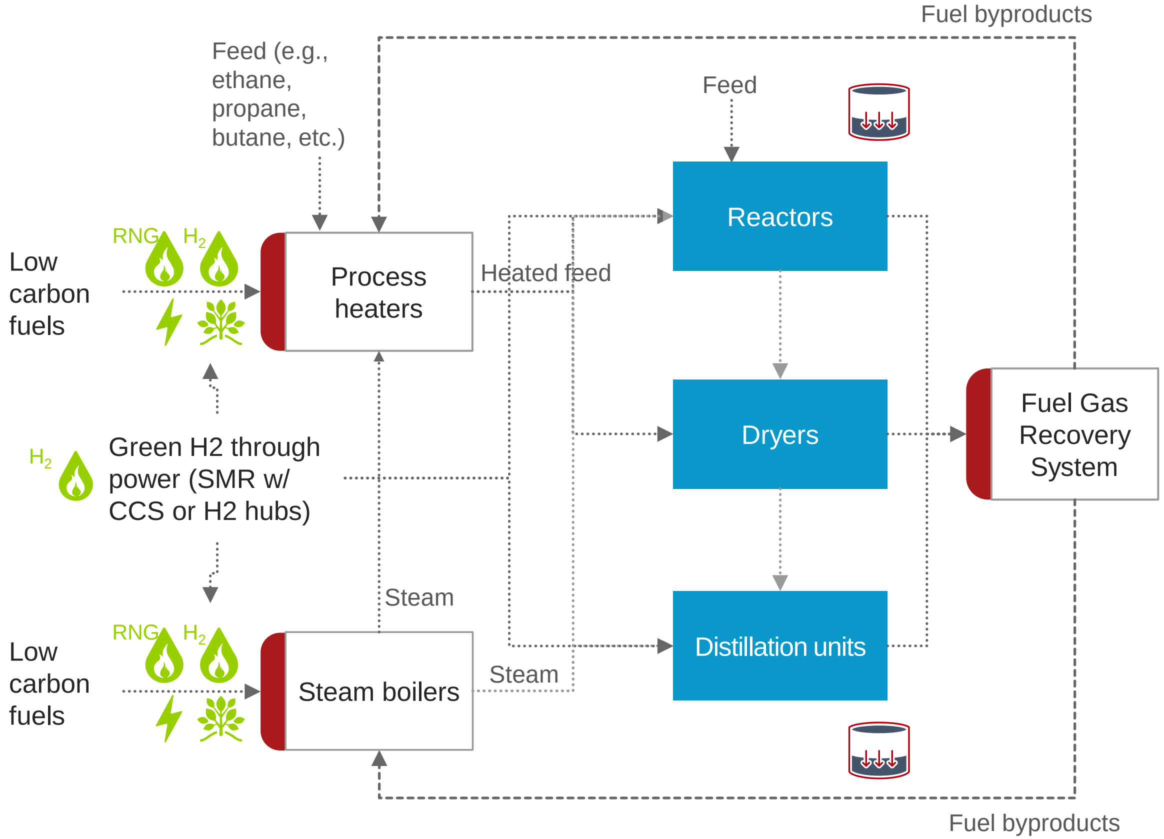
Source: DOE (2022), industry reports and papers, BCG analysis

Electrification and low carbon fuels can reduce thermal emissions; CCS is likely needed to capture the larger process emissions

Typical chemical plant processes today



Chemical plant with renewable thermal + CCS



🟥 Heat generating equipment 🟦 Thermal application NG RNG H_2 Fuel source CO_2 Thermal emissions CO_2 Process emissions CCS

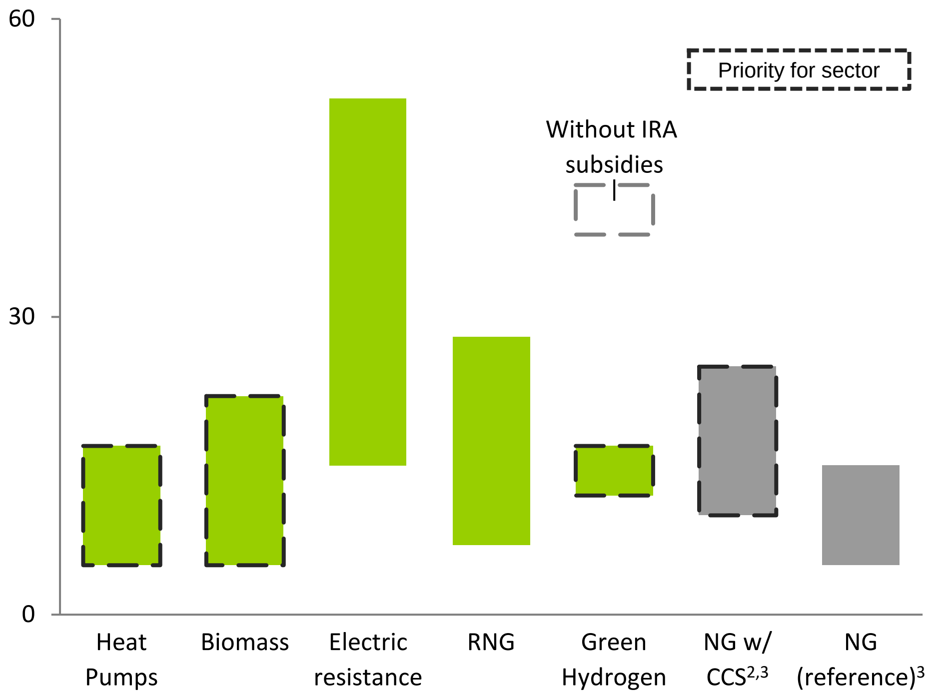
Source: DOE (2022), industry reports and papers, BCG analysis

Heat pumps, biomass and green H2 are most economic renewable fuel alternatives to natural gas, and have lower cost of heat than NG w/ CCS

2022 LCOH for relevant technologies[1]

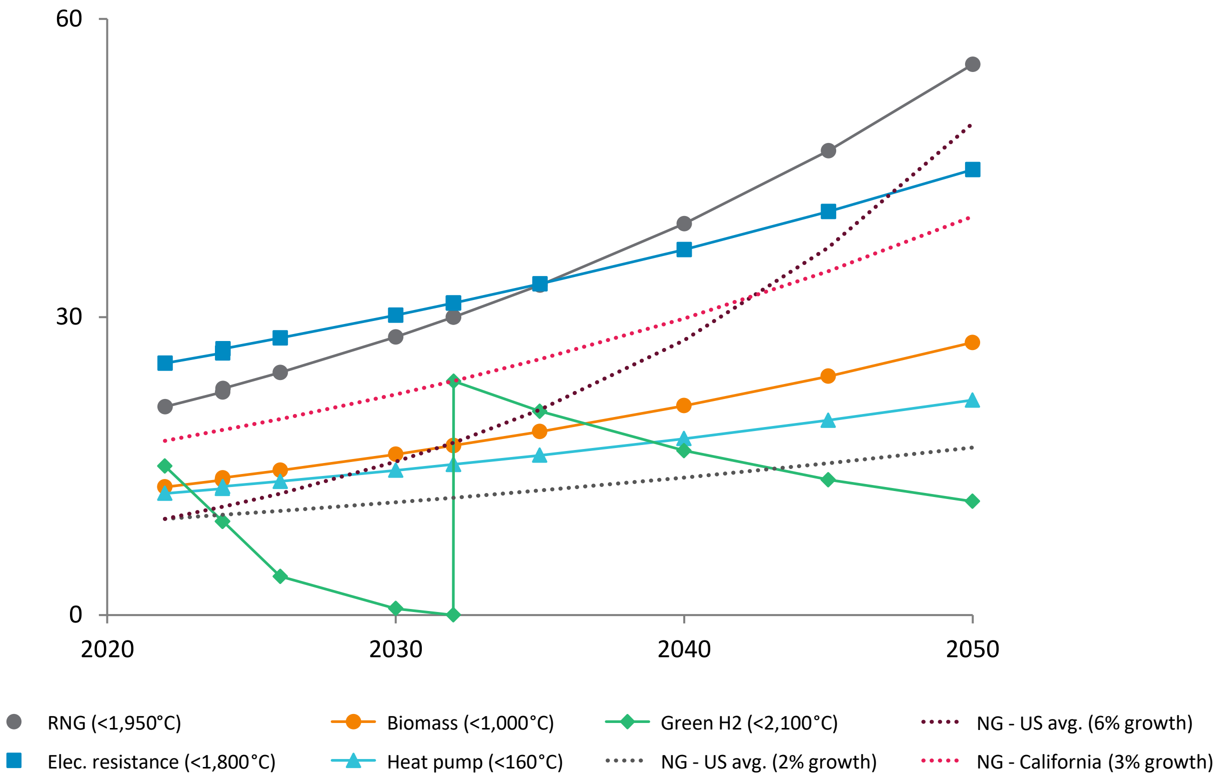
($/MMBtu)

($/MMBtu)



Projected LCOH for relevant technologies[1]

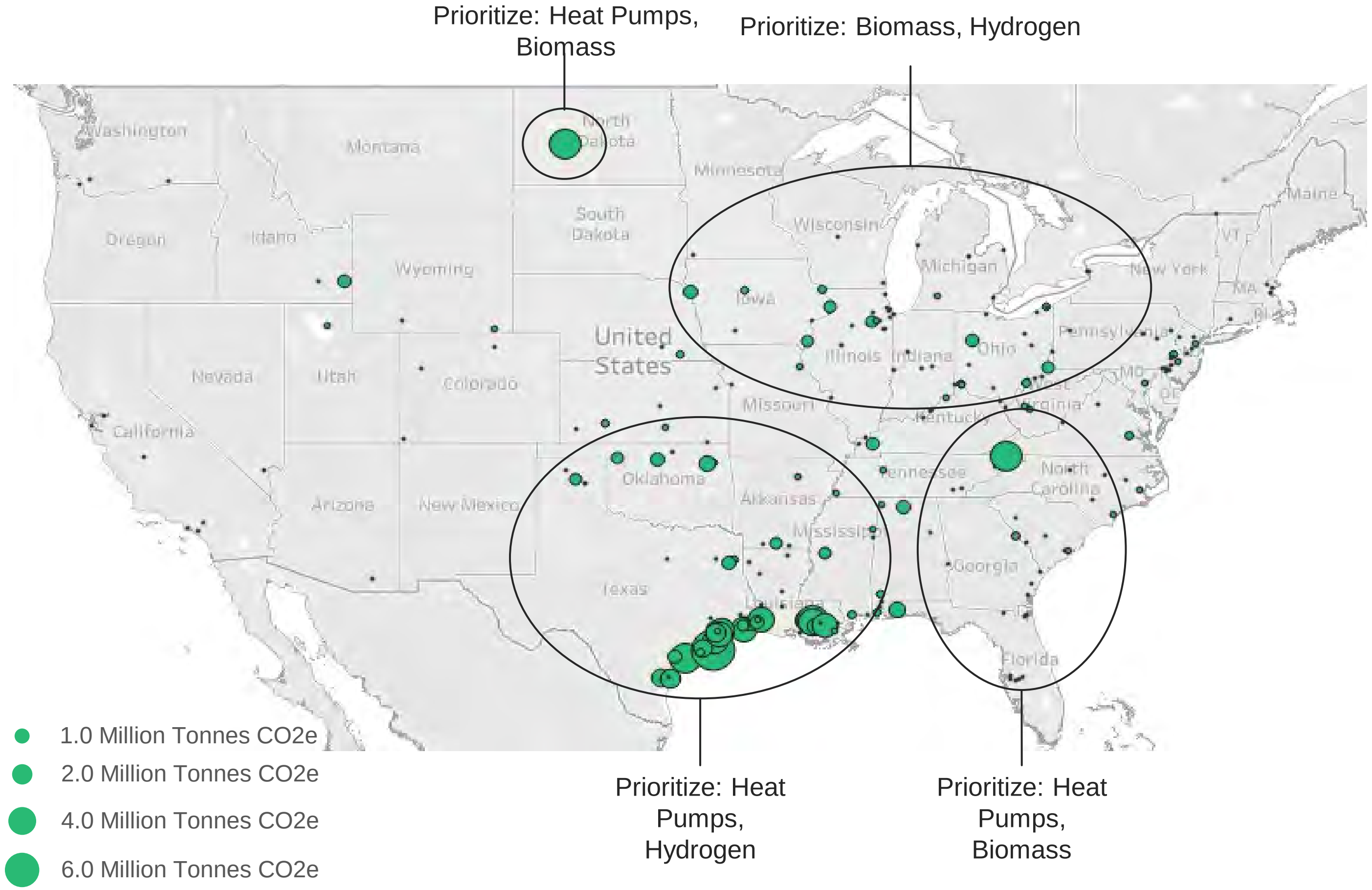
Average US LCOH ($/MMBtu)



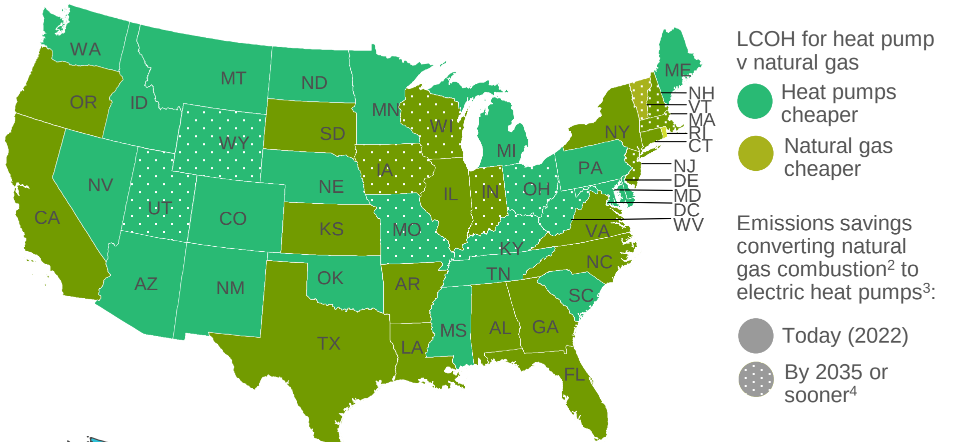
1. LCOH compares project lifetime costs against lifetime energy produced; costs include capital expense of equipment, fuel costs, and maintenance expense assumptions over the usable life of the energy asset. Electricity and natural gas pricing is based on national weighted average wholesale industrial 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

Hydrogen, biomass, and heat pumps are available in heavy-emissions areas

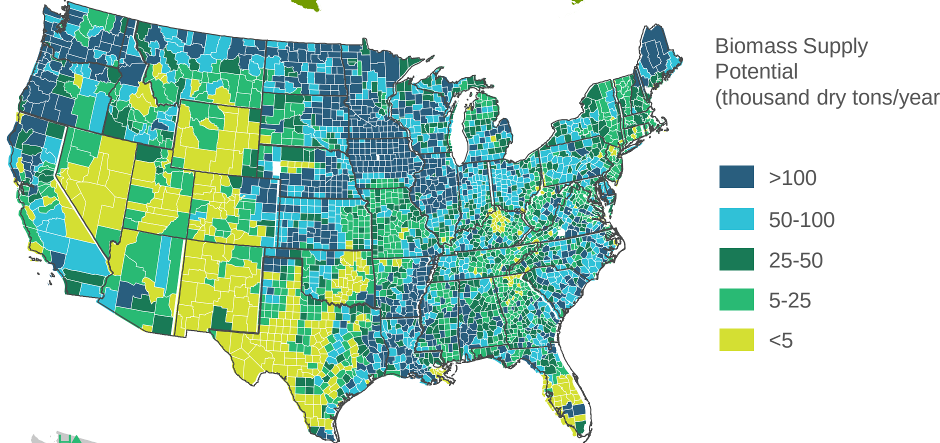
US Chemicals sector thermal emissions by zip code[1]



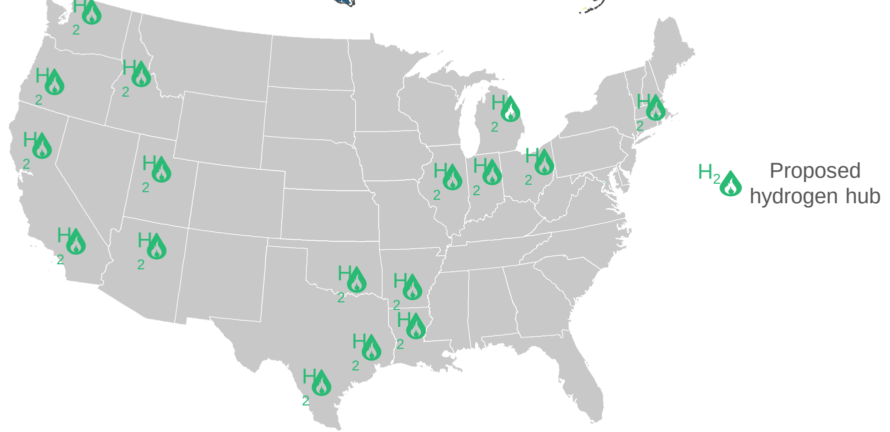
Heat pumps v. Natural gas[2,4]



Biomass supply[3]

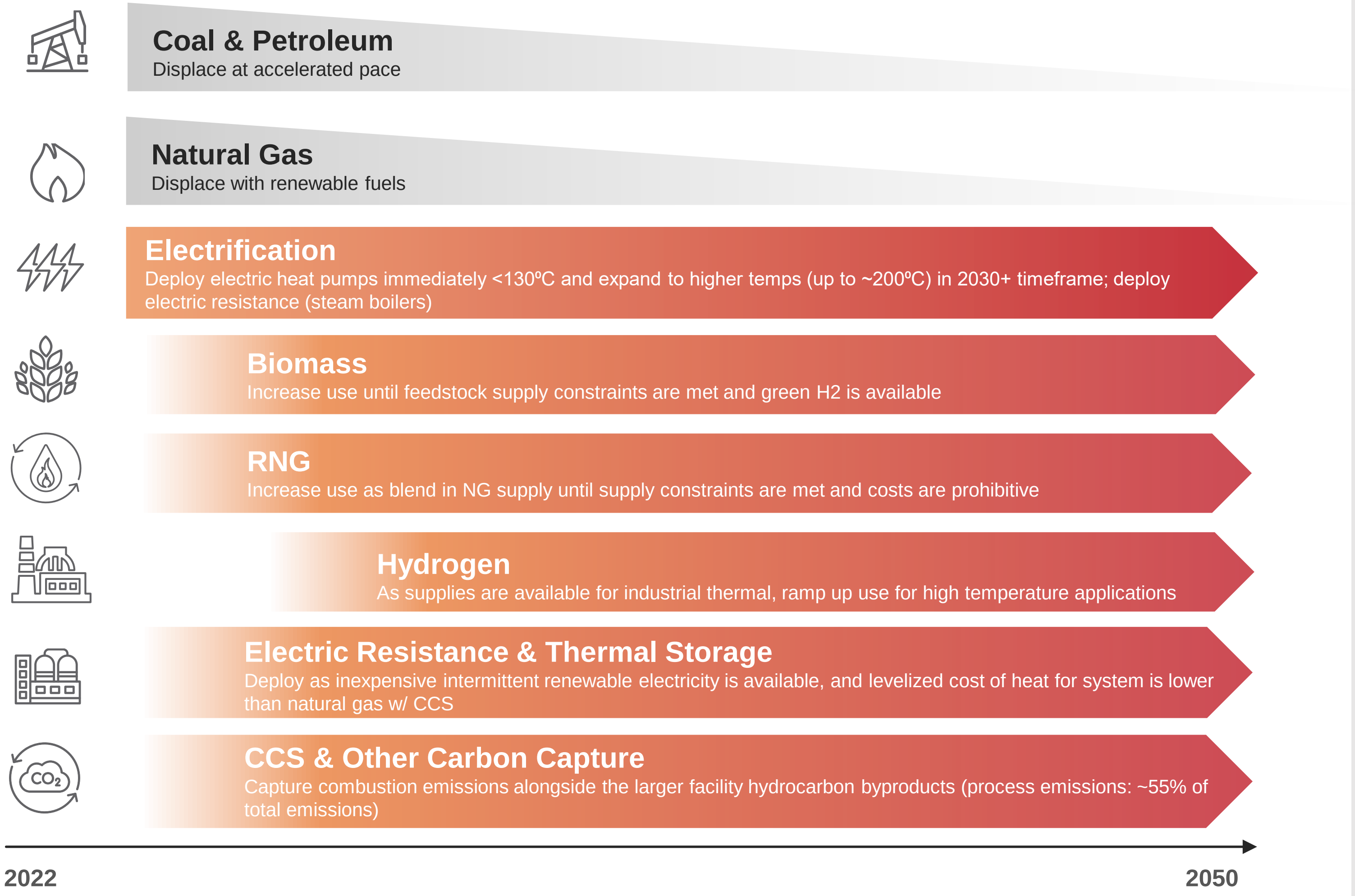


Proposed hydrogen hubs[4]



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



Coal & Petroleum
Displace at accelerated pace

Natural Gas
Displace with renewable fuels

Electrification
Deploy electric heat pumps immediately <130ºC and expand to higher temps (up to ~200ºC) in 2030+ timeframe; deploy electric resistance (steam boilers)

Biomass
Increase use until feedstock supply constraints are met and green H2 is available

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 for high temperature applications

Electric Resistance & Thermal Storage
Deploy as inexpensive intermittent renewable electricity is available, and levelized cost of heat for system is lower than natural gas w/ CCS

CCS & Other Carbon Capture
Capture combustion emissions alongside the larger facility hydrocarbon byproducts (process emissions: ~55% of total emissions)

Considerations	Target First Movers
Start with electric heat pumps and steam boilers	States with inexpensive electricity, or high NG price
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 ind. clusters
Grid or PPA supports emissions savings, viable economics	Ability to procure inexpensive intermittent electricity
Concentration of CO2 in flue gas, government subsidies	Regions with ind. clusters and adequate geology for storage

The Chemicals sector is heterogeneous with interconnected supply networks, requiring many simultaneous paths to decarbonize thermal emissions. As relevant to their circumstances, each chemicals player can explore these technologies to achieve their decarbonization goals

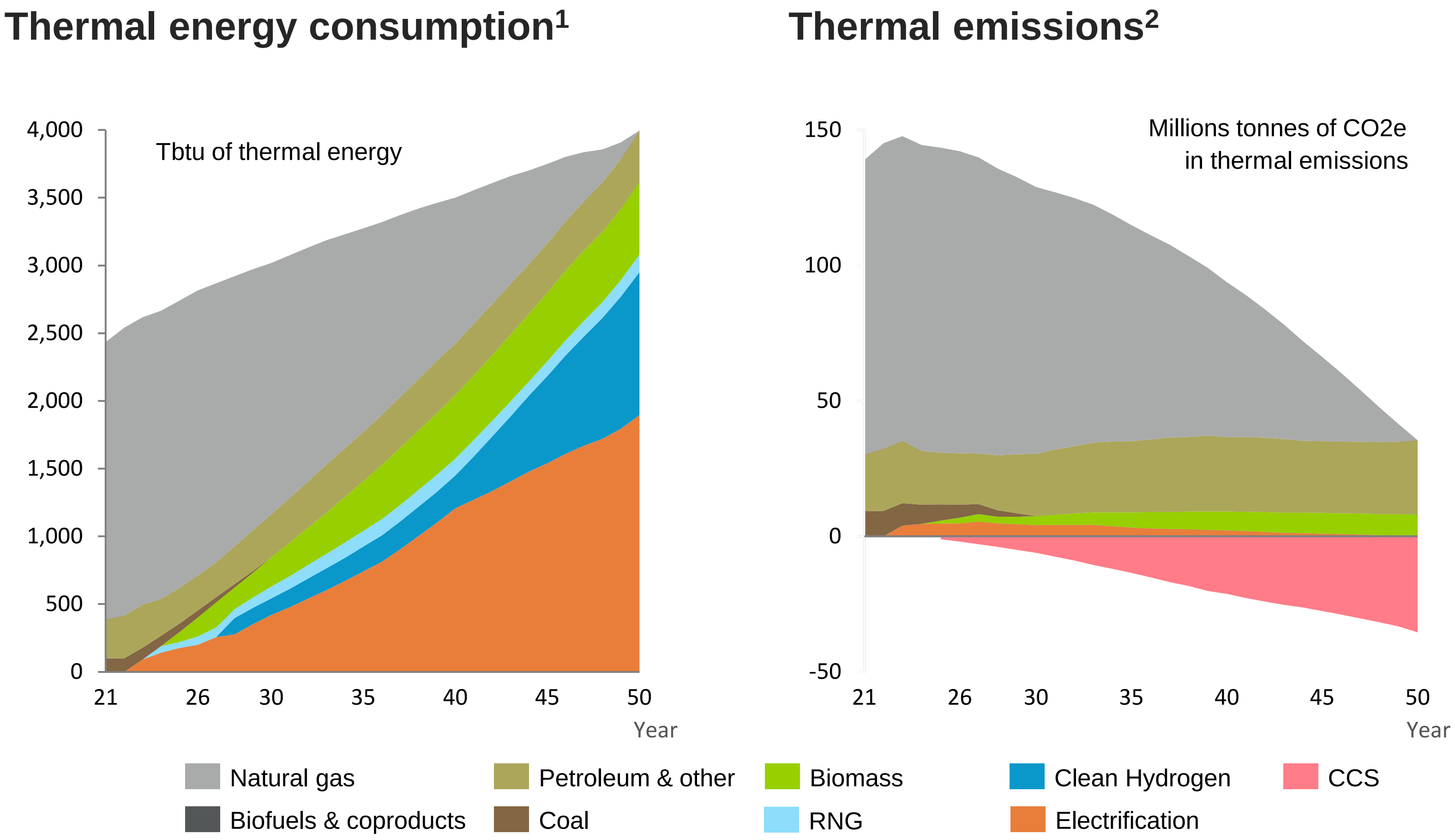
Thermal decarbonization pathways

Use of fossil natural gas is eliminated through 2050

RNG and biomass are deployed as immediate solutions for medium and high heat applications; Biomass use continues to grow over the forecast period (RNG use is not expected to scale due to RNG supply constraints)

Electrification of low and medium temperature applications is deployed beginning immediately; electric grid emissions intensity is lower than fossil NG for heat pumps in nearly all states today; can be deployed against <130ºC processes representing ~37% of total thermal emissions in the sector. As heat pumps improve to ~200ºC, higher heat applications can be electrified

CCS is expected to be deployed in the Chemicals sector to abate process emissions, which outsize thermal emissions for this sector. CCS deployments can be leveraged to abate the thermal emissions from waste products (included under petroleum & other liquids) and biomass that is combusted for heat



Thermal energy consumption[1]

Thermal emissions[2]

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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 outlook; EIA emissions intensity; BCG analysis

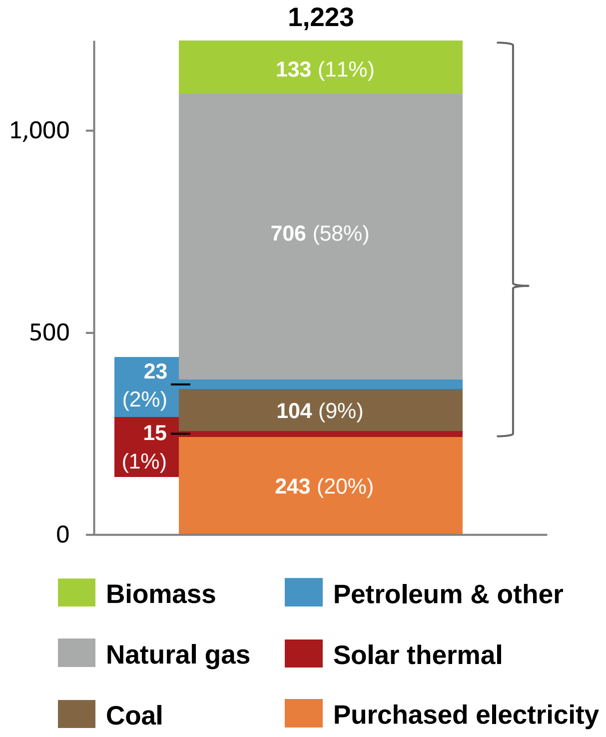
Food

Sector Perspectives

58% of energy consumption is fueled by high temperature natural gas combustion to serve low temperature needs

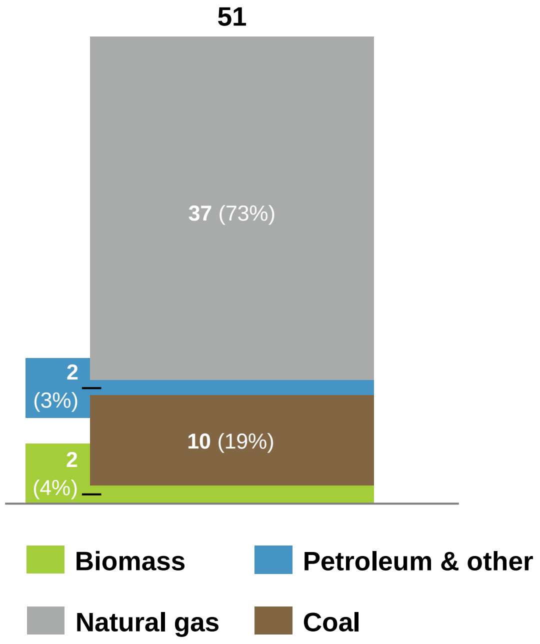
Total energy consumption (2018)[1]

Trillion Btu



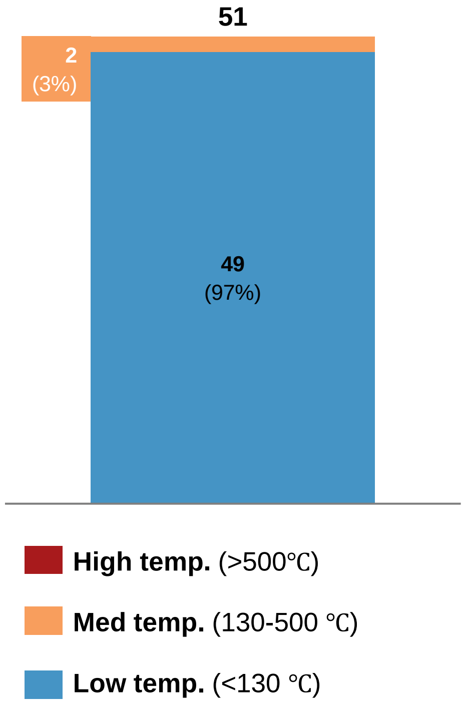
Thermal emissions (2018)[2]

Million Tonnes of CO2e



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

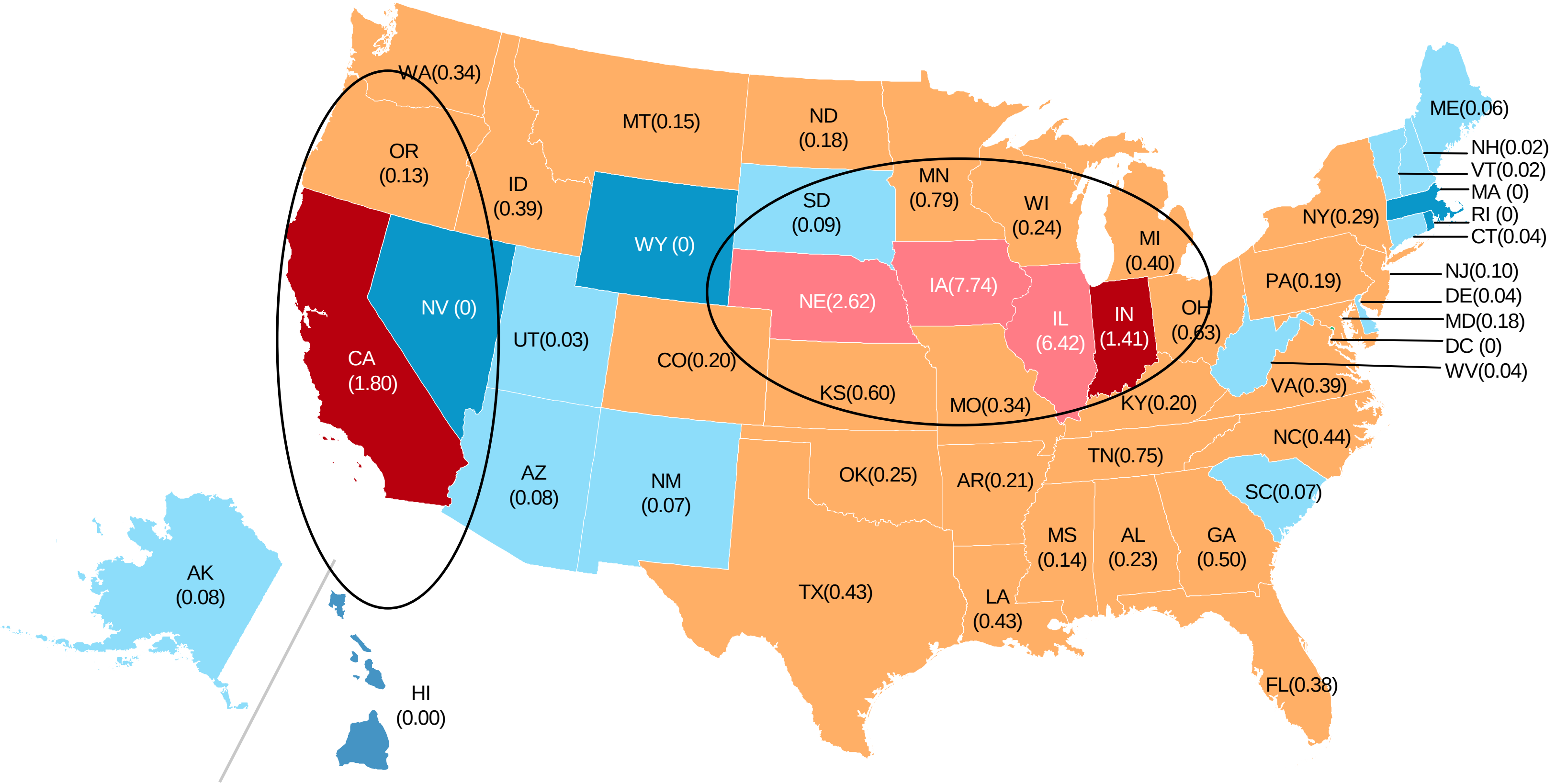
Million Tonnes of CO2e



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 concentrated in the Midwest and California

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



Food emissions concentrate in the agricultural regions of the US

● Near zero

● <0.1 Million Tonnes CO2e

● 0.1-1 Million Tonnes CO2e

● 1-2 Million Tonnes CO2e

● >2 Million Tonnes CO2e

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

Key heat applications occur in the low and medium temperature ranges

Drying | 30-90 ºC

The drying process reduces moisture in food in order to mitigate unwanted microbial proliferation and biochemical reactions, as well as reduce costs of transportation, packaging, and storage. Large dryers, usually powered by natural gas, circulate air at varying degrees of heat to achieve the appropriate moisture reduction.

Washing | 60-90 ºC

Agricultural produce is cleaned post-harvest by being **washed** with a sanitizer in heated water and subsequently hydrocooled. Larger scale farms use mechanical washing machines to wash large quantities of produce either in batches or continuously.

Pasteurizing | 60-140 ºC

Pasteurizing is a heat treatment of liquid foods (milk, juices, etc.) which extends their shelf lives by destroying organisms or enzymes that can cause spoilage. Foods are typically pasteurized using metal plates and hot water for no less than 15 seconds before being rapidly cooled.

Sterilizing | 110-120 ºC

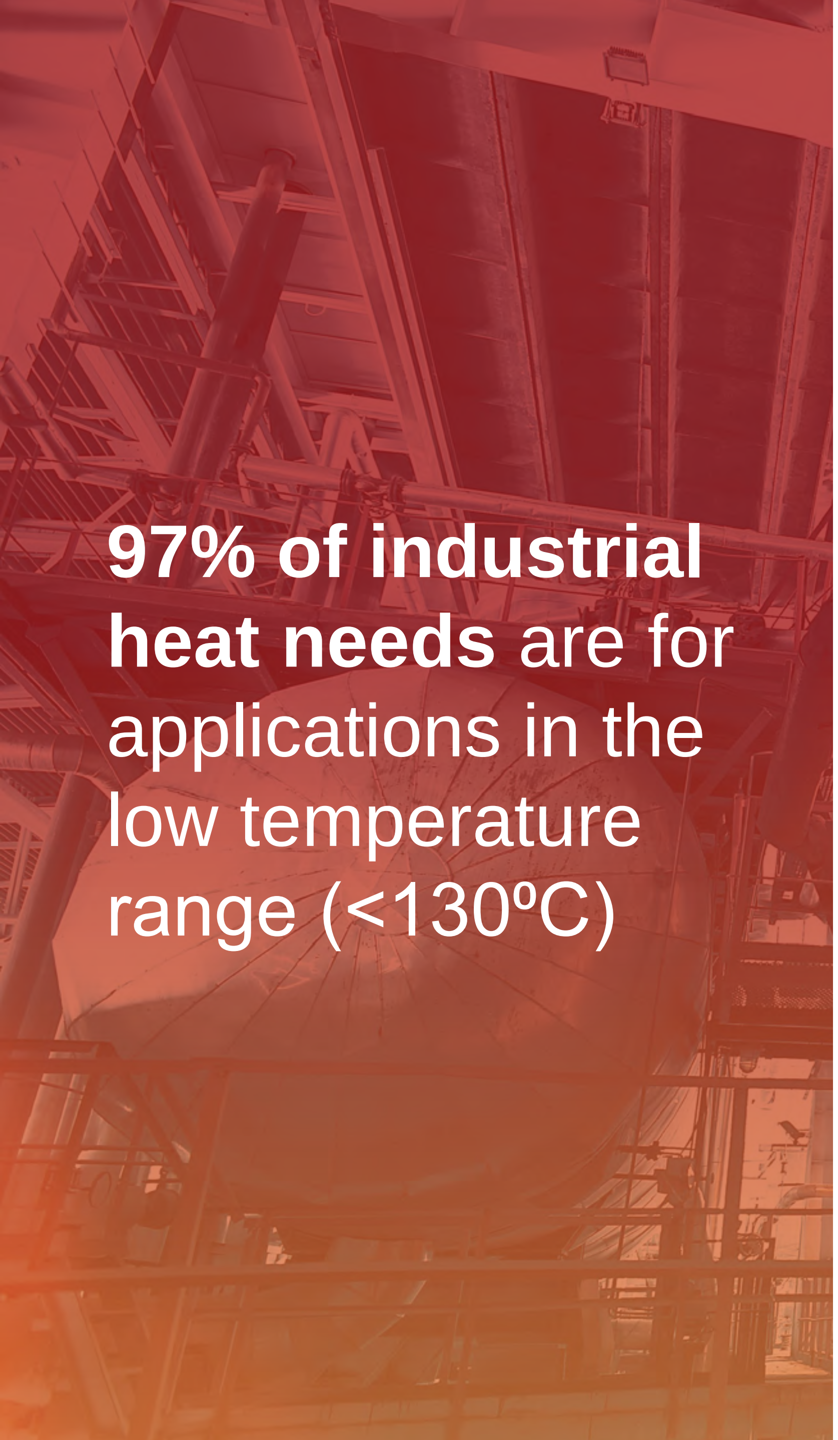
Sterilization is a process used to eliminate microbial life on raw foods such as meat, poultry, eggs, and fish. Steam, dry heat, or chemicals are commonly used for sterilizing. In the sterilization process, foods are first heated, then equilibrated and held for a certain period, and finally cooled.

Cooking | 95-200 ºC

The **cooking** process alters the texture, color, and moisture content of foodstuffs to prepare ready-to-eat products. Examples of equipment used for cooking include various types of ovens, kettles, and boilers.

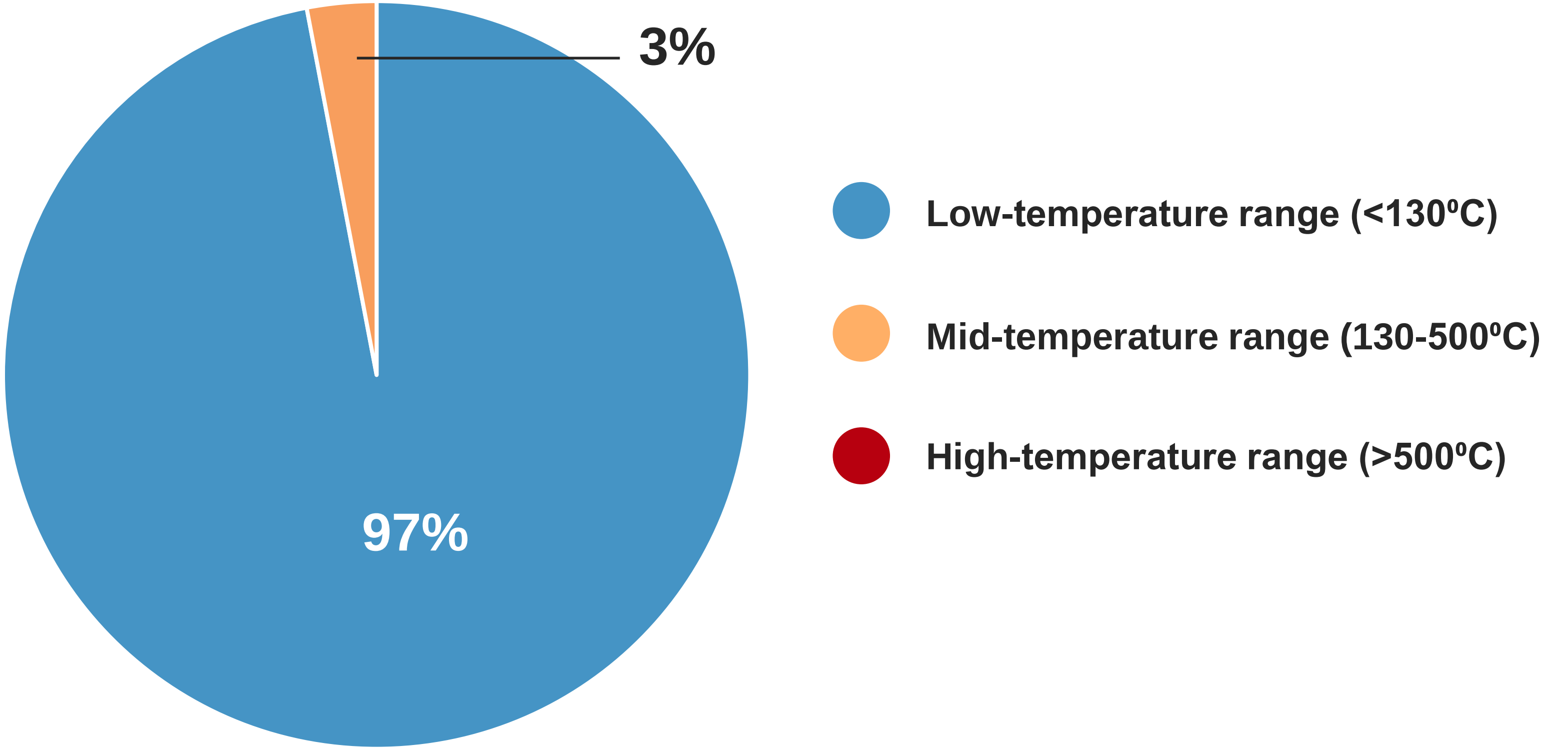
Low temperature heat processes are well suited for electrification in the immediate, mid, and long term

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



97% of industrial heat needs are for applications in the low temperature range (<130ºC)

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

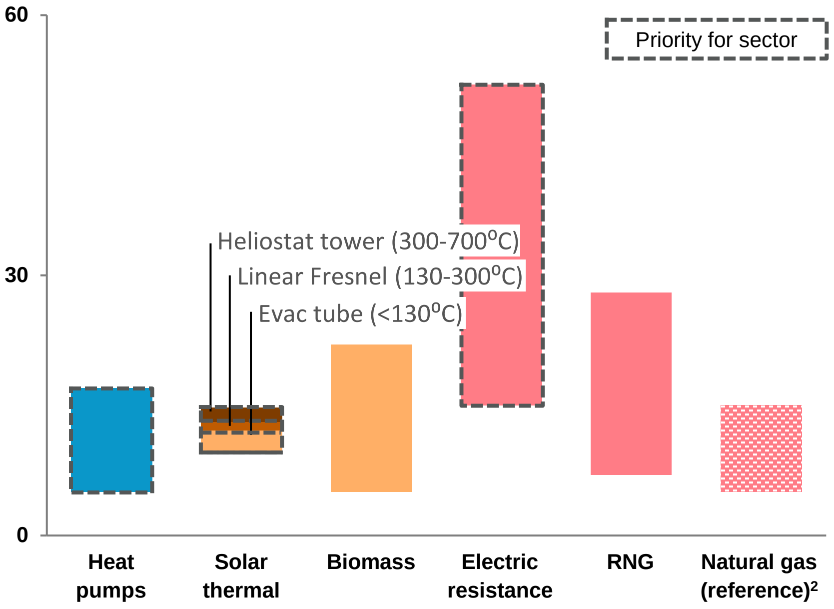


1. NREL Manufacturing Thermal Energy Use in 2014

Electrification and solar thermal offer attractive alternatives to natural gas for low heat applications

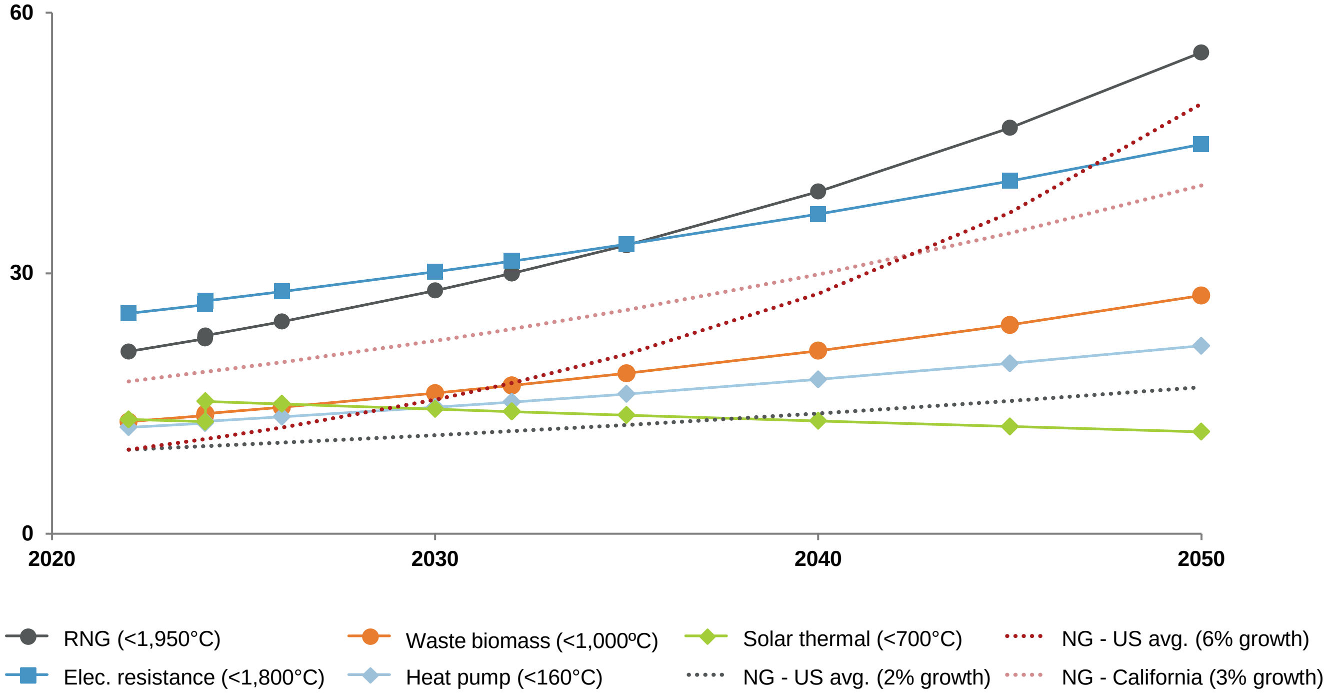
2022 LCOH for relevant technologies[1]

($/MMBtu)



Projected LCOH for relevant technologies[1]

Average US LCOH ($/MMBtu)



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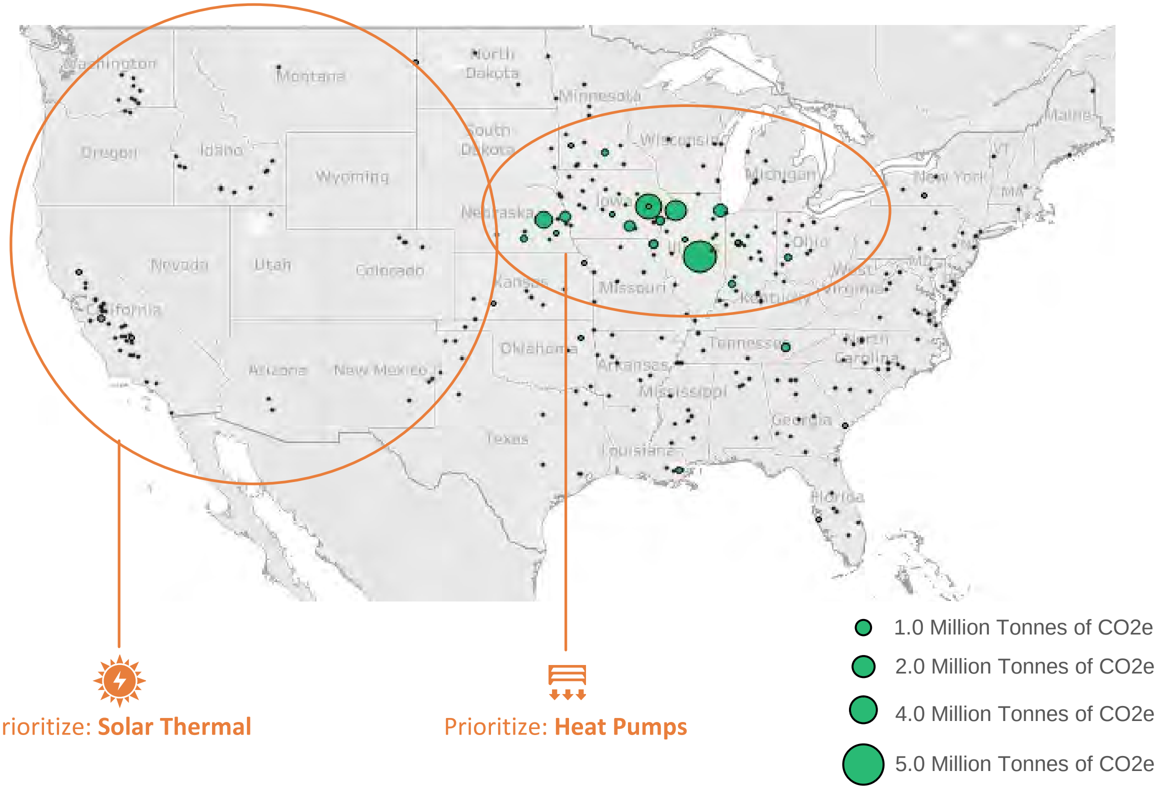
Heat pumps and solar thermal can be deployed in most heavy-emissions areas

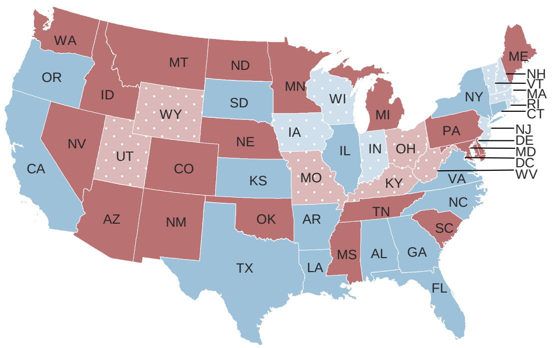
US Food thermal emissions by zip code[1]



Prioritize: **Solar Thermal**

Prioritize: **Heat Pumps**

Heat pumps v. Natural gas[2,4]



LCOH for heat pump v natural gas

● Heat pumps cheaper

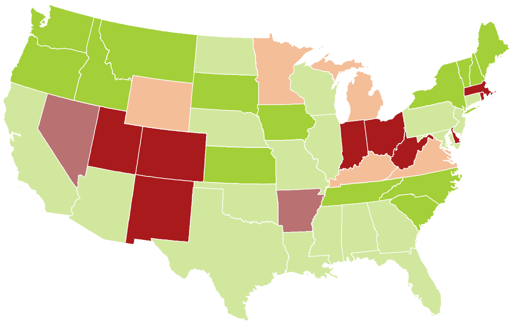
● Natural gas cheaper

Emissions savings converting natural gas combustion[2] to electric heat pumps[3]:

● Today (2022)

▨ By 2035 or sooner[4]

Elec. resistance v. NG[3]



Likely reduction in emissions by switching from NG combustion[5] to electric resistance heating:

● Today

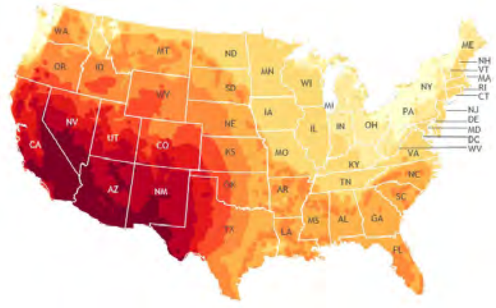
● By 2026

● By 2030

● By 2035

● Beyond 2035

Solar thermal availability[4]

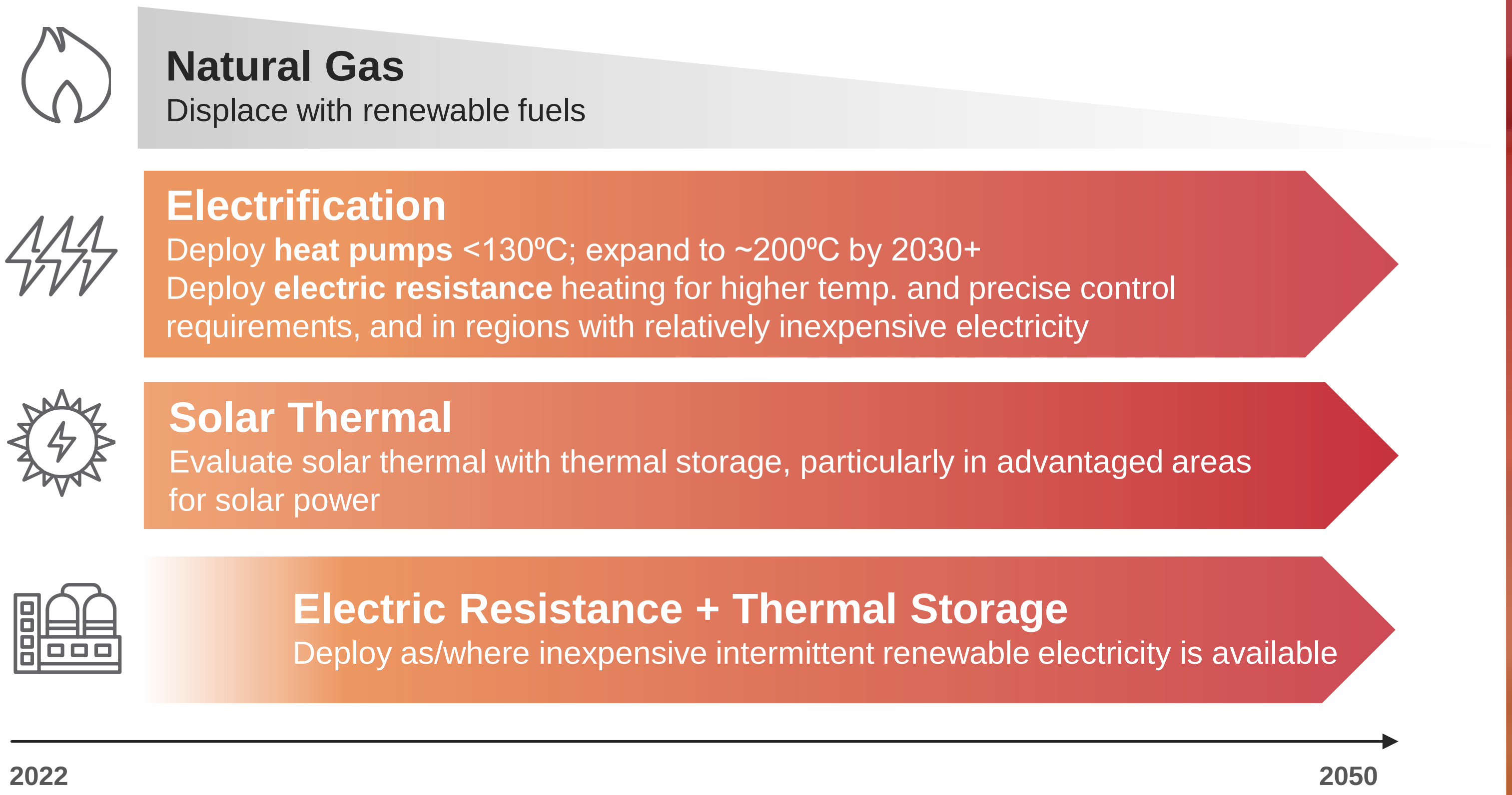


kWh/m/Day

- ≥7.5
- 7.0 to 7.4
- 6.5 to 6.9
- 6.0 to 6.4
- 5.5 to 5.9
- 5.0 to 5.4
- 4.5 to 4.9
- 4.0 to 4.4
- <4.0

1. EPA GHGRP Inventory FLIGHT Database (2018); captures actual onsite reported emissions for large emitters emitting >25k tons of CO2e per year 2. US EIA Industrial Electricity Prices (May 2022), US EIA Industrial Natural Gas Prices (May 2022), Industrial Heat Pumps: Electrifying Industry's Process Heat Supply – ACEEE; 3. US EPA GHGRP (2019); US EIA; State Renewable Portfolio Standards; IEA ETSAP Industrial Combustion Boilers Fact Sheet; BCG analysis; 4. NREL 5. Calculated using 85% efficiency for natural gas boiler; 6. Calculated using a conservative COP of 3

Decarbonization pathways

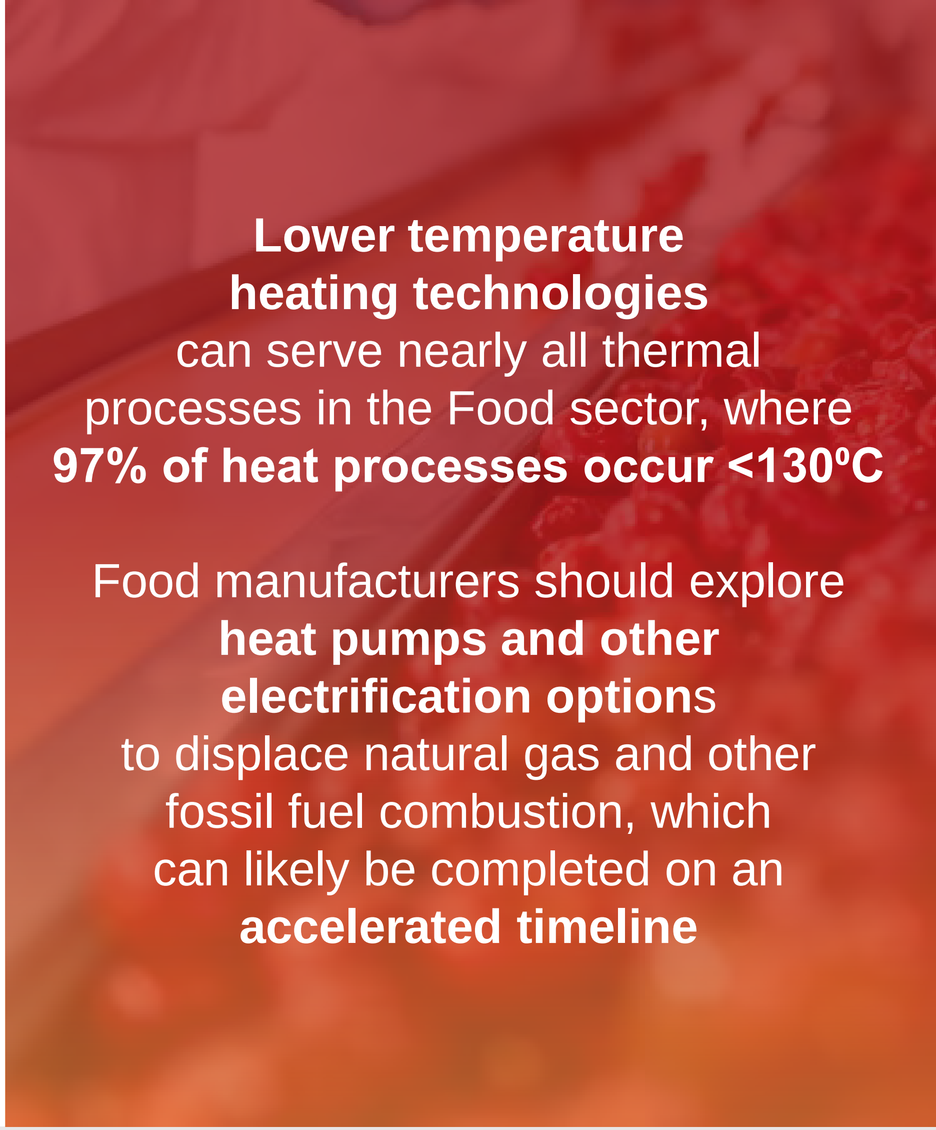


Natural Gas
Displace with renewable fuels

Electrification
Deploy **heat pumps** <130ºC; expand to ~200ºC by 2030+
Deploy **electric resistance** heating for higher temp. and precise control requirements, and in regions with relatively inexpensive electricity

Solar Thermal
Evaluate solar thermal with thermal storage, particularly in advantaged areas for solar power

Electric Resistance + Thermal Storage
Deploy as/where inexpensive intermittent renewable electricity is available



Lower temperature heating technologies can serve nearly all thermal processes in the Food sector, where **97% of heat processes occur <130ºC**

Food manufacturers should explore **heat pumps and other electrification options** to displace natural gas and other fossil fuel combustion, which can likely be completed on an **accelerated timeline**

Considerations

- Ability to reach desired temperatures, cost of equipment and facility reconfiguration, grid or PPA supports emissions savings
- Thermal storage lowers costs and expands usability of solar energy
- Grid or PPA supports emissions savings, viable economics

Target First Movers

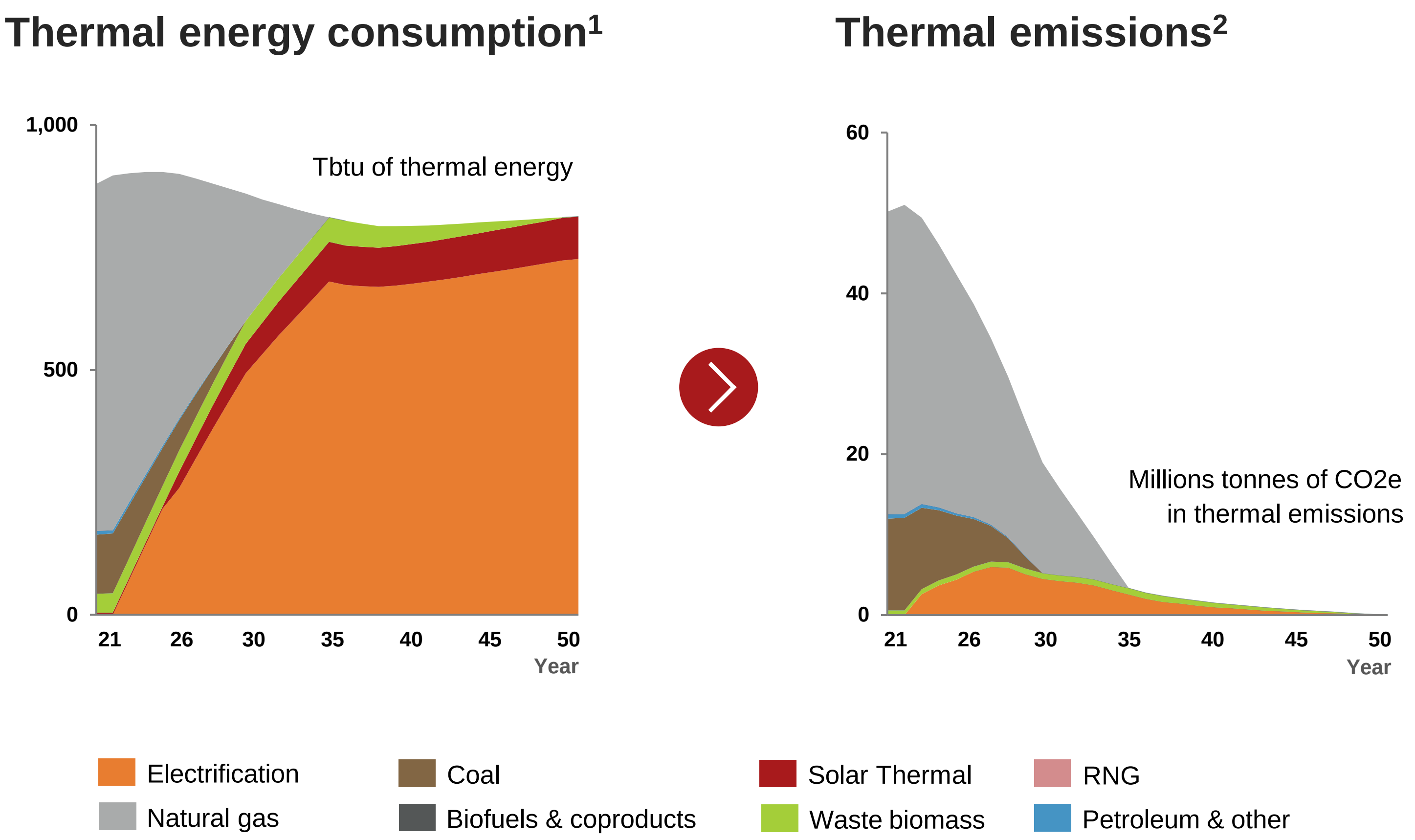
- Regions with relatively inexpensive and clean electricity
- CA and Southwest states; access to land for solar
- Ability to procure inexpensive intermittent electricity (e.g. states / electricity grids with high renewables)

Thermal decarbonization pathways

97% of industrial heat needs are for applications is in the low temperature range (<130ºC), which can be **decarbonized on an accelerated timeline** with electrification and heat pumps. Natural gas, which combusts at ~1,850ºC is not required for most heat needs in the sector.

Use of fossil coal and petroleum is **phased out by 2030**, and natural gas **phased out by 2035** – replaced with electrification.

Solar thermal energy with battery storage should also be considered, particularly in the US Southwest, and/or when electric heat pumps have a higher cost to generate heat than fossil natural gas (e.g. California).



Thermal energy consumption[1]

Thermal emissions[2]

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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 assuming 80% and 100% renewables by 2030 and 2050 Source: EIA outlook; EIA emissions intensity; BCG analysis

Iron & Steel

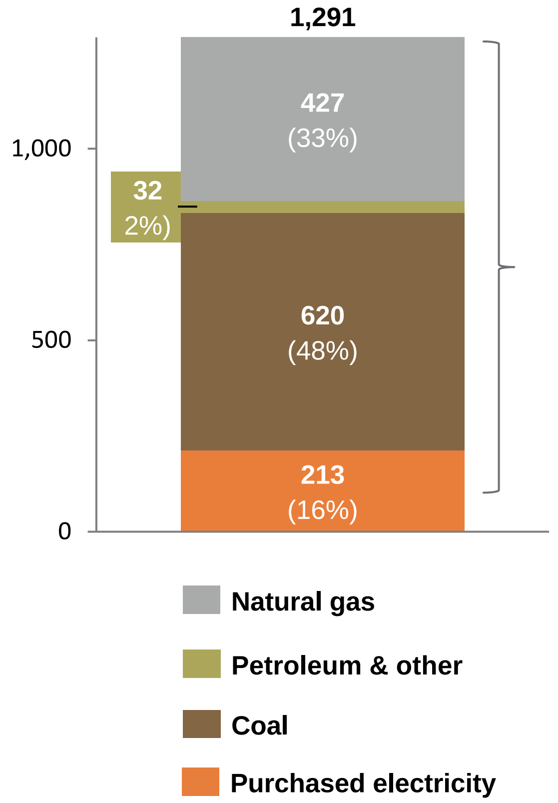
Sector Perspectives

RENEWABLE
THERMAL
COLLABORATIVE

Thermal applications are fueled by coal, natural gas and electricity (electric arc furnaces[4])

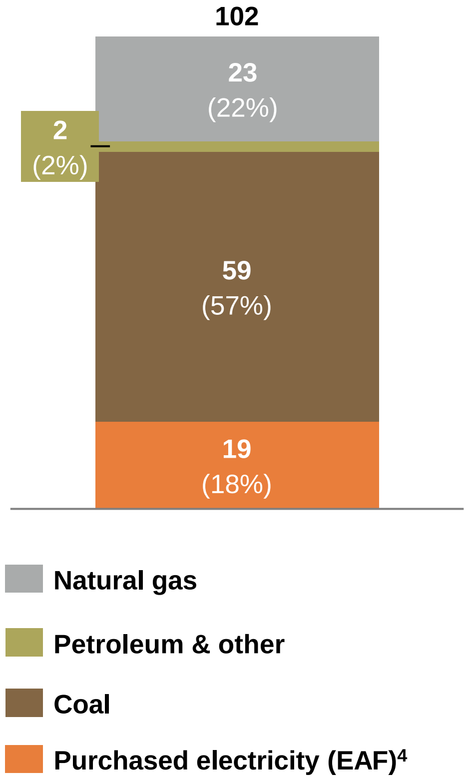
Total energy consumption (2018)[1]

Trillion Btu



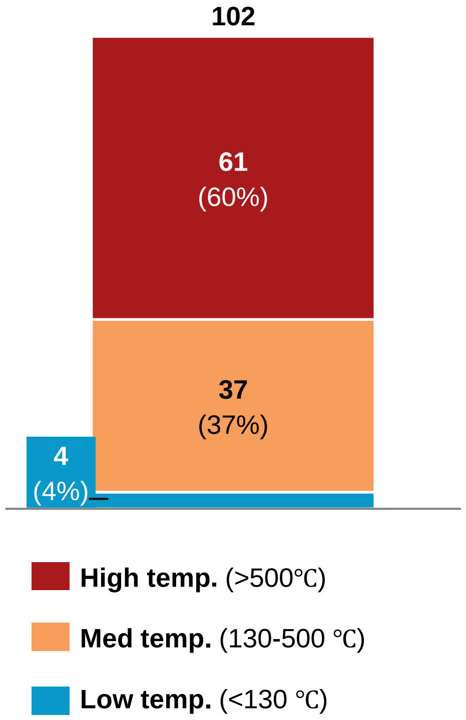
Thermal emissions (2018)[2]

Million Tonnes of CO2e



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

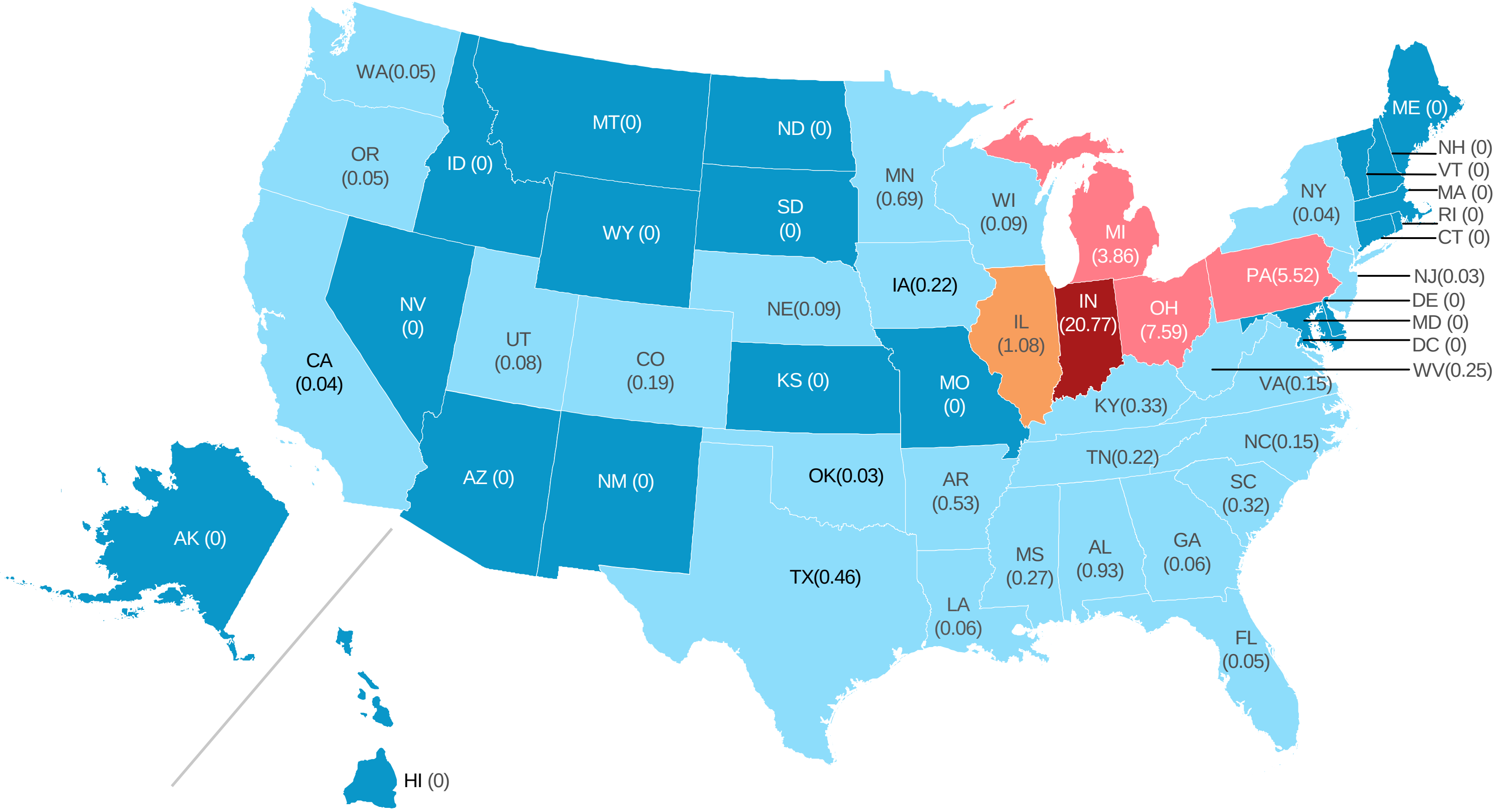
Million Tonnes of CO2e



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. More than 2/3rds of Iron & Steel facilities use electric arc furnaces (instead of blast furnaces); for purposes of this analysis ~50% of purchased electricity is estimated to be used for thermal applications (electric arc furnaces) Source: EIA; EPA; NREL; BCG analysis

Thermal emissions are concentrated in the Midwest

Iron & Steel thermal emissions by state (Million Tonnes of CO2e)[1]



Iron & Steel emissions are focused in the Midwest primarily due to the concentration of iron and steel production facilities

● Near zero

● <1 Million Tonnes CO2e

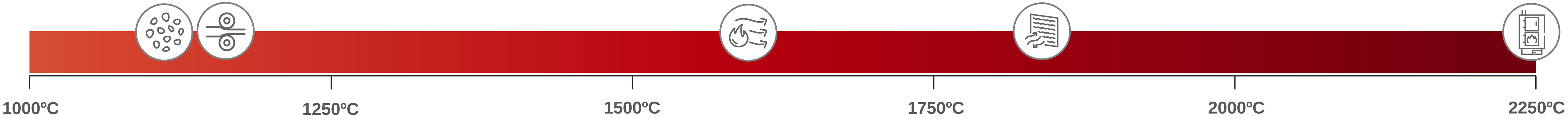
● 1-2 Million Tonnes CO2e

● 2-10 Million Tonnes CO2e

● >10 Million Tonnes CO2e

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

Core applications occur at high temperatures



Pelletizing

1000-1200 ºC

In order to be fed into blast furnaces, iron ore must go through a **pelletizing** process. After being finely ground, the iron is mixed with fluxing and binding agents to form pellets. Next, the pellets are fed into and heated in an induration machine which dries, hardens, and cools the pellets for use in a blast furnace.

Blast Furnace

2200-2300 ºC

Blast furnaces are used to produce pig iron from iron ore pellets. Pre-heated air is fed into the bottom of the furnace along with a fuel such as oil or natural gas, while iron ore, coke, and flux, such as limestone, are fed into the top. The end products are carbon monoxide, liquid iron, and slag.

Basic Oxygen Furnace

1600 ºC

Steel is made by reducing the carbon content of pig iron. After pig iron is formed in the blast furnace, **oxygen** is blown through it in a furnace to remove excess carbon and impurities such as silicon and phosphorous.

Electric Arc Furnace

1800 ºC

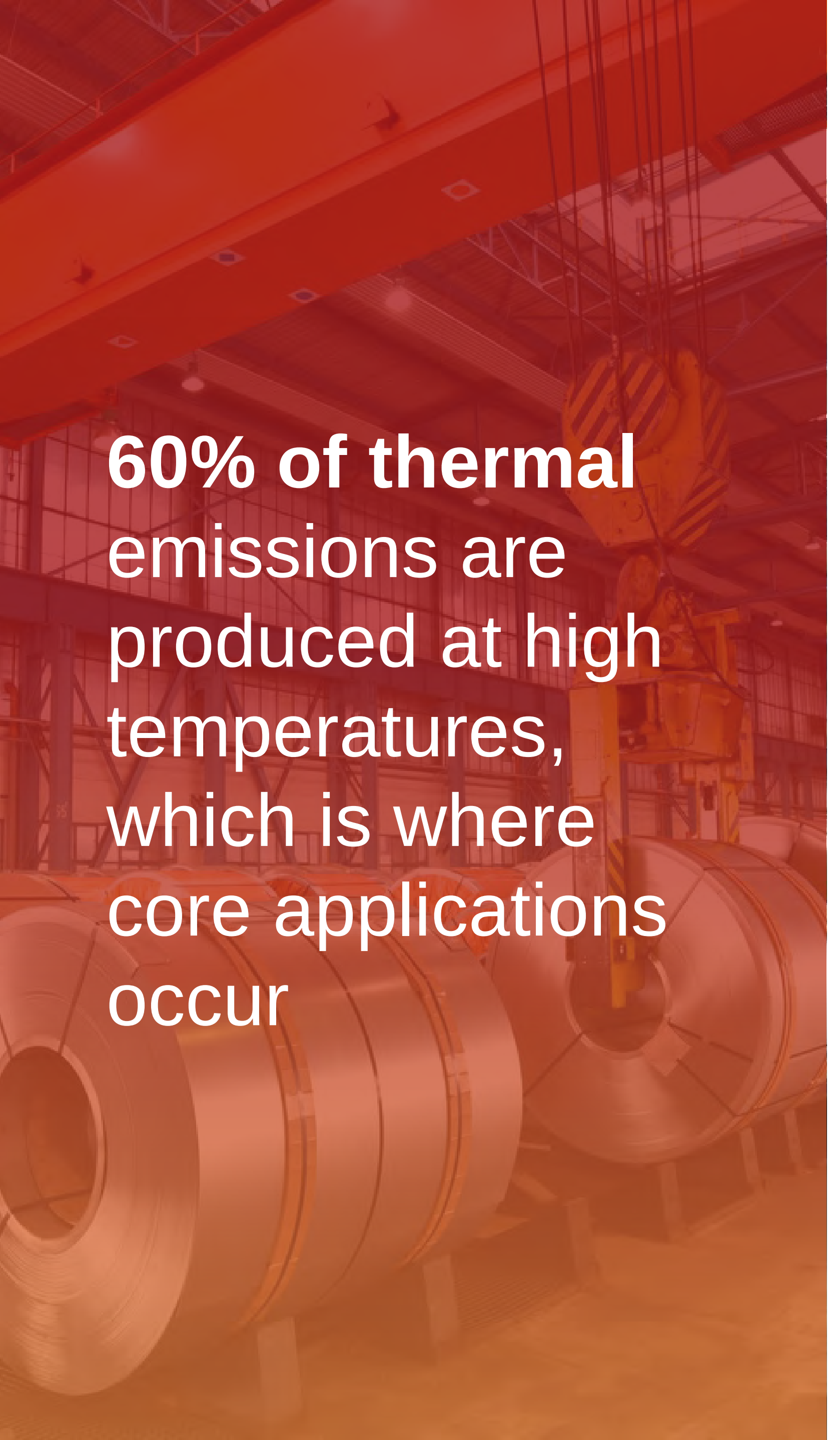
Recently, more manufacturers have been adopting **electric arc furnaces (EAF**) as a cleaner alternative to basic oxygen furnaces. In an EAF, the feed is first melted before oxygen is blown through. Scrap metal is usually used as feed, but direct reduced iron is sometimes used for higher quality steel.

Rolling

1000-1300 ºC

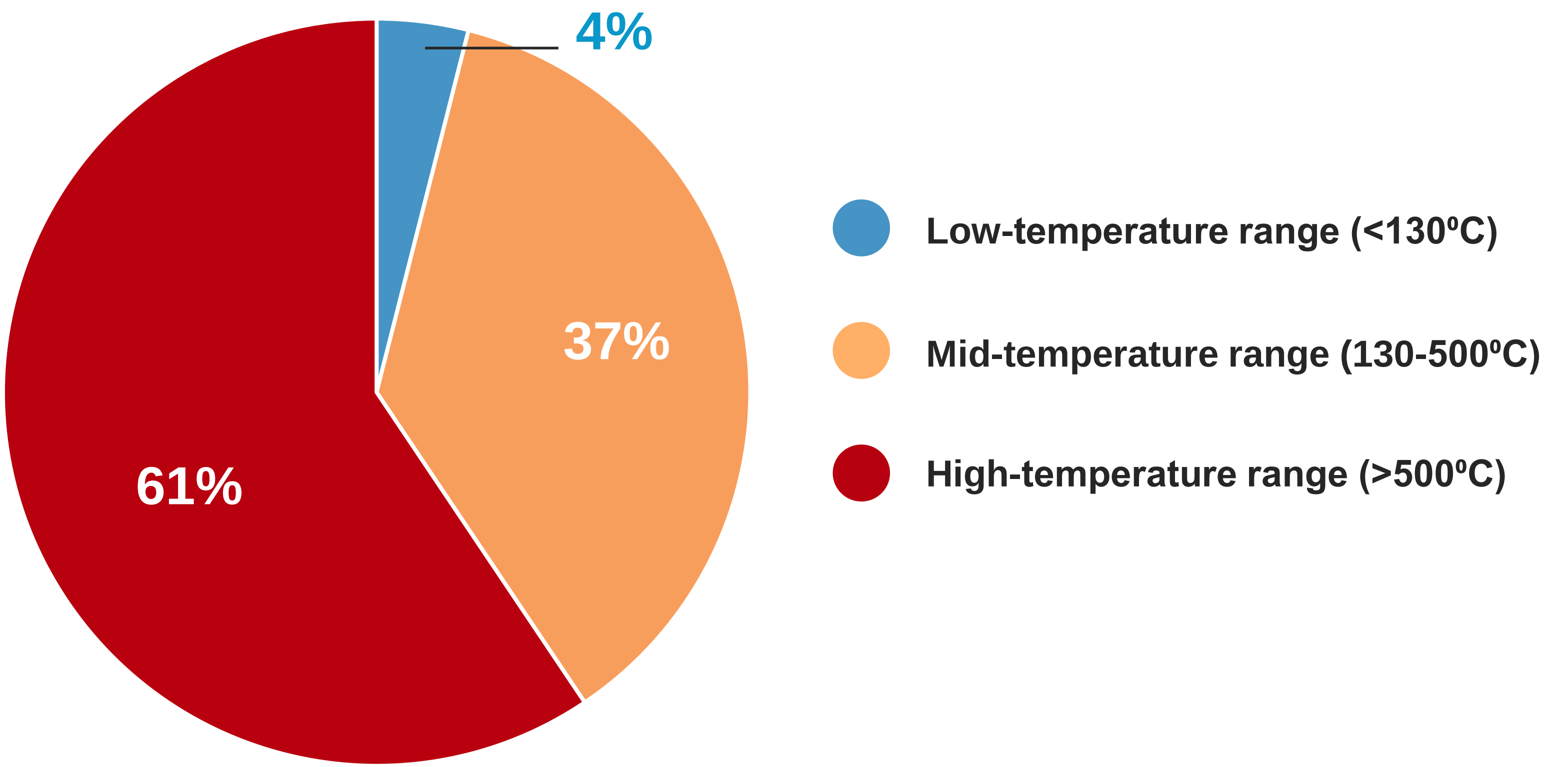
Rolling is a process in which steel billets or slabs are heated in a reheating furnace and passed through one or more pairs of rollers to reduce the thickness of the steel and form it according to the desired dimensions.

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



60% of thermal emissions are produced at high temperatures, which is where core applications occur

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



1. Calculated using the NREL MECS survey data for thermal energy use (2014)

There are three types of facilities in the US; the Blast Furnace-Basic Oxygen Furnace plants are the heaviest emitters

BF-BOF
(Blast furnace – Basic oxygen furnace)

~10 facilities[1]

The conventional method of producing steel involves the use of blast furnaces and basic oxygen furnaces

This process uses coal, is highly carbon intensive, and accounts for the vast majority of thermal emissions in the steel industry

~77% of thermal emissions[1]

Scrap-EAF
(scrap metal with electric arc furnace)

~100 facilities

EAFs produce steel by heating metal feedstock to temperatures up to 1800ºC

EAFs are electrified, less energy intensive, can rapidly start and stop, and produce significantly fewer thermal emissions vs. BF-BOFs

Most US steel facilities use EAFs with scrap metal as feedstock; this produces lower grade steel than the BF-BOFs process

DRI-EAF
(direct reduced iron with electric arc furnace)

3 facilities

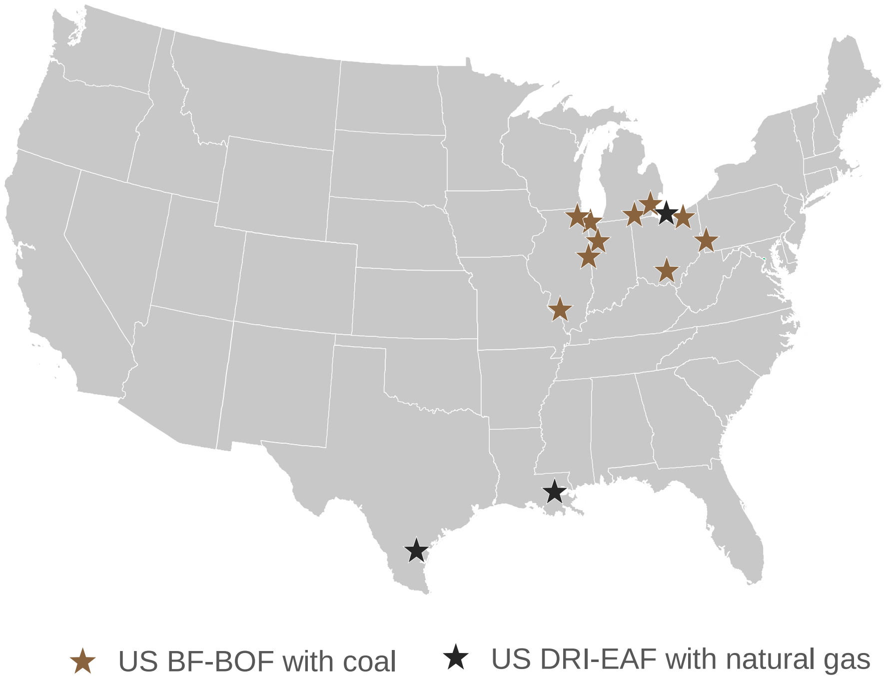
To produce higher quality steel, DRI (direct reduced iron) can be fed into EAFs along with scrap metal

DRI is largely produced using natural gas for combustion and as a feedstock; however, green hydrogen is a viable substitute for heat and as feedstock in next 10-20 years

Clean hydrogen and DRI production scaling is needed to decarbonize BF-BOFs

~23% of thermal emissions

US BF-BOF & DRI-EAF locations



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[1] There were 10 active plants running BF-BOFs the US in 2018, representing 34 million tonnes of CO2e and 77% of sector thermal emissions; this represents 8% of the total US industrial thermal emissions across all sectors included in this analysis; in 2020, one BF-BOF plant shut down its BF-BOFs and there are now approximately 9 plants operating BF-BOFs in the US Source: EPA GHGRP 2018; BCG analysis

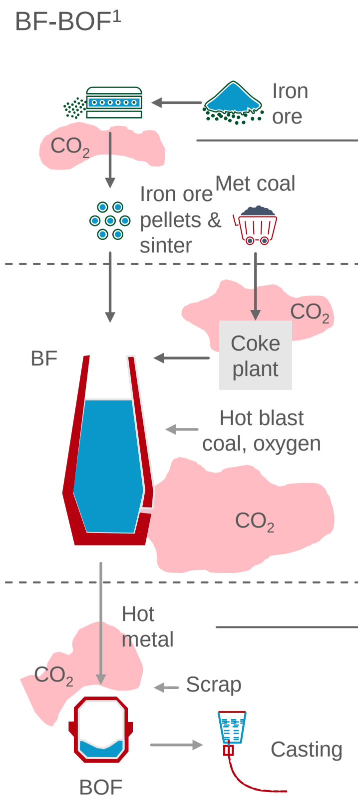
~9 US steel plants running BF-BOFs represent ~7-8% of total US industrial thermal emissions[1]

Starting point: BF-BOF[2]

Raw material inputs

Ironmaking

Steelmaking & casting



Upstream processes such as pelletization emit thermal emissions by heating up the iron ore

Many iron and steelmaking plants include coke plants, which emit thermal emissions in the process of converting coal to blast furnace coke

Blast furnaces produce thermal emissions from heating of input materials, as well as process emissions from the furnace reactions

Steelmaking in the BOF requires heating of oxygen and pig iron, which produce thermal emissions

Several downstream processes such as rolling and reheating produce additional thermal emissions

Area represents amount of CO_2 emissions

1. There were 10 active plants running BF-BOFs the US in 2018, representing 34 million MT of CO2e and 77% of sector thermal emissions; this represents 8% of the total US industrial thermal emissions across all sectors included in this analysis; in 2020, one of the plants shut down its BF-BOFs and there are approximately 9 plants remaining operating BF-BOFs in the US 2. Blast Furnace-Basic Oxygen Furnace

Source: EPA GHGRP 2018; BCG analysis

Primary decarbonizing approaches divide in two main pathways

BF-BOF plants (~77% of emissions)

EAF plants (~23% of emissions)

Switch to DRI-EAF with H_2

Switch to Direct Reduced Iron with an Electric Arc Furnace; use **hydrogen** as primary vector instead of fossil fuels

Natural gas can be used to produce DRI as intermediate step before switching to **green hydrogen** to fully decarbonize

Represents a process change

OR

Deploy CCS

Deploy **CCS in current BF-BOF plants to capture thermal and process-related CO_2** in the remaining US BF-BOF plants

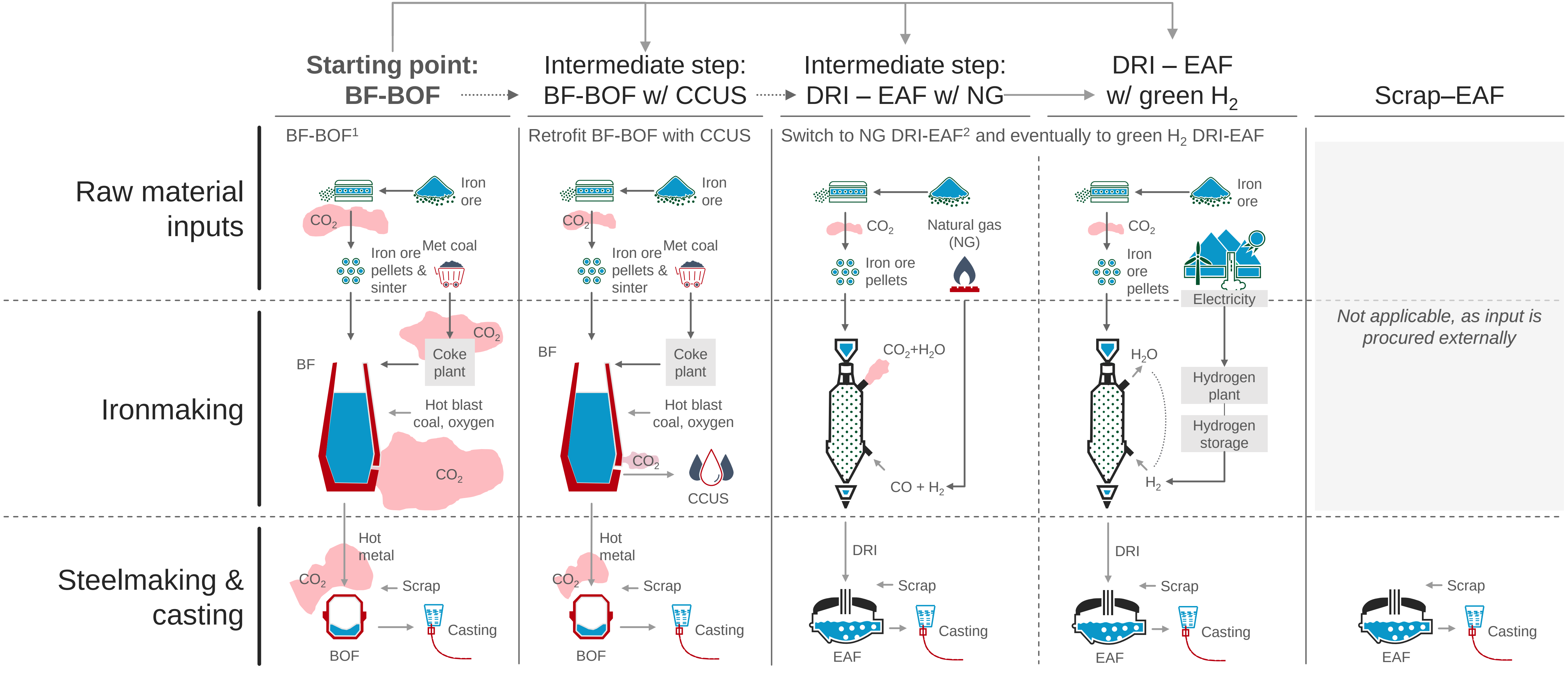
CCS is likely to be deployed earlier on due to insufficient DRI supply in the US to make high quality steel; US development of clean hydrogen is needed to sustainably produce DRI

Eliminate fossil fuel combustion

Displace fossil fuel combustion in upstream and downstream processes (e.g. pelletizing, rolling, casting, etc.) with low carbon fuels and electrification

For any DRI-EAF using natural gas combustion, switch to green hydrogen to fully decarbonize

Evolution from BF-BOF to DRI–EAF with green hydrogen



Starting point: BF-BOF → Intermediate step: BF-BOF w/ CCUS → Intermediate step: DRI – EAF w/ NG → DRI – EAF w/ green H_2

Scrap–EAF

Raw material inputs

Ironmaking

Steelmaking & casting

BF-BOF[1]

Iron ore
CO_2
Iron ore pellets & sinter
Met coal
CO_2
BF
Coke plant
Hot blast coal, oxygen
CO_2
Hot metal
CO_2
Scrap
Casting
BOF

Retrofit BF-BOF with CCUS

Iron ore
CO_2
Iron ore pellets & sinter
Met coal
BF
Coke plant
Hot blast coal, oxygen
CO_2
CCUS
Hot metal
CO_2
Scrap
Casting
BOF

Switch to NG DRI-EAF[2] and eventually to green H_2 DRI-EAF

CO_2
Natural gas (NG)
Iron ore pellets
CO_2+H_2O
CO + H_2
DRI
Scrap
Casting
EAF

Iron ore
CO_2
Iron ore pellets
Electricity
H_2O
Hydrogen plant
Hydrogen storage
H_2
DRI
Scrap
Casting
EAF

Not applicable, as input is procured externally
Scrap
Casting
EAF

Area represents amount of CO_2 emissions

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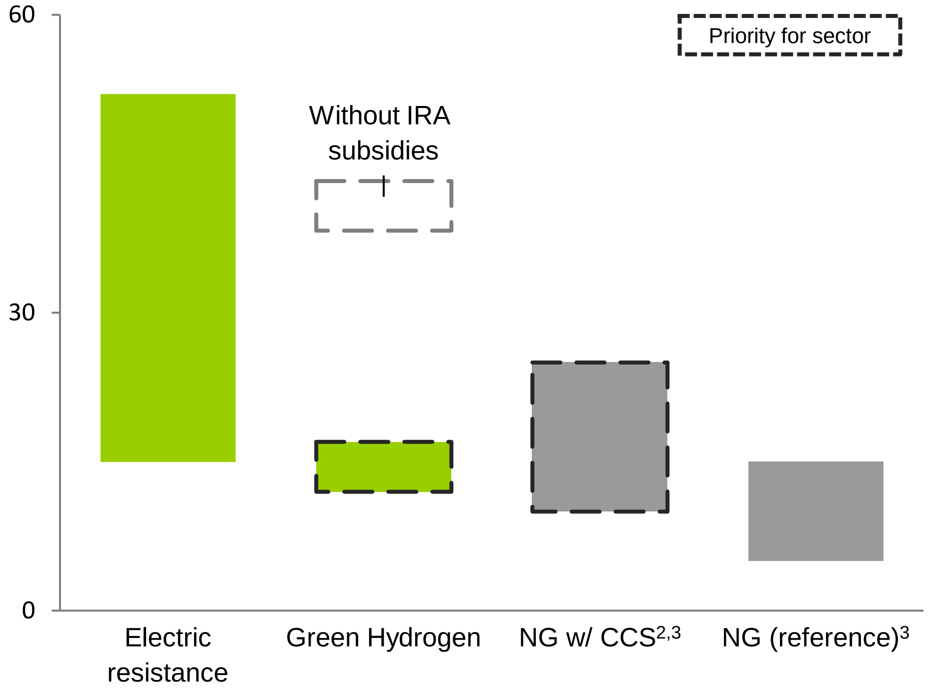
1. Blast Furnace-Basic Oxygen Furnace 2. Direct Reduced Iron-Electric Arc Furnace

Source: BCG analysis

NG w/ CCS & green H2 are most economic alternatives to NG combustion as the sector transitions away from coal to DRI-EAF w/ green H2

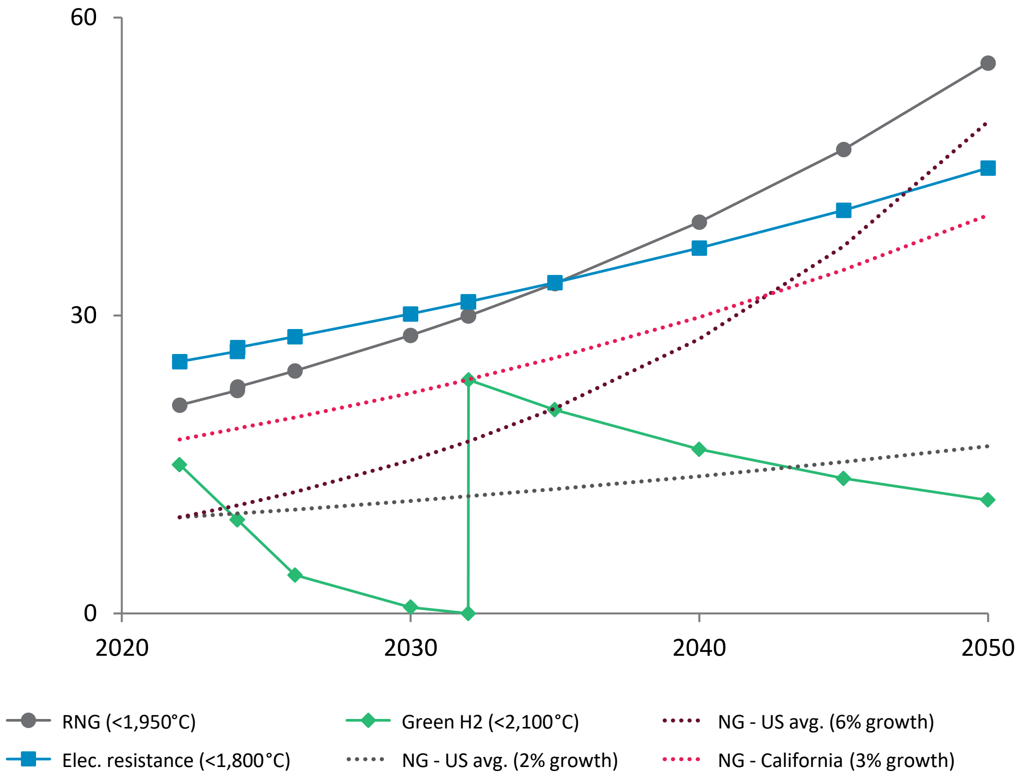
2022 LCOH for relevant technologies[1]

($/MMBtu)



Projected LCOH for relevant technologies[1]

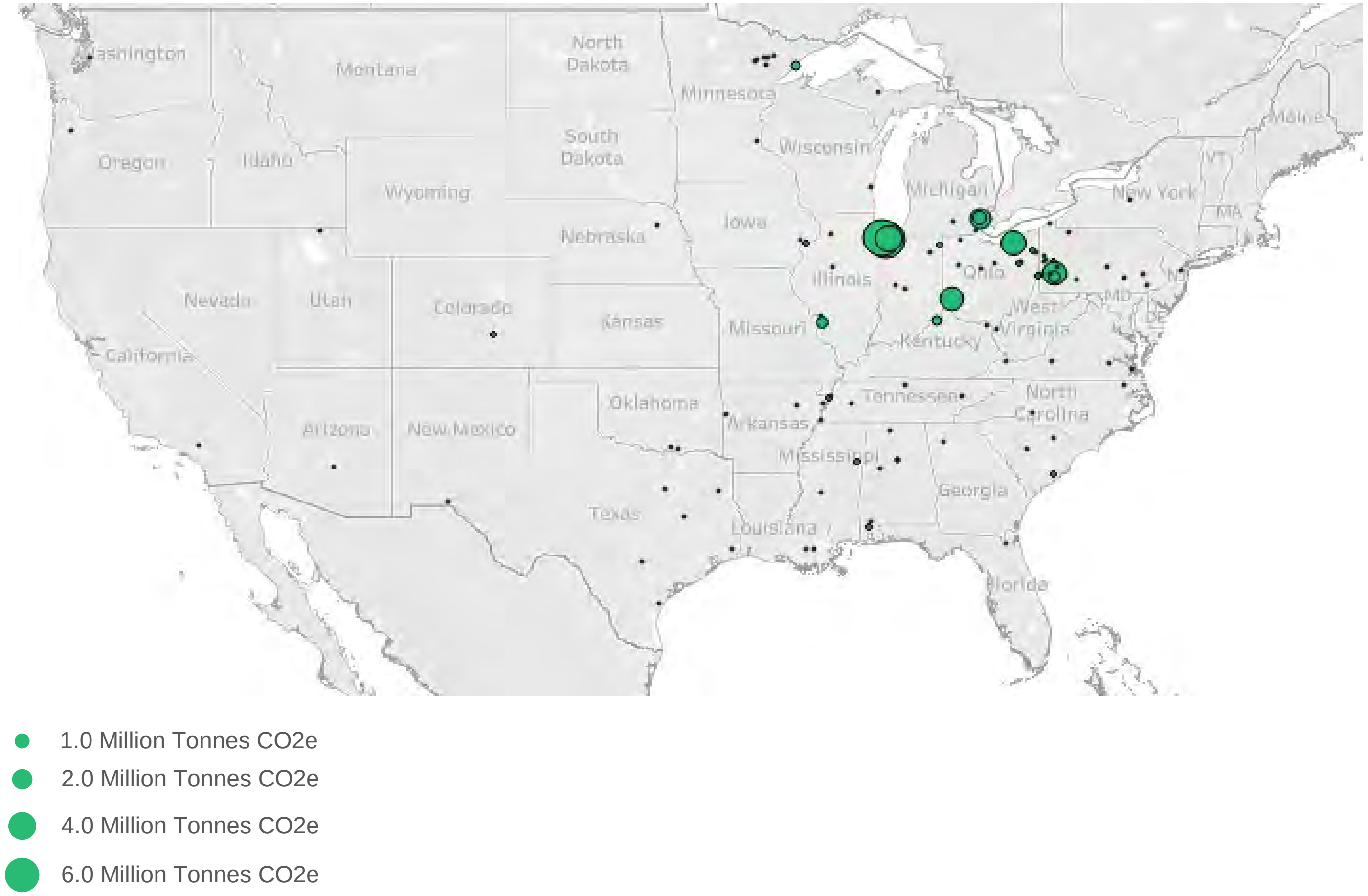
Average US LCOH ($/MMBtu)



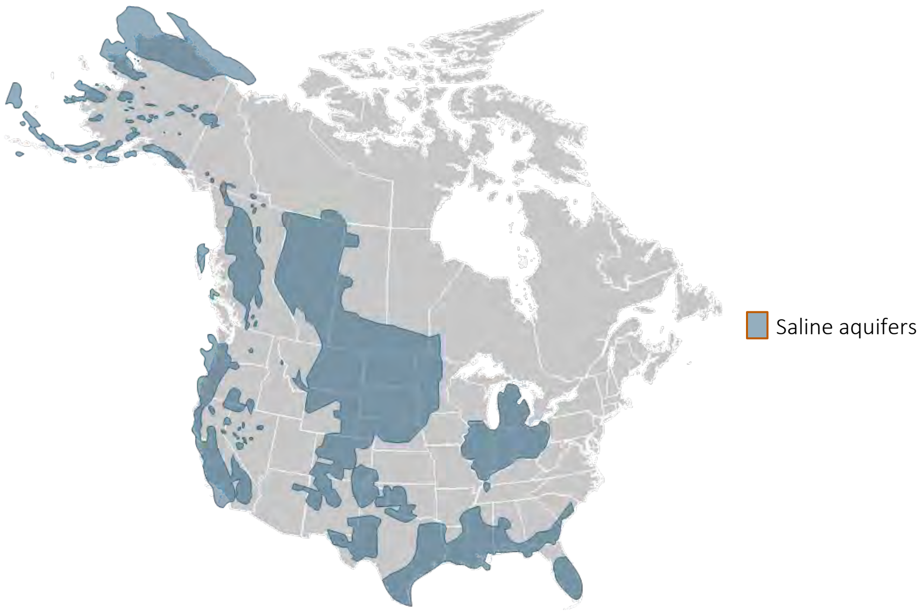
1. LCOH compares project lifetime costs against lifetime energy produced; costs include capital expense of equipment, fuel costs, and maintenance expense assumptions over the usable life of the energy asset. Electricity and natural gas pricing is based on national weighted average wholesale industrial 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

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

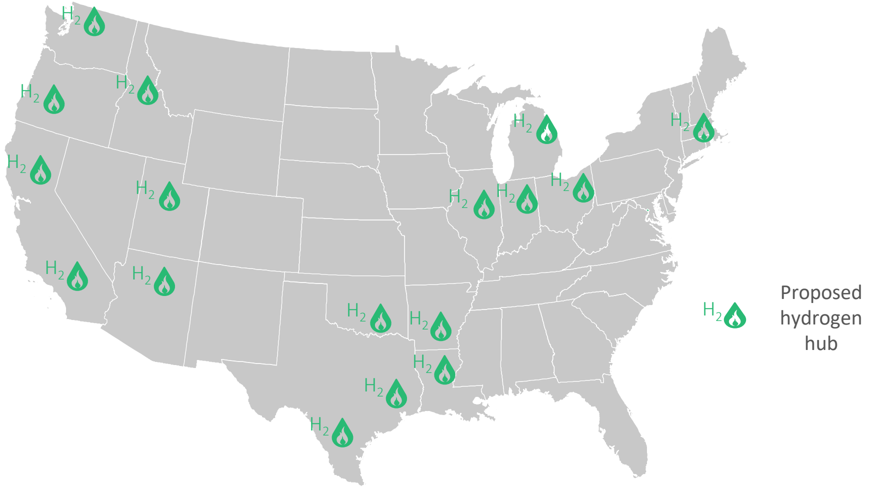
US Iron & Steel sector thermal emissions by zip code[1]



CCS sequestration geographies[2]



Proposed hydrogen hubs[3]



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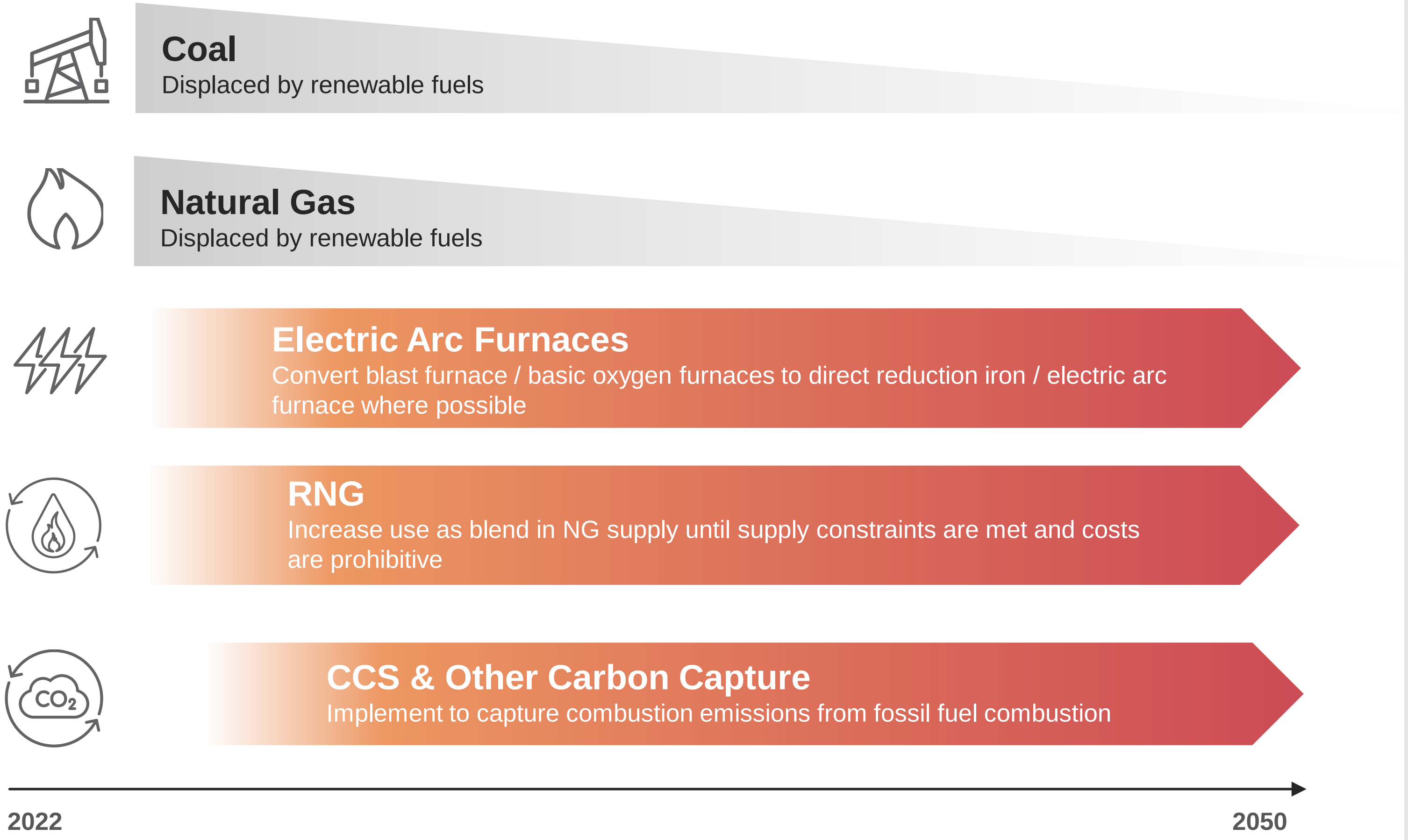
1. EPA GHGRP Inventory FLIGHT Database (2018); captures actual onsite reported emissions for large emitters emitting >25K tonnes of CO2e per year 2. USGS, NETL NATCAB 3. CSIS (2022)

Decarbonization pathways



Coal
Displaced by renewable fuels

Natural Gas
Displaced by renewable fuels

Electric Arc Furnaces
Convert blast furnace / basic oxygen furnaces to direct reduction iron / electric arc furnace where possible

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

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

Considerations	Target First Movers
Iron and steel making value chain (i.e., simultaneous deployment of DRI with EAF), grid or PPA supports emissions savings	End-of-life or greenfield steel mills, ability to procure inexpensive electricity
Adequate supply of fuel	Regions with grid RNG blending (Midwest, Southeast)
Concentration of CO2 in flue gas, government subsidies	Regions with iron & steel clusters and adequate geology for storage

The majority of current US steel production is from EAF, but several BF/BOF iron and steelmaking facilities contribute disproportionately to total sector emissions. To reduce thermal emissions, **iron and steel makers should phase out BF/BOF to DRI/EAF or deploy CCS**.

Thermal decarbonization pathways

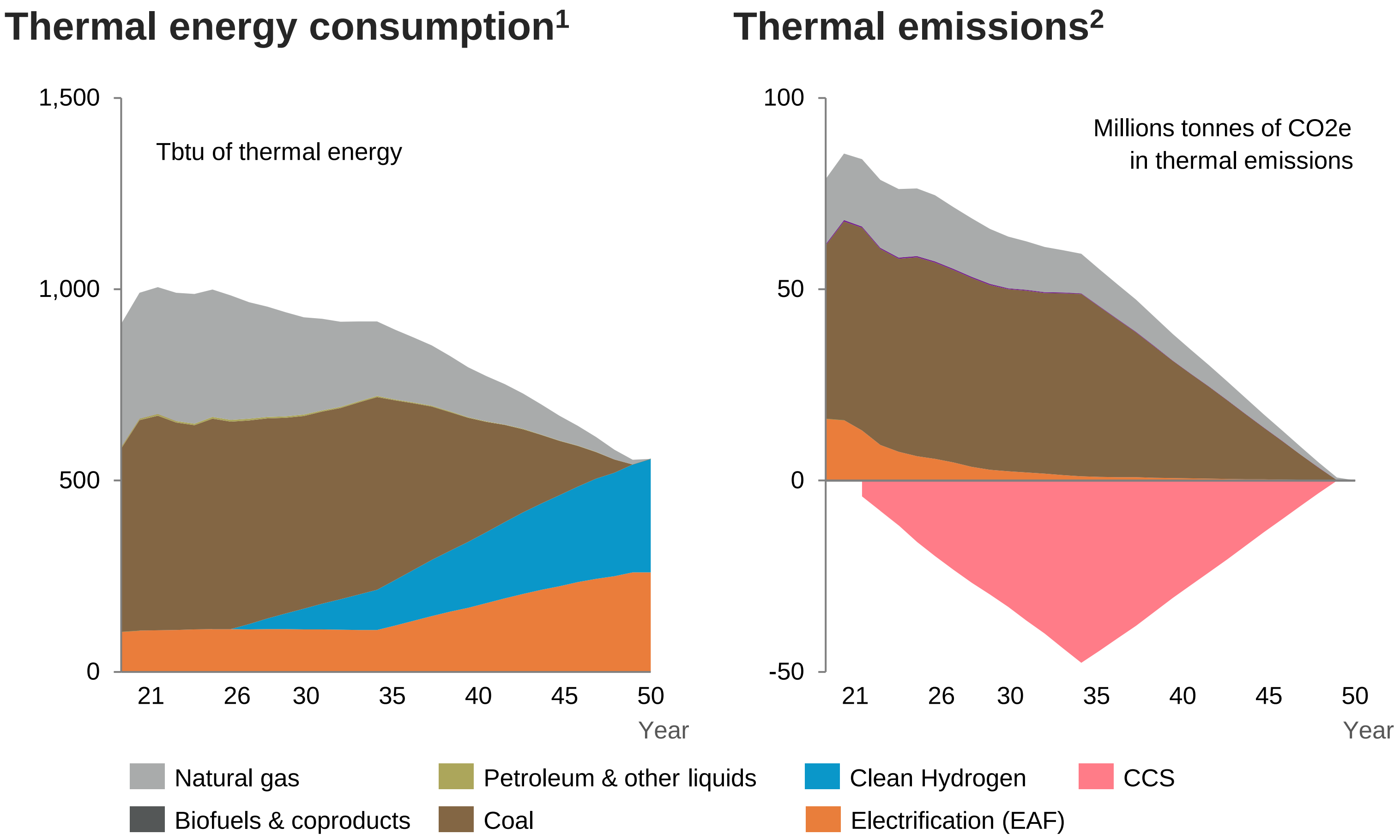
Primary decarbonizing pathway is **transitioning away from blast furnaces (BF) and basic oxygen furnaces (BOF)**, which use coal, to electrified processes – producing direct reduced iron (DRI) with electricity & clean hydrogen (replaces BF) and using an **electric arc furnace** (EAF; replaced BOF). This process largely eliminates use of coal. DRI-EAF with green hydrogen is less energy intensive than BF-BOF and total thermal energy consumption is expected to decline as sector transitions

More than 2/3 of US steel facilities today use EAFs, and only ~10 facilities remain operating ~14 total blast furnaces - these facilities generated 77% of total thermal emissions for the sector in 2018

Data suggests current stock of BF-BOFs will require upgrades from 2023-2036 period, however, due to various sector specific factors including insufficient DRI supply to produce high quality steel, the remaining BF-BOFs are not expected to convert to DRI-EAF w/ green hydrogen in the short and medium term. The decarbonization pathway model delays converting BF-BOFs to 2036 and converts all ~14 BF-BOFs by 2050.

In the interim period, the sector should deploy CCS to capture emissions while the transition to DRI-EAF w/ green hydrogen occurs, upon which CCS can be phased out

This sector also combusts natural gas for heat in upstream and downstream heat applications (e.g. hot rolling); **use of fossil combustion can be displaced through 2050 with green hydrogen**



Thermal energy consumption[1]

Thermal emissions[2]

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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 outlook; EIA emissions intensity; BCG analysis

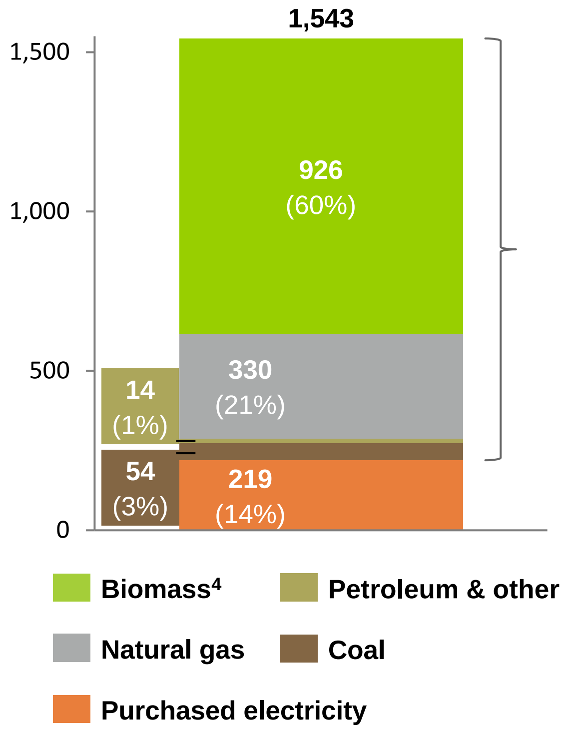
Paper

Sector Perspectives

60% of thermal energy is from combustion of biofuels, which produces unrecorded biogenic emissions of over 100 million tonnes of CO2e annually

Total energy consumption (2018)[1]

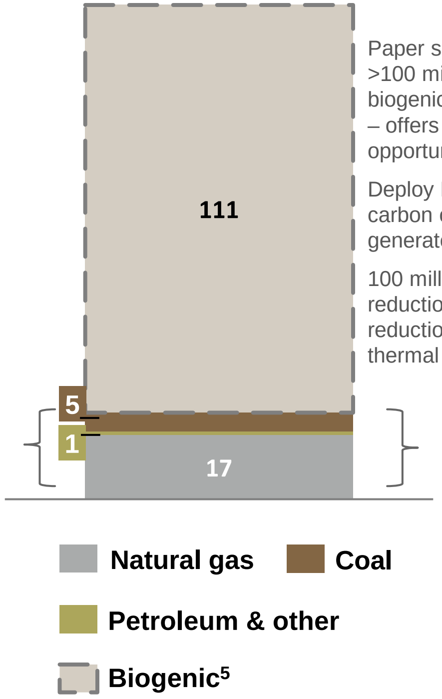
Trillion Btu



Thermal emissions (2018)[2]

Million Tonnes of CO2e

24 (fossil) + 111 (biogenic) = **135 total**



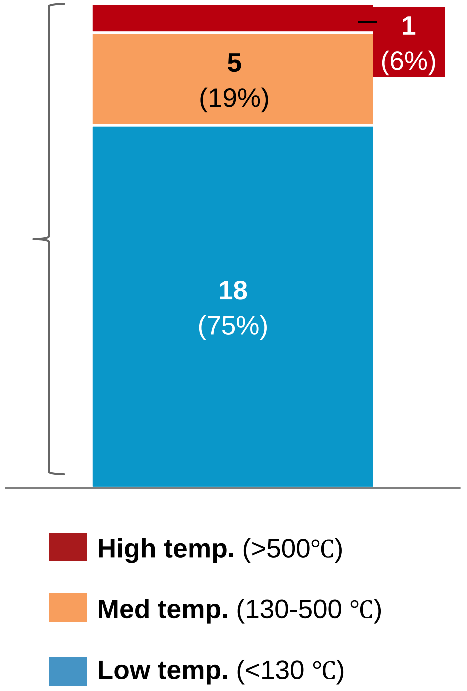
Paper sector generates >100 million tonnes of biogenic emissions annually – offers sizeable abatement opportunity:

Deploy BECCS using IRA carbon capture credits and generate negative emissions

100 million tonne emissions reduction equates to a ~15% reduction in US industrial thermal emissions

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

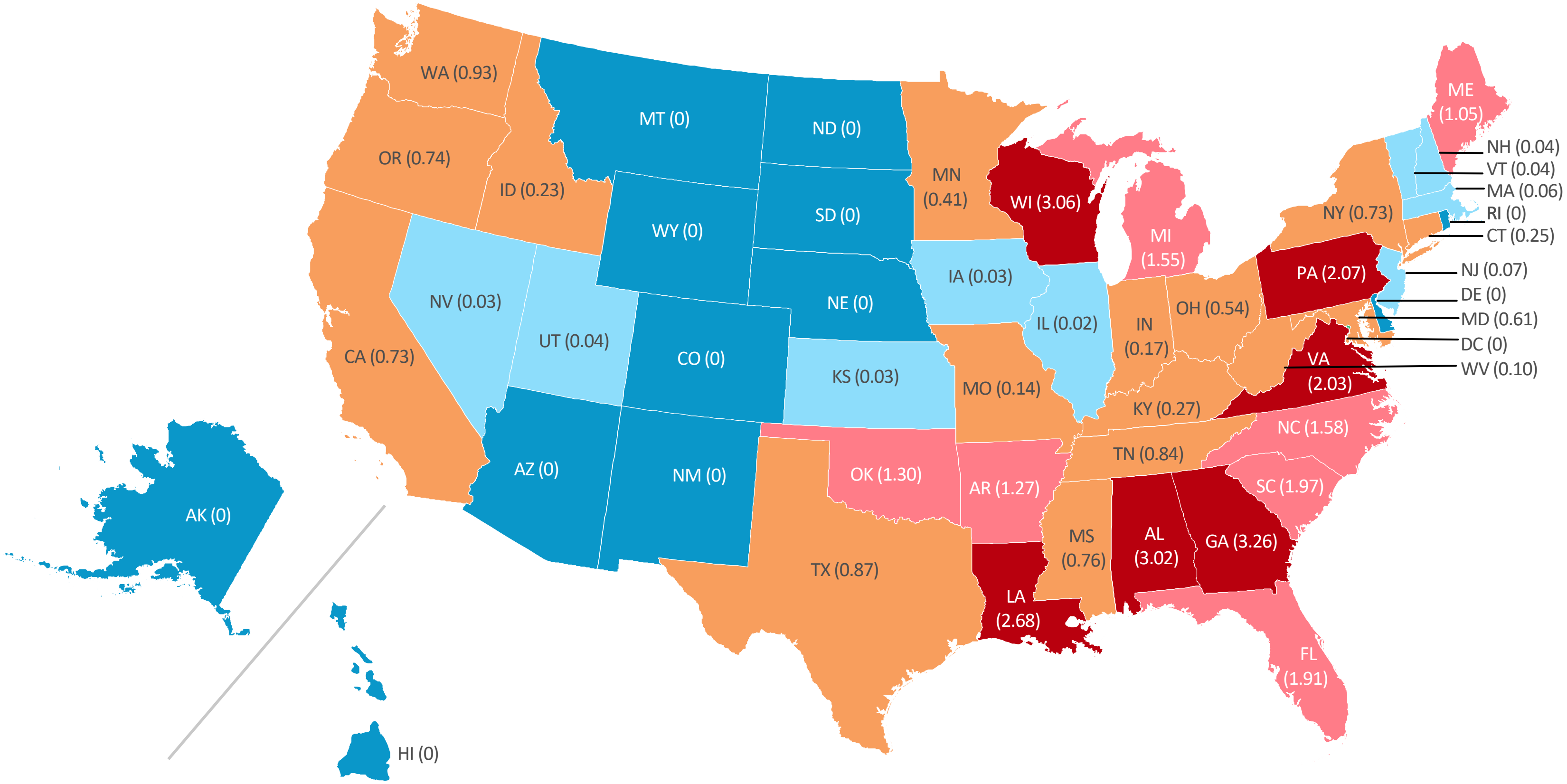
Million Tonnes of CO2e



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. Biomass emissions are considered net zero by EPA and related biogenic emissions are not recorded in EPA thermal emissions data 5. Total paper sector biogenic CO2e emissions exceed 111 million tonnes in 2018 with the top 50 facilities generating ~75 million tonnes of biogenic CO2e; biogenic emissions primarily result from combustion of woody biomass and black liquor Source: EIA; EPA; NREL; BCG analysis

Thermal emissions are concentrated in the Southeast and Great Lakes

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



Paper industries are focused in the Southeast and Great Lakes regions, where there are abundant and fast-growing wood resources

- ● Near zero
- ● <0.1 Million Tonnes CO2e
- ● 0.1-1 Million Tonnes CO2e
- ● 1-2 Million Tonnes CO2e
- ● >2 Million Tonnes CO2e

1. EPA GHGRP Inventory FLIGHT Database (2018); captures actual onsite reported emissions for large emitters emitting >25K tonnes of CO2e/year 2. May include some process emissions (<25% of total)

Key heat applications require low & medium temperatures and can be electrified; several processes are already electrified at some facilities

Wood Processing

200 ºC

The paper making process usually begins with **wood processing**, which involves the de-barking and chipping of wood (e.g. whole trees, short wood, wood chips, woody biomass) to produce wood chips that can be used in pulp production.

Evaporation & Chemical Preparation

60-200 ºC

Processed woodchips are cooked in a **pressurized digester** to break down lignin and produce pulp. The chips are heated under pressure along with white liquor (strong alkaline solution composed of NaOH and Na2S). The resultant pulp is called brown liquor and the byproduct is called black liquor.

Bleaching

60-150 ºC

The chemically processed pulp is often **bleached** in order to lighten its color. The major bleaching agents used in paper mills today include chlorine dioxide, oxygen, hydrogen peroxide, and ozone. Steam from boilers is used in the bleaching process to add heat to the pulp.

Stock Steaming Preparation

60-150 ºC

After bleaching, pulp is fed into a **stock machine**, in which the pulp's fibers are blended, refined, diluted, and metered. Various fillers are also added for purposes such as whitening, strength, and opacity.

Drying

70-150 ºC

The **drying process** typically involves refined and pressed pulp sheets being winded over heated steam cans, causing most of the moisture to evaporate. This is the second most energy-intensive process in papermaking, after chemical preparation.

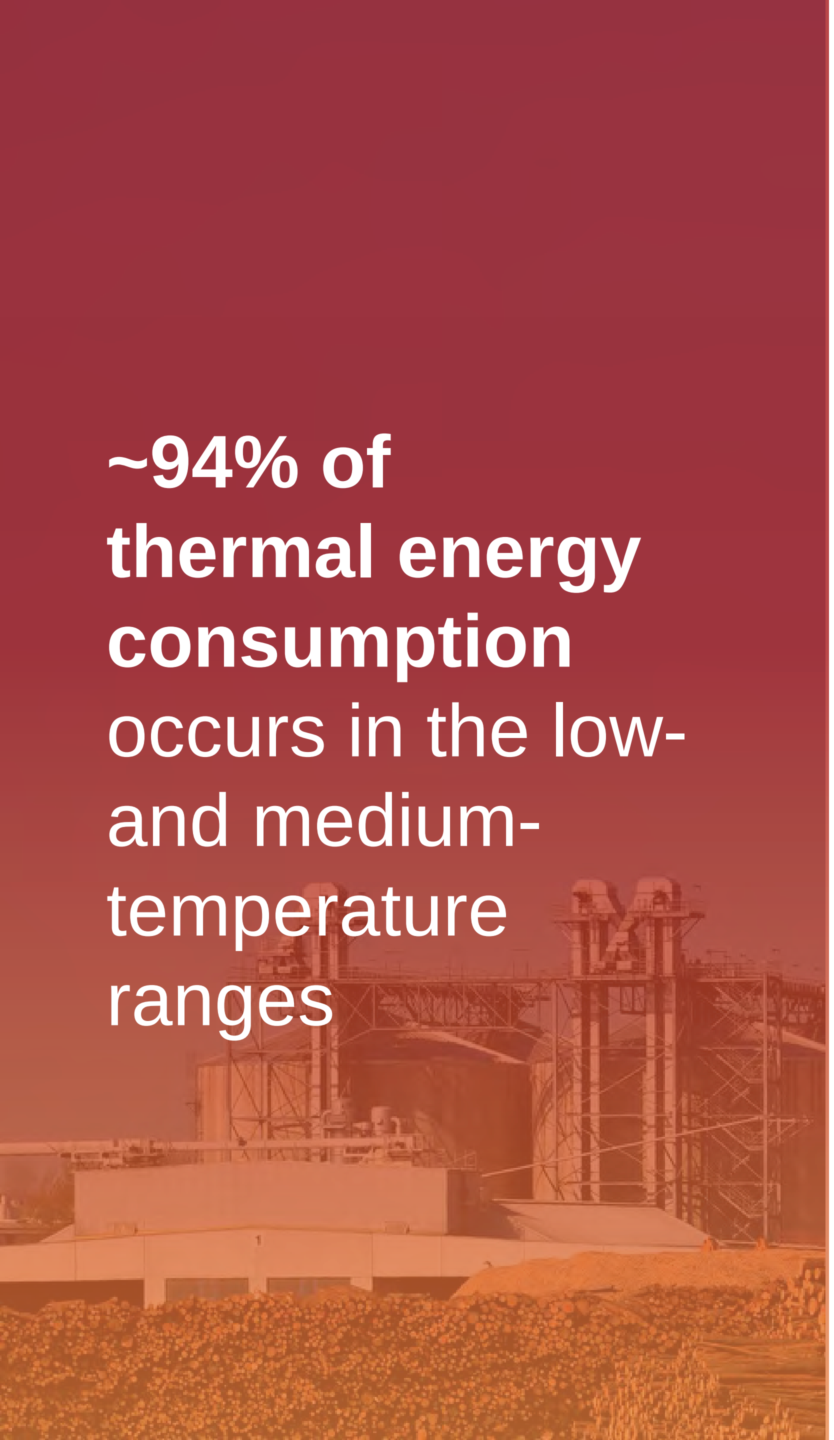
Re-causticizing

800-1200 ºC

In order to optimize the efficiency of the chemical digestion process, recovery boilers and lime kilns are used to convert green liquor (sodium carbonate) to white liquor (sodium hydroxide), which is used for chemical digestion. This process is known as **re-causticizing**.

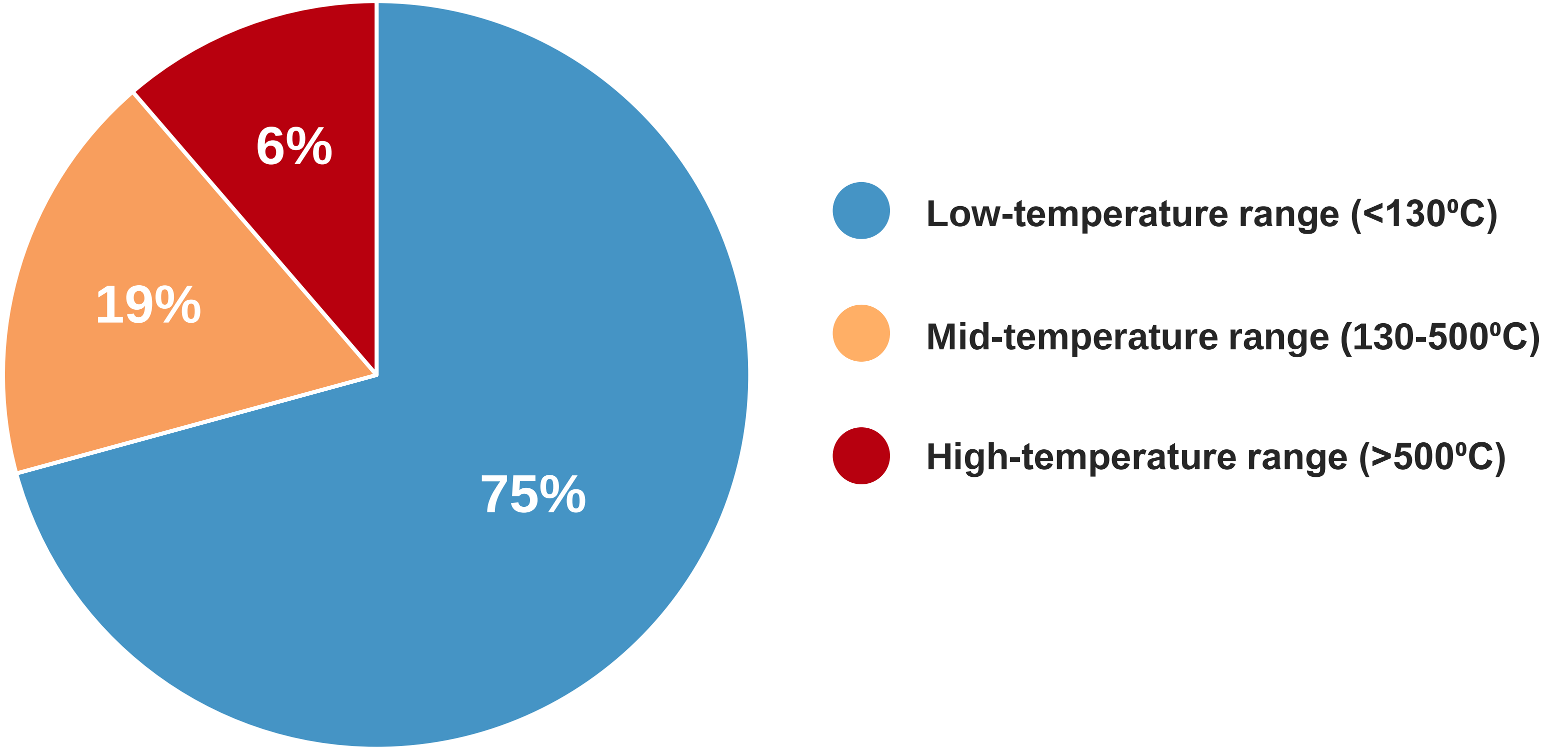
Low-temperature heat processes are well suited for electrification, solar thermal, biomass

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



~94% of thermal energy consumption occurs in the low- and medium-temperature ranges

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

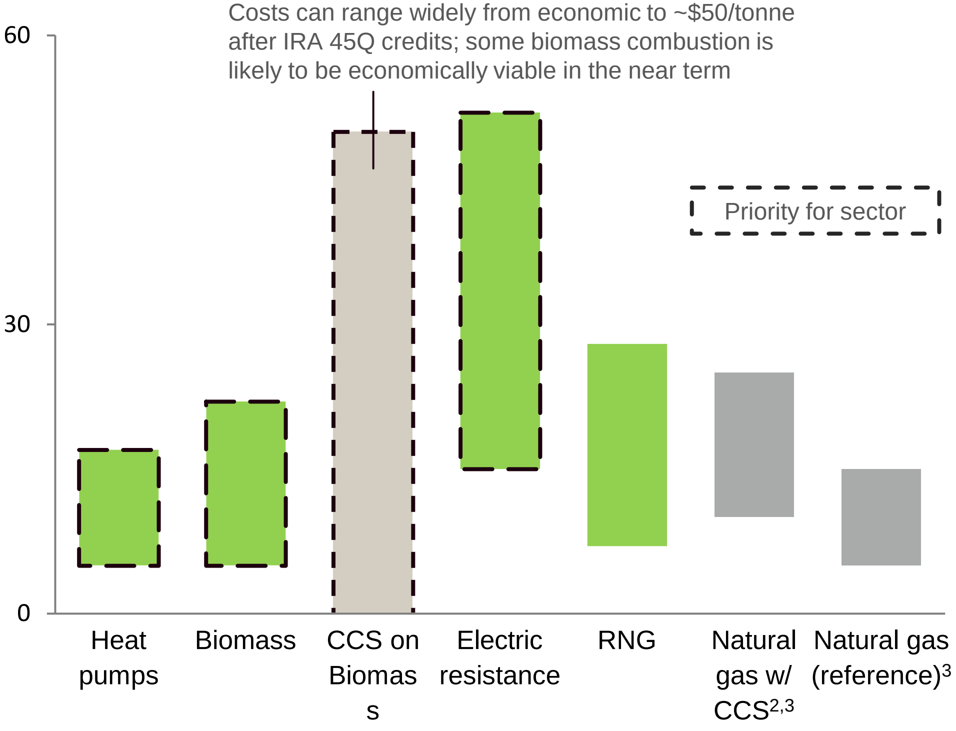


[1] NREL Manufacturing Thermal Energy Use in 2014
Source: DOE (2022), industry reports and papers, BCG analysis

Biomass and heat pumps are the most economic renewable fuel alternatives to natural gas in the short, medium and long term

2022 LCOH for relevant technologies[1]

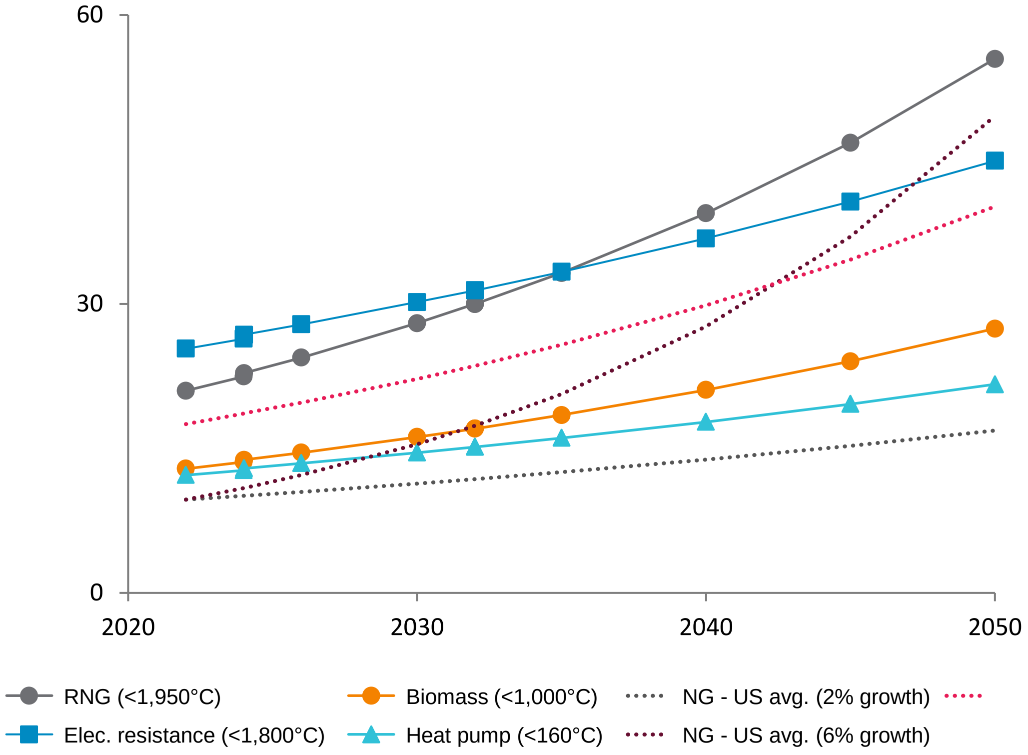
($/MMBtu)



Costs can range widely from economic to ~$50/tonne after IRA 45Q credits; some biomass combustion is likely to be economically viable in the near term

Projected LCOH for relevant technologies[1]

Average US LCOH ($/MMBtu)



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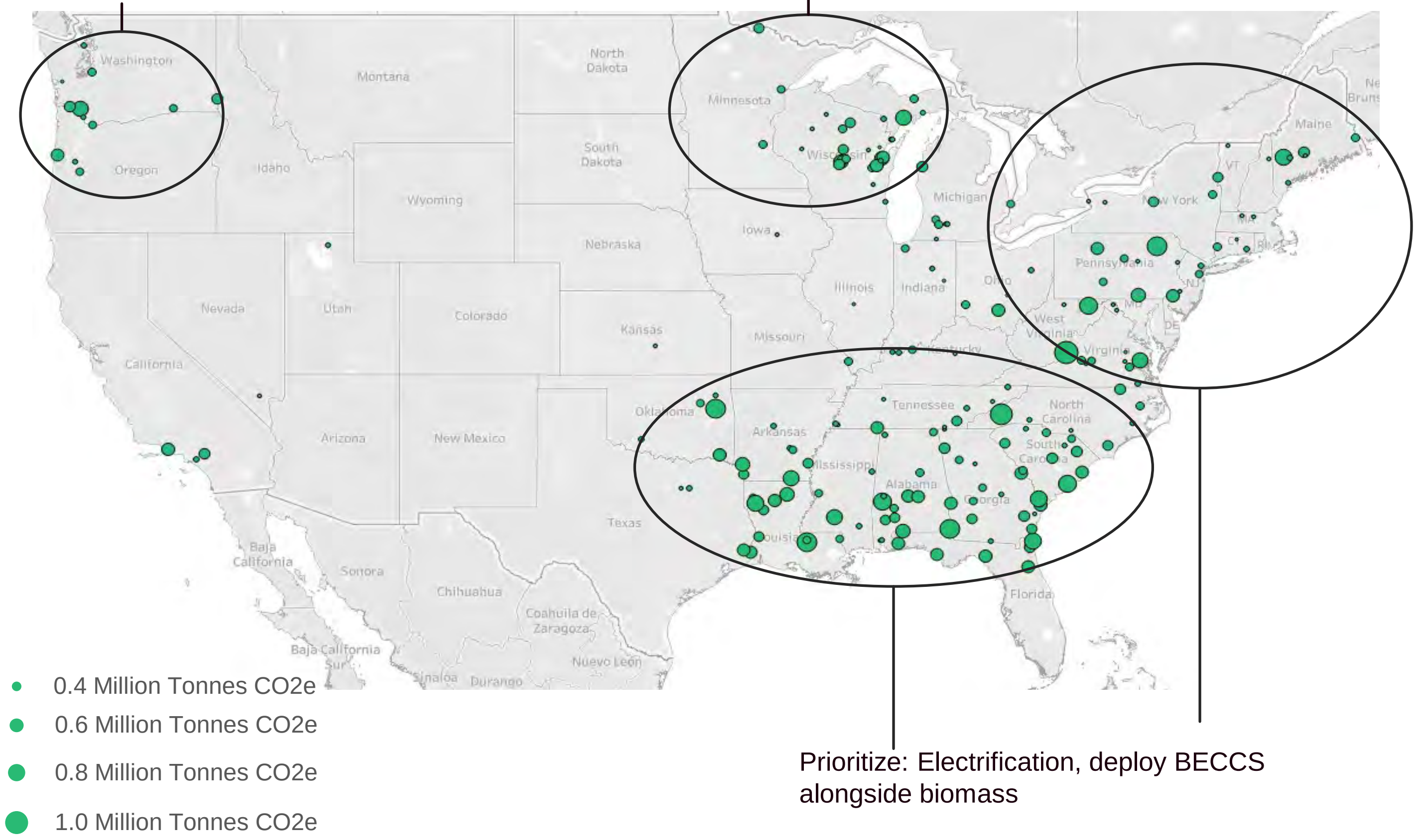
1. LCOH compares project lifetime costs against lifetime energy produced; costs include capital expense of equipment, fuel costs, and maintenance expense assumptions over the usable life of the energy asset. Electricity and natural gas pricing is based on national weighted average wholesale industrial 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

Heat pumps appear cost effective and reduce emissions in ~45 states today

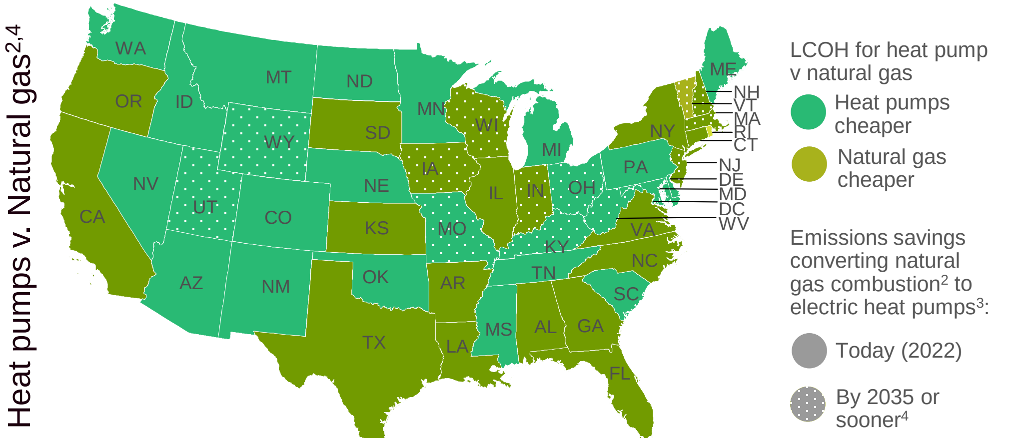
US Paper Sector thermal emissions by zip code[1]



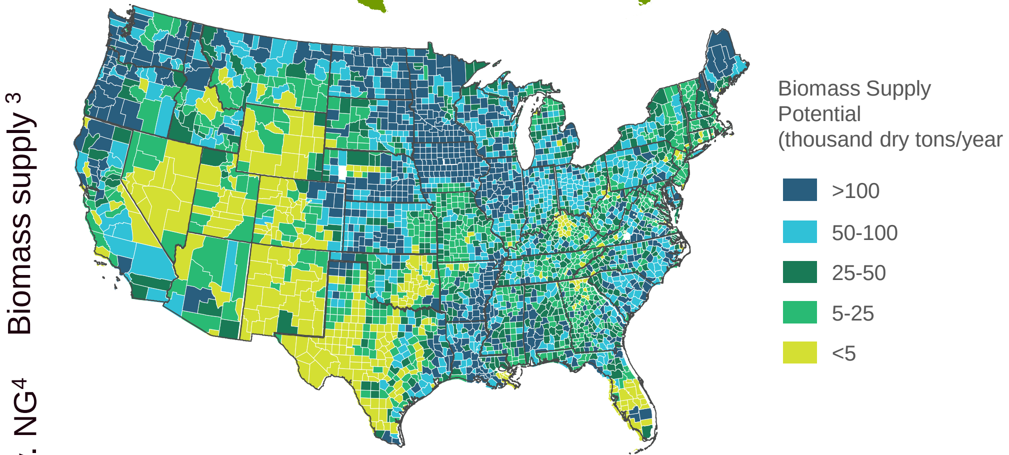
Prioritize: Electrification, BECCS

Prioritize: Biomass, BECCS, Electrification

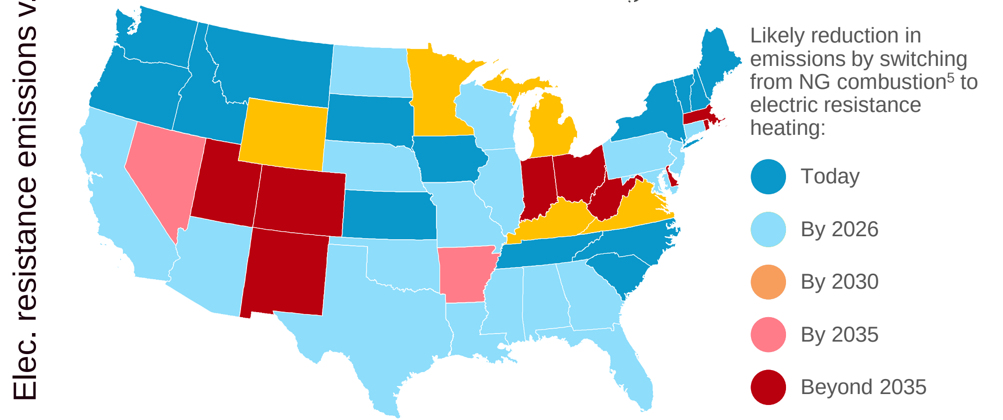
Prioritize: Electrification, deploy BECCS alongside biomass



Heat pumps v. Natural gas[2,4]



Biomass supply 3



Elec. resistance emissions v. NG[4]

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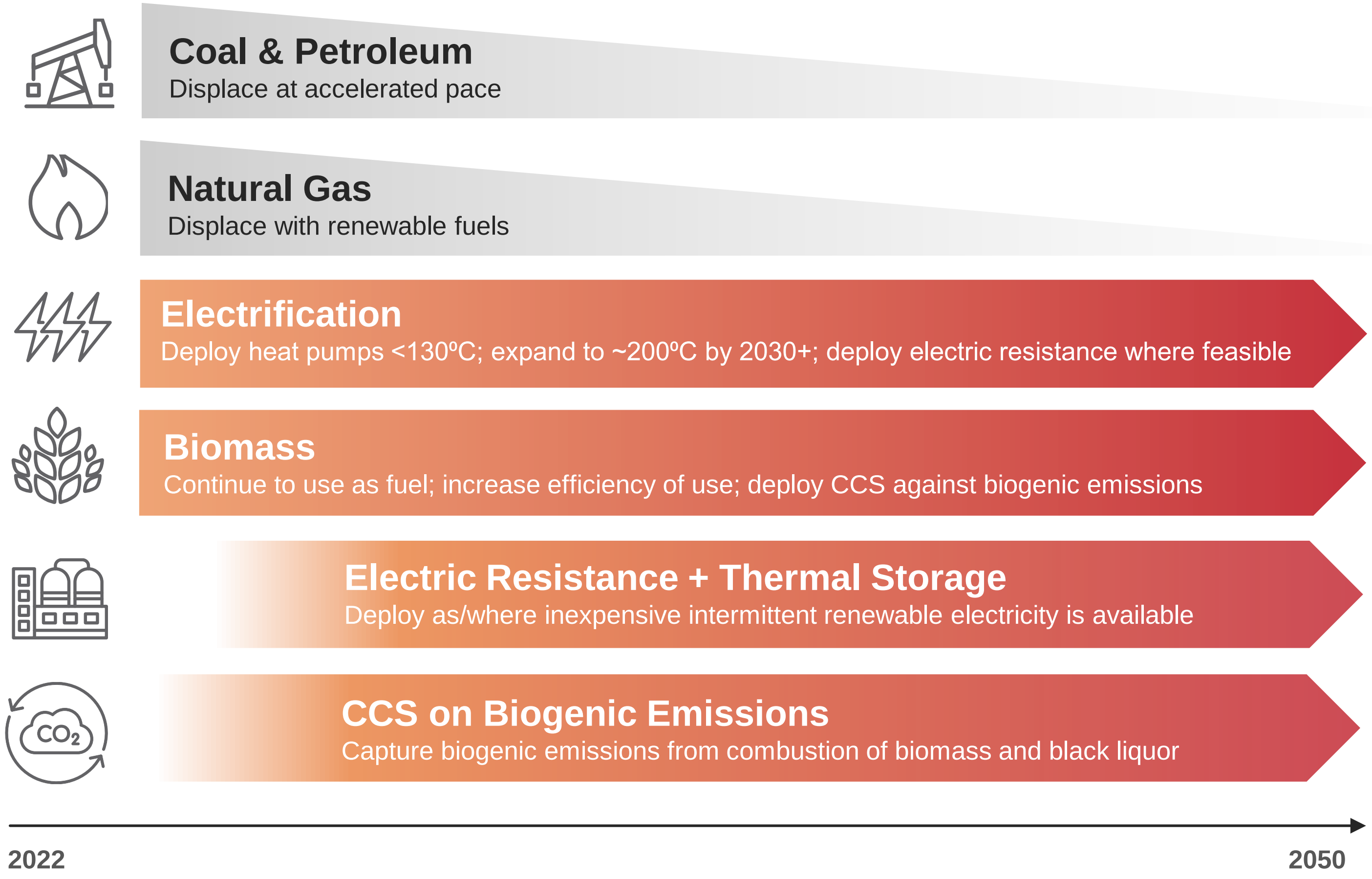
1. EPA GHGRP Inventory FLIGHT Database (2018); captures actual onsite reported emissions for large emitters emitting >25k tons of CO2e per year 2. US EIA Industrial Electricity Prices (May 2022), US EIA Industrial Natural Gas Prices (May 2022), Industrial Heat Pumps: Electrifying Industry's Process Heat Supply – ACEEE 3. NREL Biofuels Atlas 4. US EPA GHGRP (2019); US EIA; State Renewable Portfolio Standards; IEA ETSAP Industrial Combustion Boilers Fact Sheet; BCG analysis 5. Calculated using 85% efficiency for natural gas boiler 6. Calculated using a conservative COP of 3

Decarbonization pathways



Coal & Petroleum
Displace at accelerated pace

Natural Gas
Displace with renewable fuels

Electrification
Deploy heat pumps <130ºC; expand to ~200ºC by 2030+; deploy electric resistance where feasible

Biomass
Continue to use as fuel; increase efficiency of use; deploy CCS against biogenic emissions

Electric Resistance + Thermal Storage
Deploy as/where inexpensive intermittent renewable electricity is available

CCS on Biogenic Emissions
Capture biogenic emissions from combustion of biomass and black liquor

Considerations	Target First Movers
State electricity grid emissions intensity for elec. resistance	States with inexpensive electricity, or high NG price
Availability and sustainability of wood waste and byproducts	Current pulp and paper manufacturers
Grid or PPA supports emissions savings, viable economics	Ability to procure inexpensive intermittent electricity
Potential to produce 100 million tonnes of negative emissions (annually)	Regions with paper clusters and adequate geology for storage or location for transport of carbon

Biomass combustion constitutes the majority of thermal energy with the remainder fueled by natural gas and petroleum — **fossil fuels can be displaced with electrification and increased use of waste biomass**

Combustion of biomass and black liquor appears to generate biogenic emissions of **100+ million tonnes** of CO2e annually – CCS should be evaluated across the sector to identify economically viable opportunities for BECCS to create negative emissions (using IRA 48Q tax credits of $85/tonne)

Thermal decarbonization pathways

94% of industrial heat is in low (75%) and medium (19%) temperature ranges, which can be **decarbonized on an accelerated timeline** with electrification and heat pumps

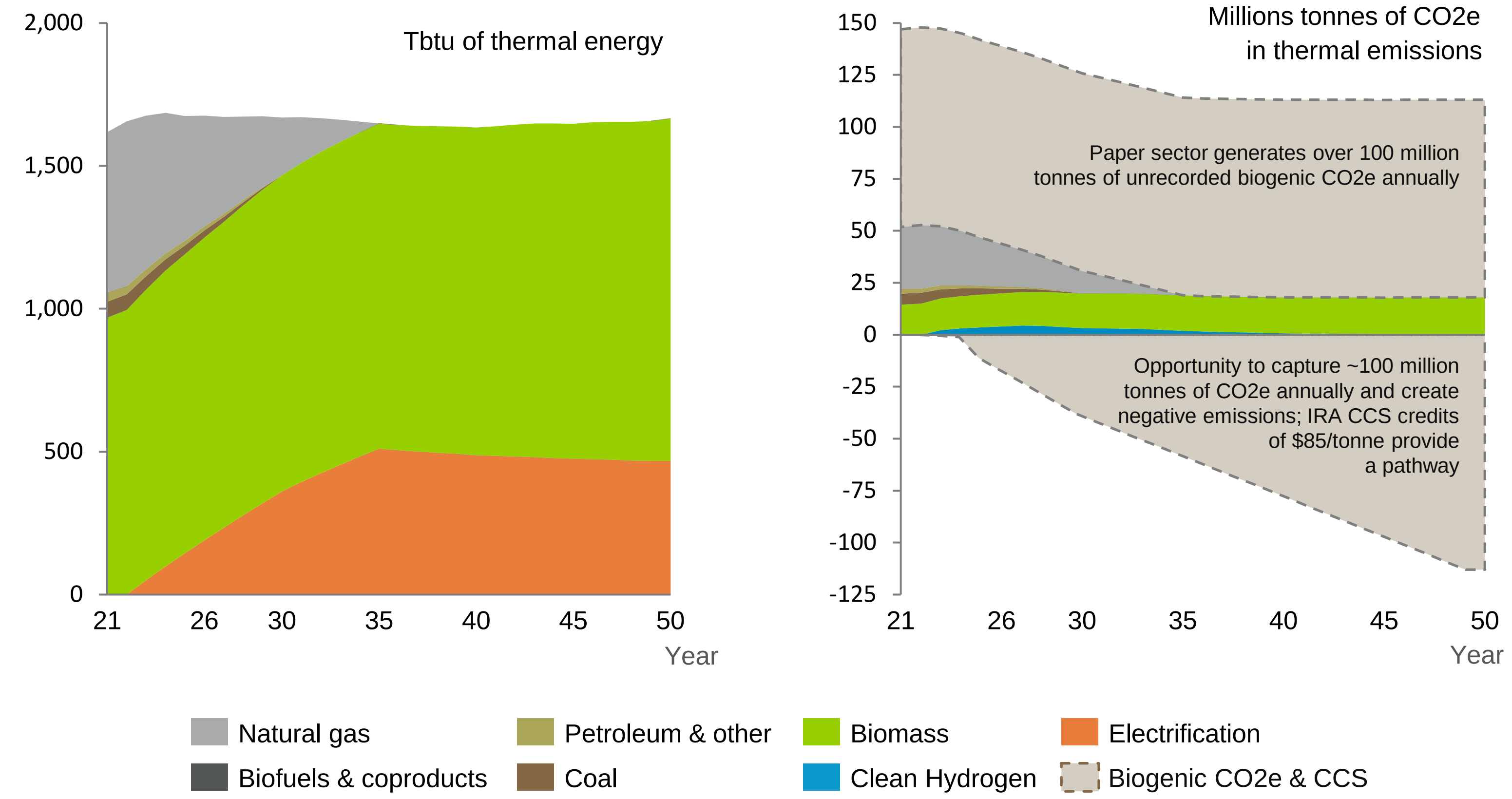
Use of fossil coal and petroleum is **phased out by 2030**, and natural gas **phased out by 2035** – replaced primarily by electrification
Woody biomass represents majority of current energy consumption; increased efficiency in use of biomass is recommended to reduce released carbon from waste

The sector generated 111 million tonnes of biogenic CO2e3,4 in 2018 primarily due to combustion; while these emissions are unreported, there is an opportunity for the sector to capture this carbon, which would equate to a ~15% reduction in total industrial thermal emissions.

Bio-energy with carbon capture and sequestration (BECCS) should be evaluated and deployed using the Inflation Reduction Act carbon capture credits of $85/tonne of carbon; these credits may allow a portion of the total biogenic emissions to be captured cost effectively today. Given mid-long term cost efficiencies in CCS technology, these biogenic emissions could become “in the money”

Thermal energy consumption[1]

Thermal emissions[2]



Paper sector generates over 100 million tonnes of unrecorded biogenic CO2e annually

Opportunity to capture ~100 million tonnes of CO2e annually and create negative emissions; IRA CCS credits of $85/tonne provide a pathway

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 outlook; EIA emissions intensity; BCG analysis

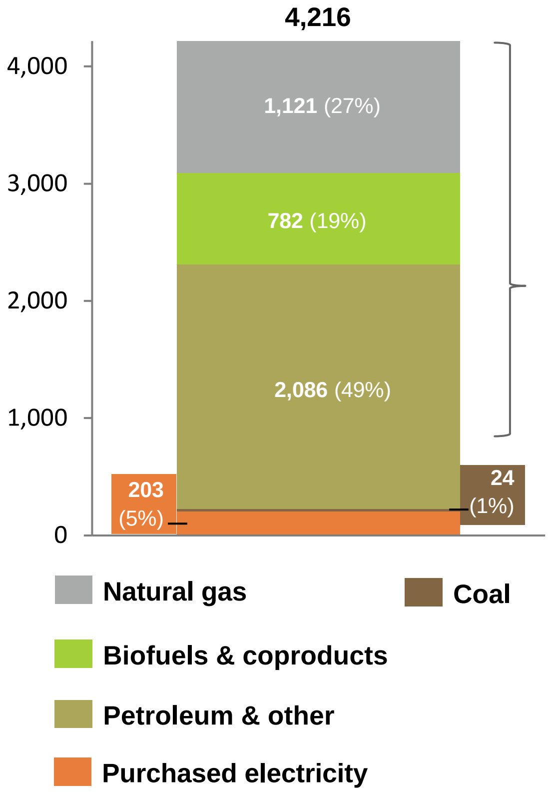
Refineries

Sector Perspectives

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

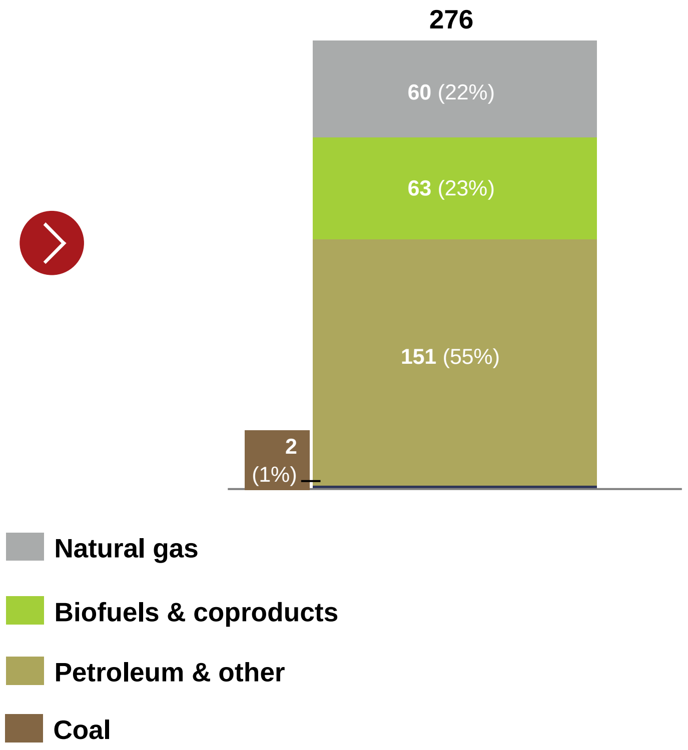
Total energy consumption (2018)[1]

Trillion Btu



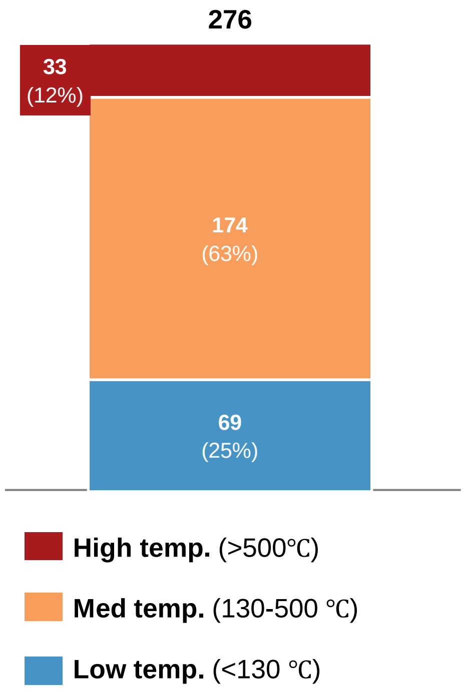
Thermal emissions (2018)[2]

Million Tonnes of CO2e



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

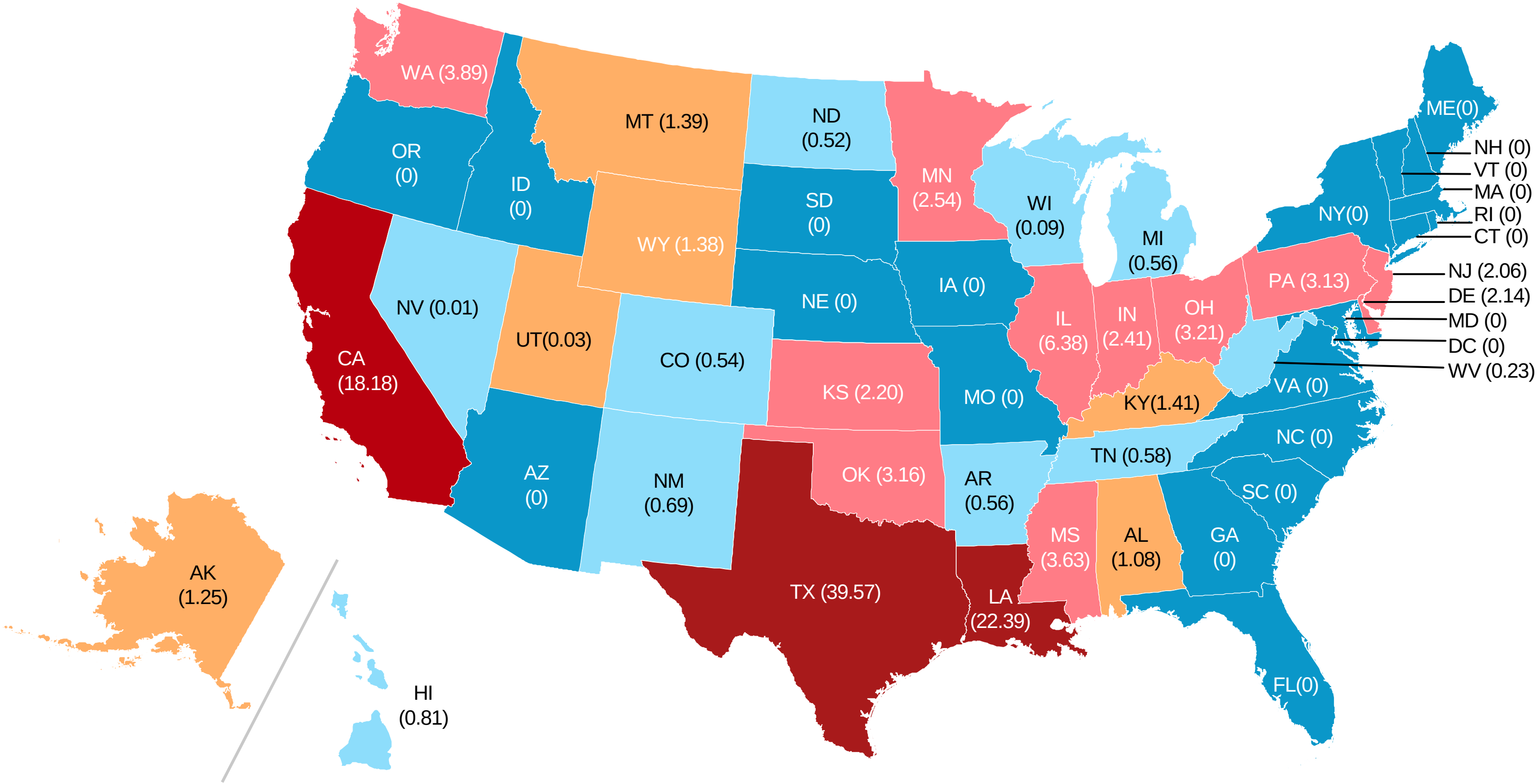
Million Tonnes of CO2e



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

●	Near zero
●	<1 Million Tonnes CO2e
●	1-2 Million Tonnes CO2e
●	2-10 Million Tonnes CO2e
●	>10 Million Tonnes CO2e

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[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

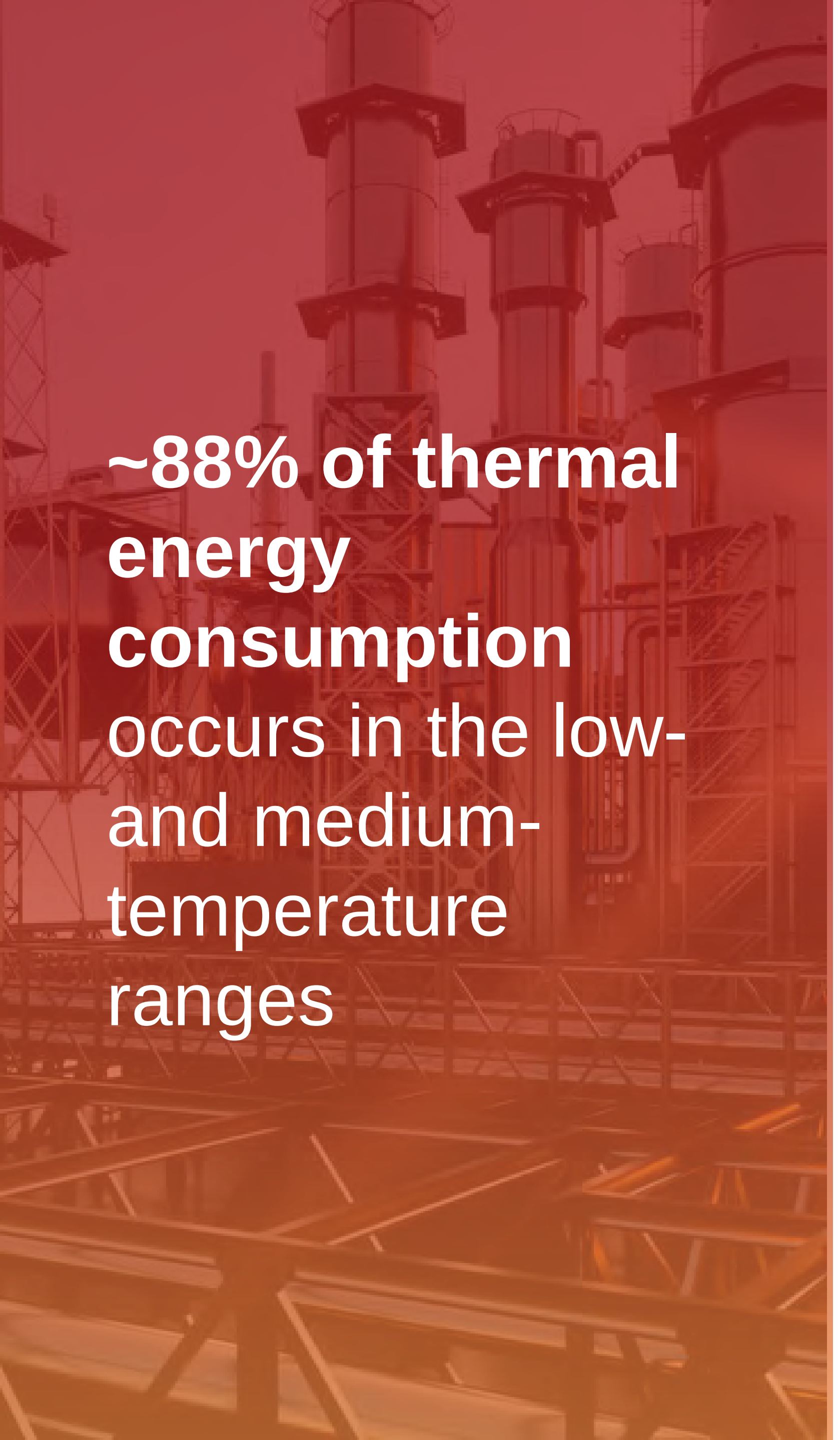
Distillation | ~150-370 ºC

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

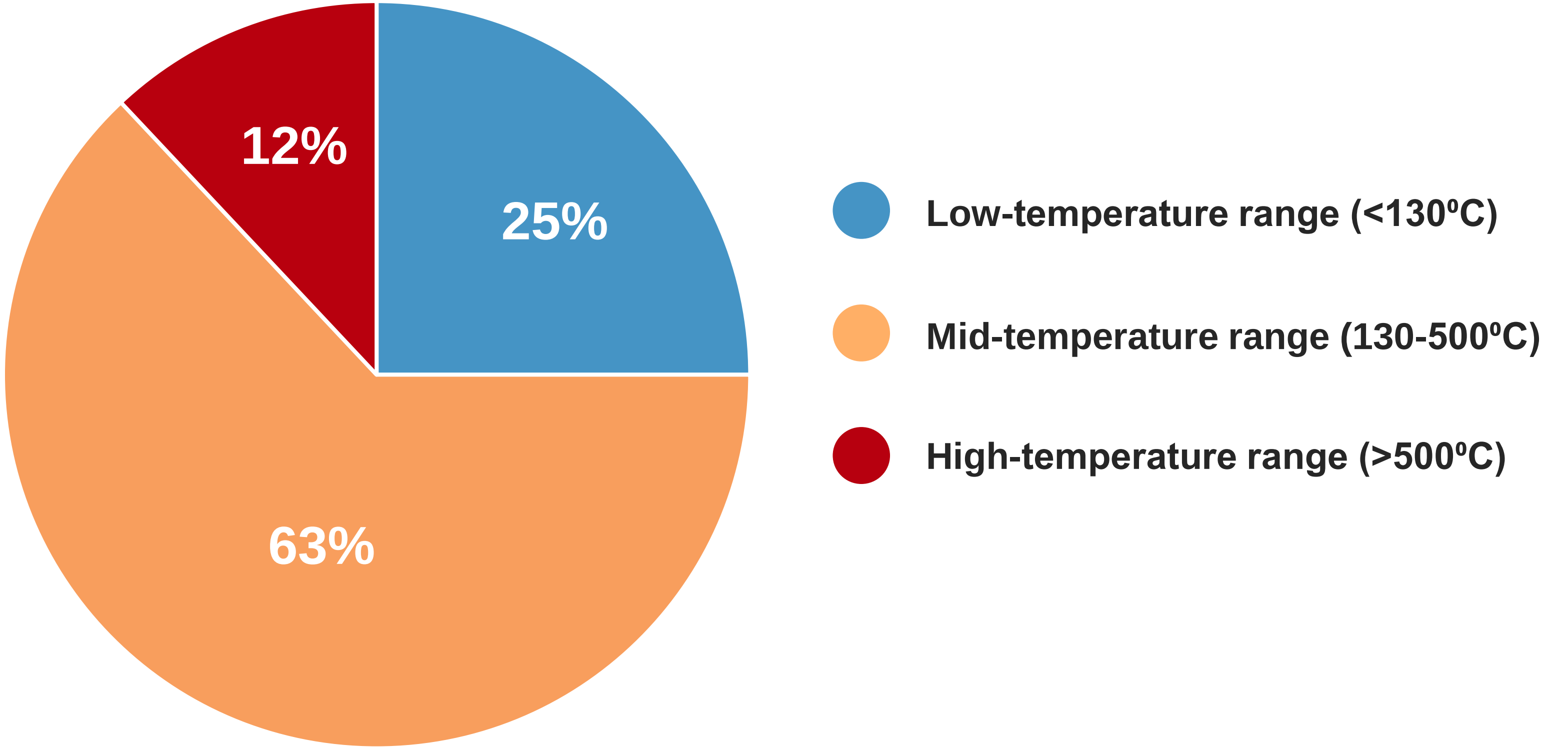
Components that have been separated out in the distillation process may be sent to a **reactor** in order to remove or convert certain compounds. One of the most energy-intensive reactors is the naphtha hydrotreater, which takes in heavy naphtha from distillation columns and removes sulphur and nitrogen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

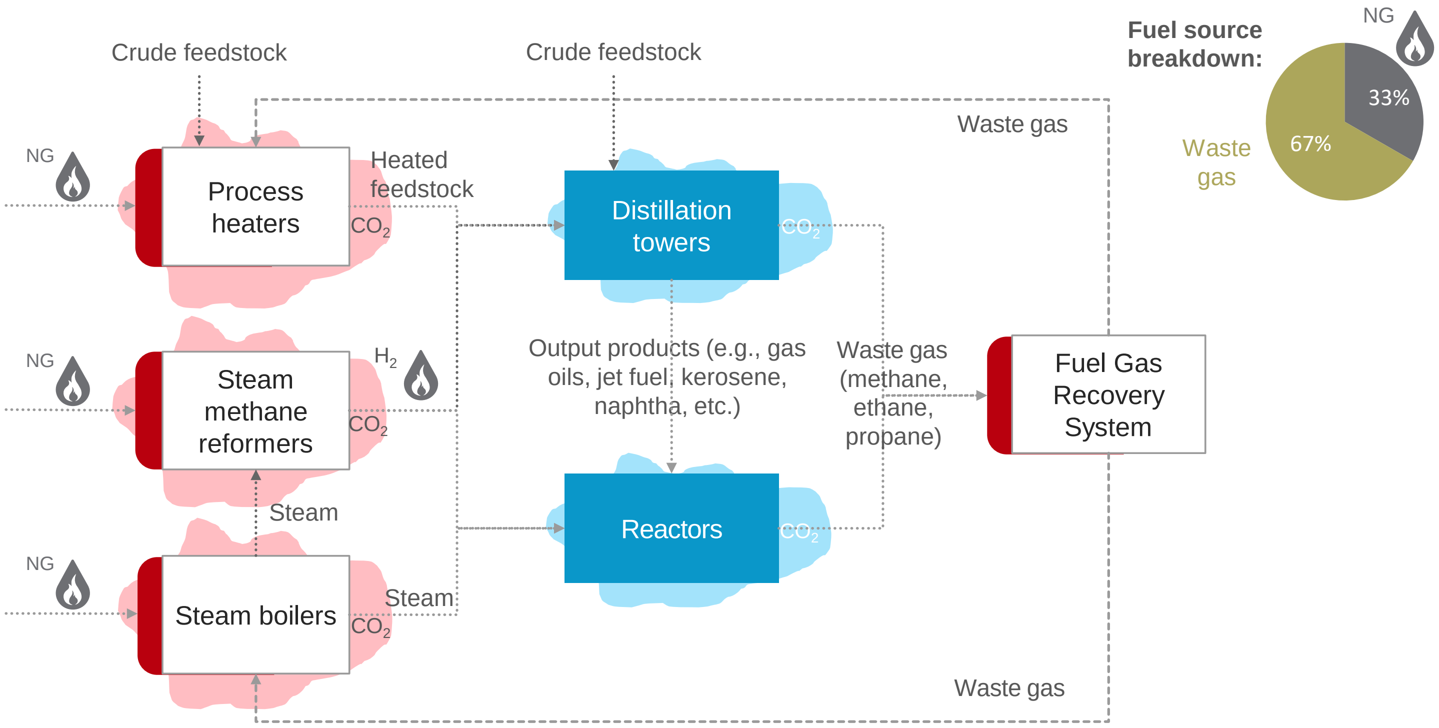
Thermal energy consumption (TBtu) by heat temperature range (ºC)[1]



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



Crude feedstock

Crude feedstock

NG

Process heaters

Heated feedstock

CO_2

Distillation towers

CO_2

Waste gas

NG

Steam methane reformers

H_2

CO_2

Output products (e.g., gas oils, jet fuel, kerosene, naphtha, etc.)

Waste gas (methane, ethane, propane)

Fuel Gas Recovery System

Steam

NG

Steam boilers

Steam

CO_2

Reactors

CO_2

Waste gas

Fuel source breakdown:

NG 33%

Waste gas 67%

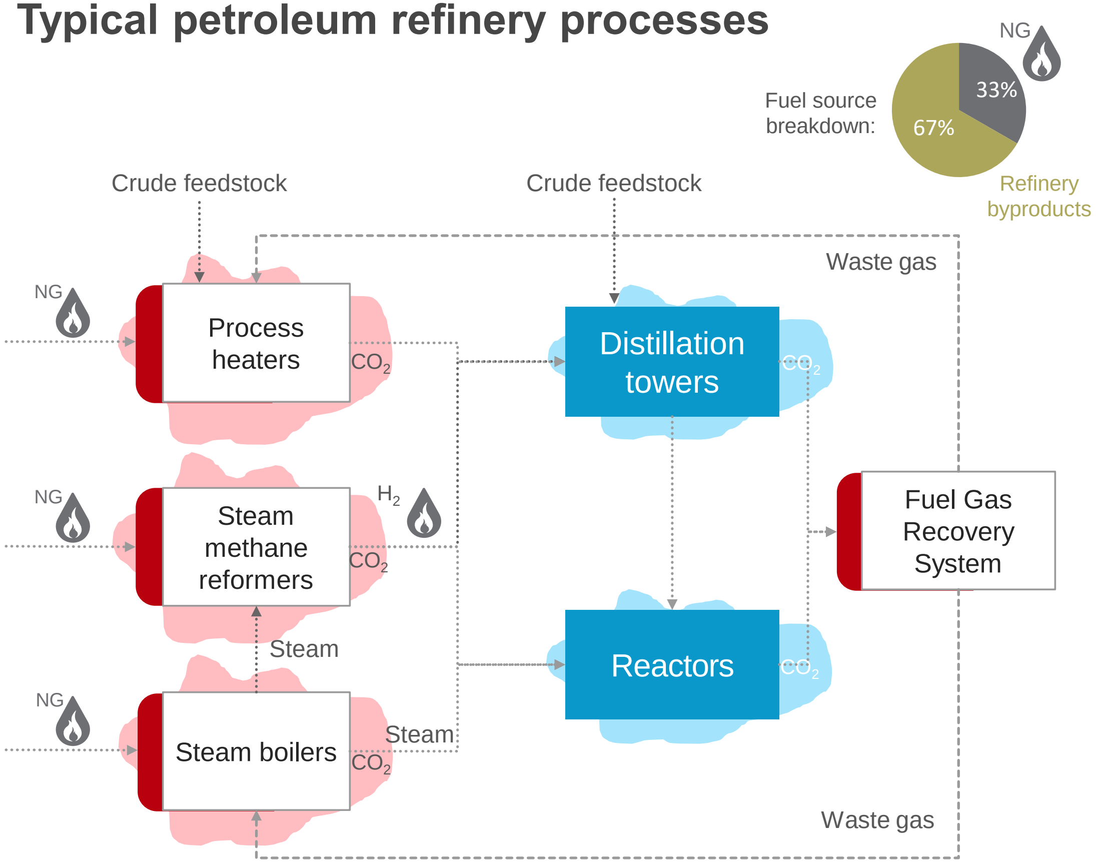
🟥 Heat generating equipment 🟦 Thermal application NG RNG H_2 Fuel source CO_2 Thermal emissions CO_2 Process emissions

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

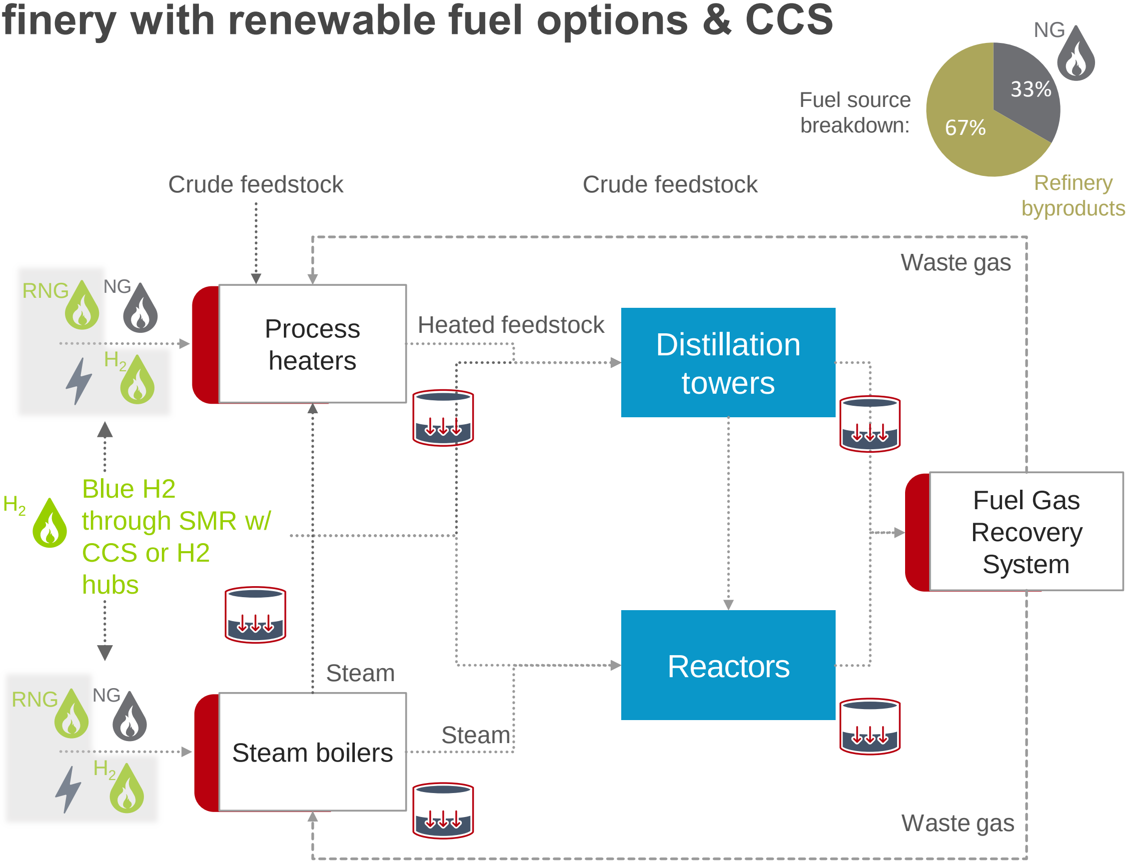
- Petroleum refineries typically use process heaters and steam boilers that burn natural gas to create steam heat, which is moved around the facility through a steam network system distributing heated steam to applications
- Natural gas is also used in steam methane reformers to produce hydrogen; NG 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

Typical petroleum refinery processes



Refinery with renewable fuel options & CCS



🟥 Heat generating equipment

🟦 Thermal application

NG RNG H2 Fuel source

CO2 Thermal emissions

CO2 Process emissions

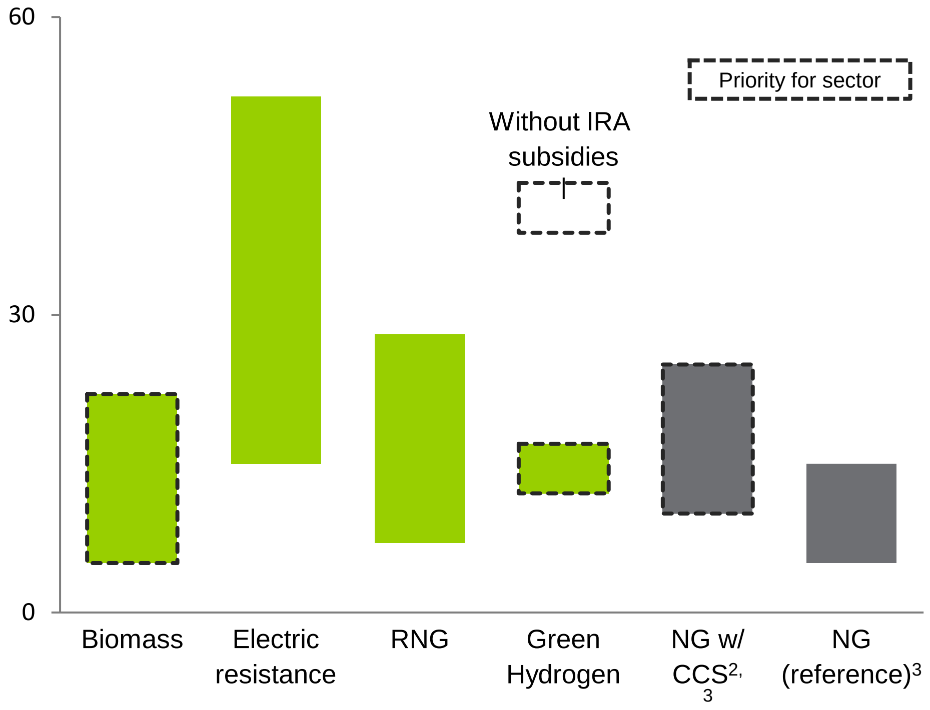
CCS

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

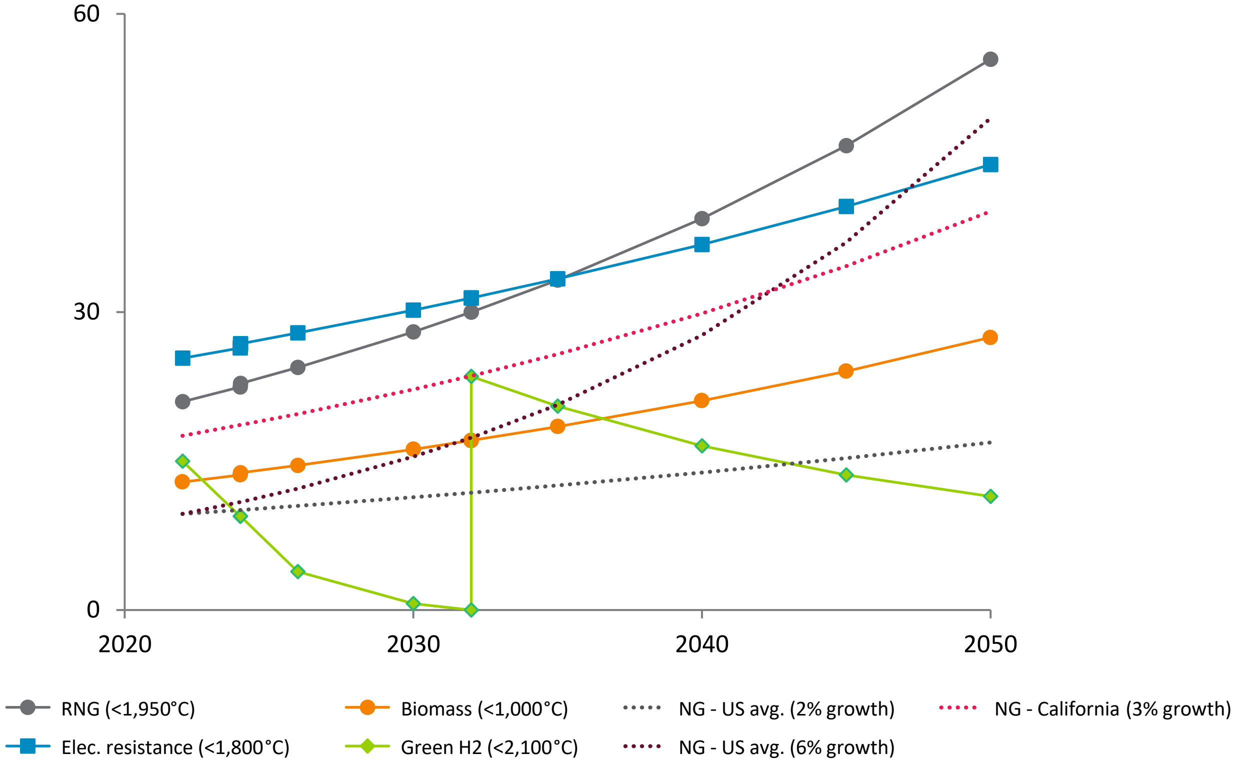
2022 LCOH for relevant technologies[1]

($/MMBtu)



Projected LCOH for relevant technologies[1]

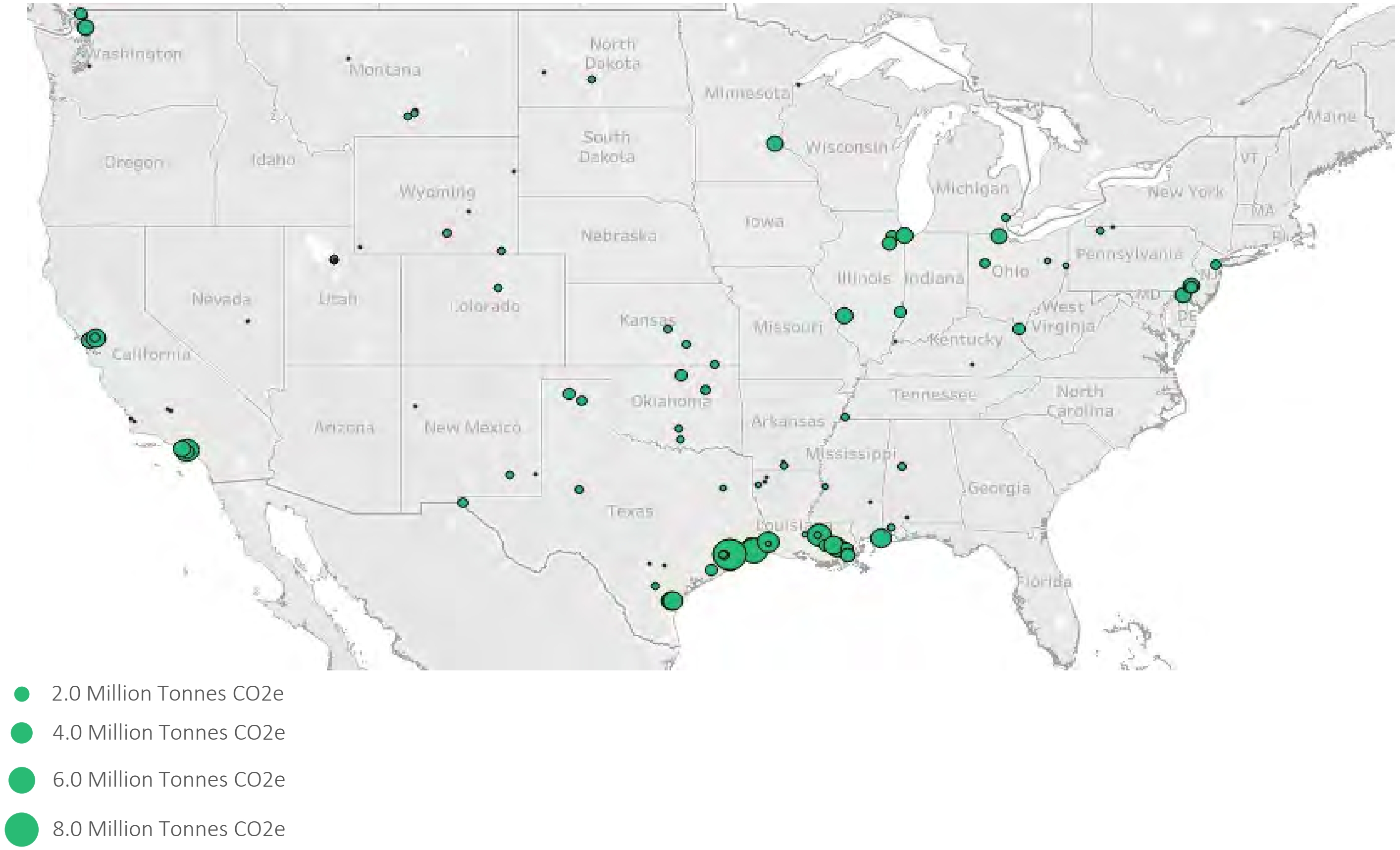
Average US LCOH ($/MMBtu)



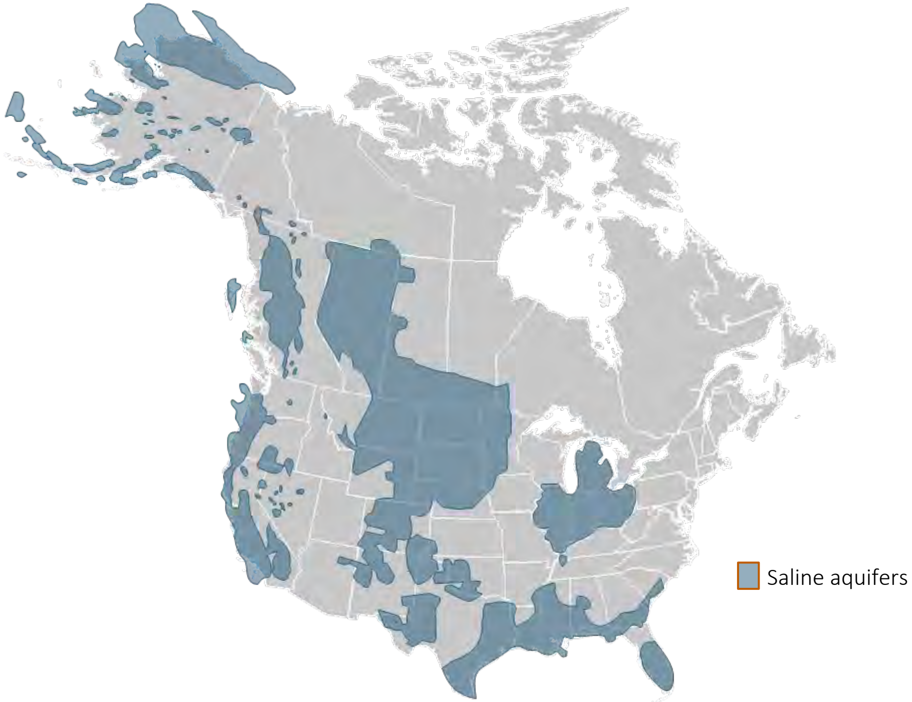
1. LCOH compares project lifetime costs against lifetime energy produced; costs include capital expense of equipment, fuel costs, and maintenance expense assumptions over the usable life of the energy asset. Electricity and natural gas pricing is based on national weighted average wholesale industrial 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

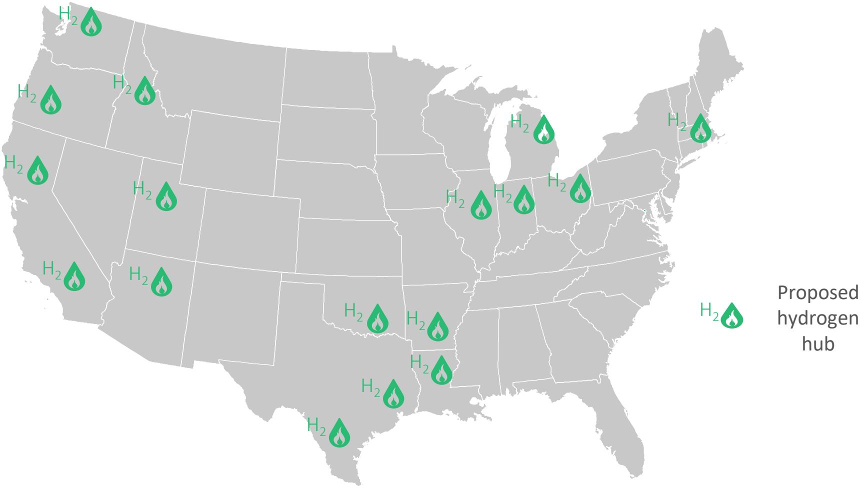
US Refineries thermal emissions by zip code[1]



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**

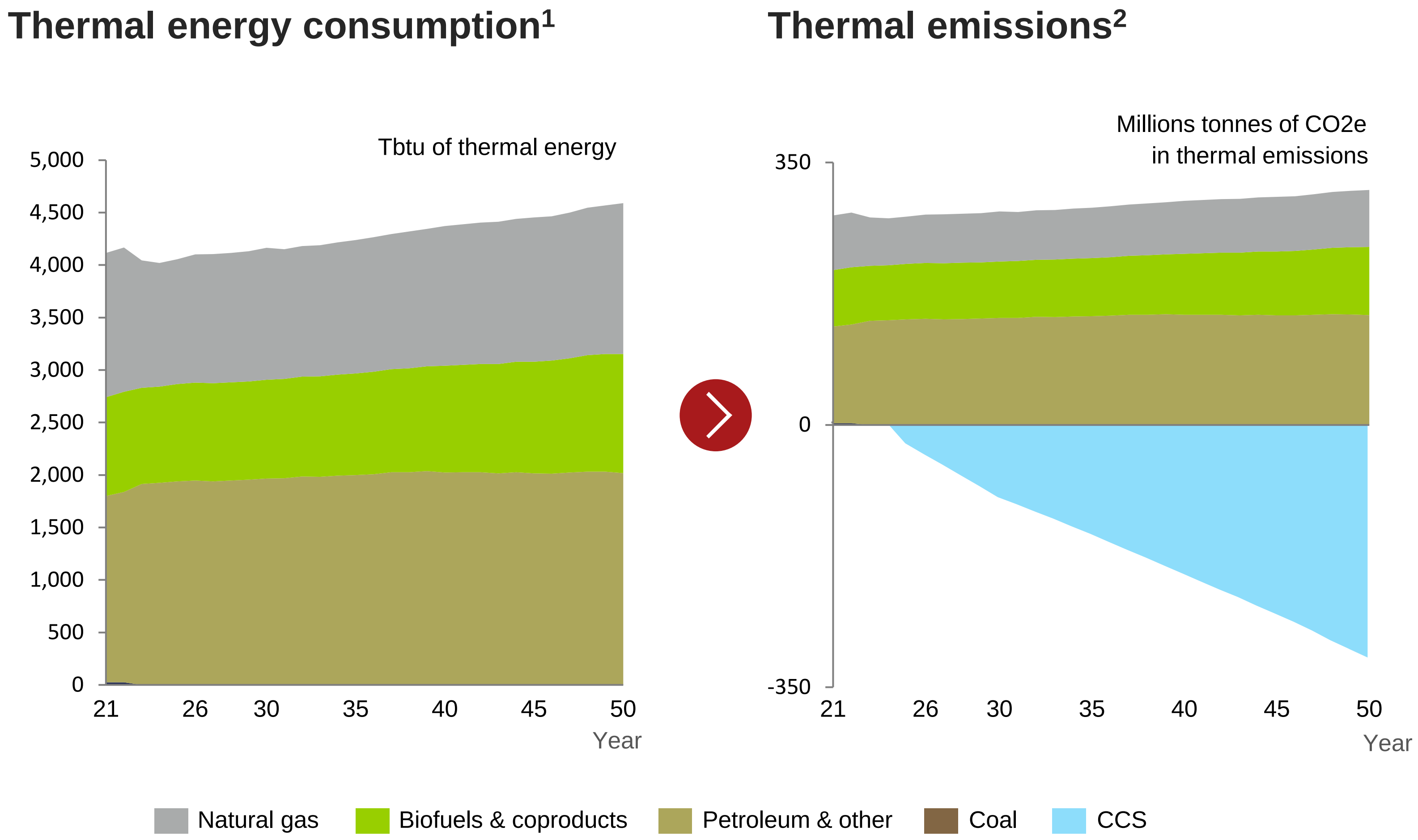
Thermal decarbonization pathways

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]

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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 outlook; EIA emissions intensity; BCG analysis

Carbon capture for use or sequestration

Renewable Thermal Technology

RENEWABLE
THERMAL
COLLABORATIVE

Carbon capture is applicable for a range of large stationary combustion and process emitters

Industrial: *Concentrated CO_2*

Petrochemicals
Byproduct from production of methanol, carbon black, etc.

Ammonia
Byproduct from use of fossil fuels to produce hydrogen for ammonia

Ethanol
Byproduct of fermentation of glucose for ethanol production

☆ Nearly all applications also produce combustion emissions for **industrial heating**

Industrial: *Dilute CO_2*

Refining
Mostly fuel combustion for boilers & furnaces to refine raw materials

Cement
Byproduct of calcination of limestone to produce clinker

Iron & Steel
Several sources of CO_2 including coking coal, blast furnaces

Aluminium
Reduction process creates CO_2 from alumina electrolysis

Power sector (not focus of this fact base)

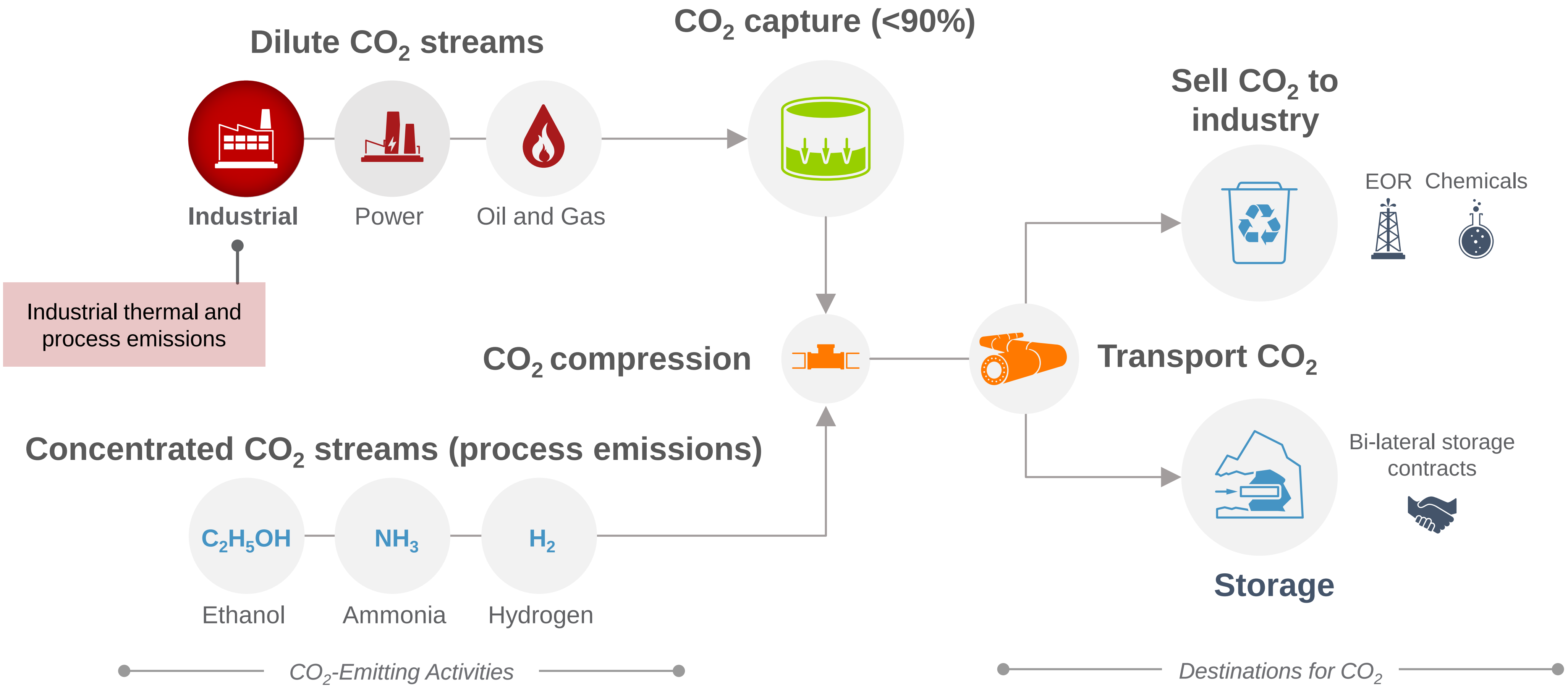
Coal-to-Power
Combustion of coal for electric power produces dilute CO_2 offgas

Gas-to-Power
Combustion of gas for electric power produces dilute CO_2 offgas

Biofuels-to-Power
Combustion of biomass for electric power produces dilute CO_2 offgas

List not exhaustive, many smaller emitting industrial sectors also appropriate for CCUS

CCUS captures up to 90% of CO_2 from stationary emitters and transports it for storage or utilisation



Four main drivers determine the technical and economic viability of CCUS for thermal combustion applications

Concentration

- Cost of carbon capture inversely correlated with level (i.e., partial pressure) of CO2 in capture stream

Location

- CO2 source location important for:
  - aggregating emission streams
  - transport of captured CO2
  - storage or use of CO2

Source of Heat

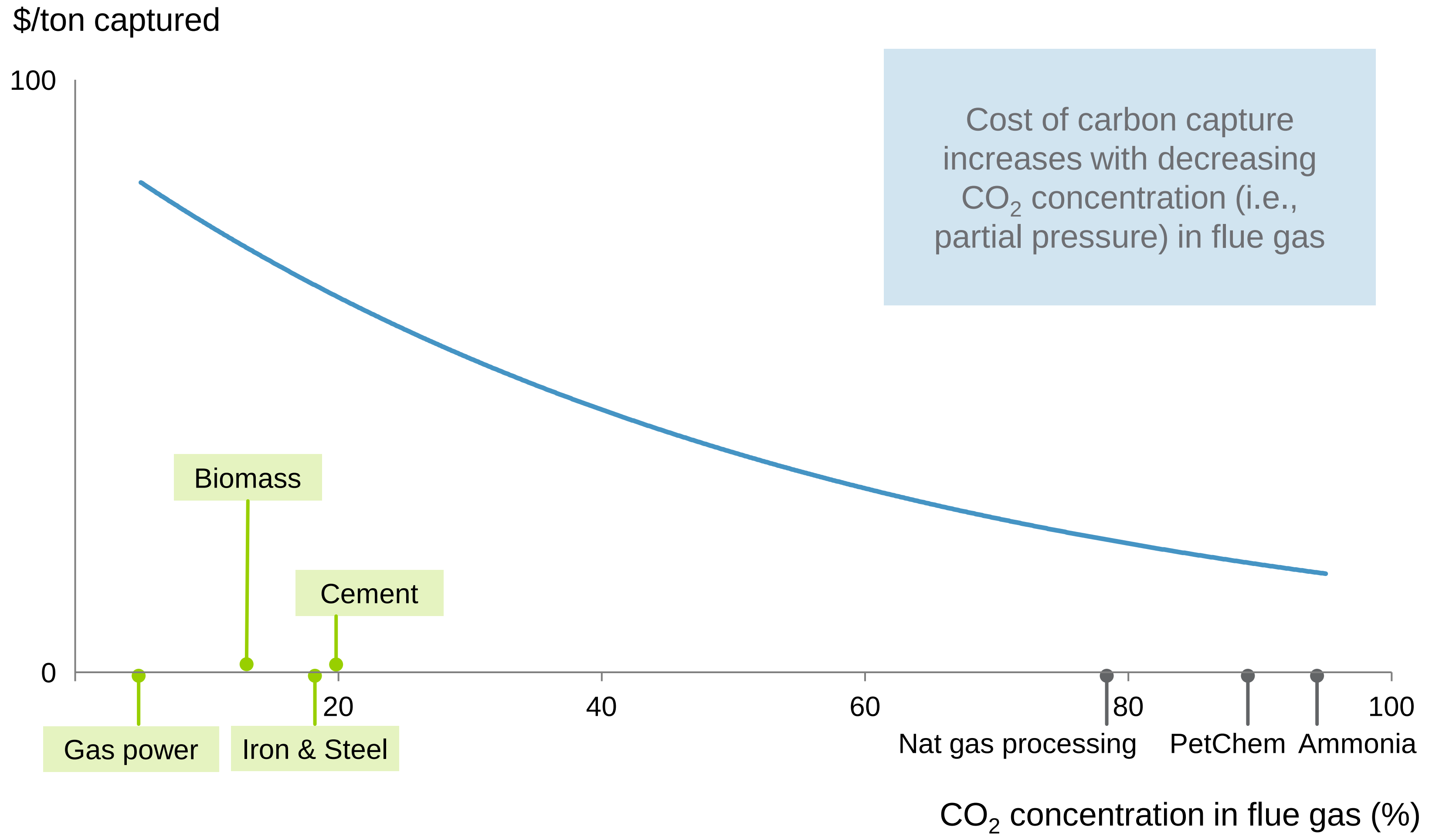
- Regeneration of carbon capture solvent typically requires low-cost heat at ~120ºC

Process Emissions

- Opportunity to simultaneously capture non-combustion process emissions

Concentration

Level of CO2 in flue gas is a key cost driver

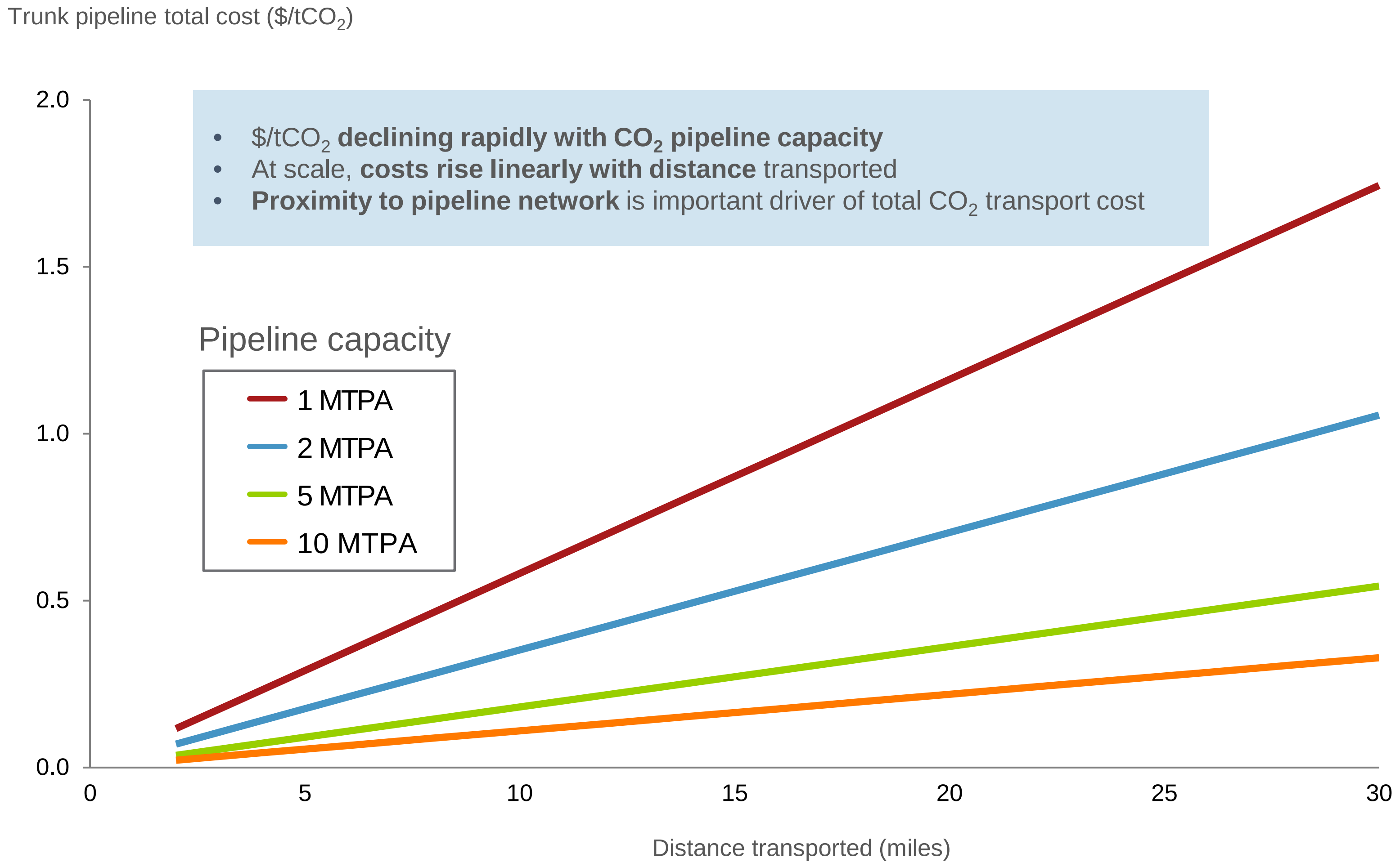


Note: Assuming 8% WACC, 85% utilization rate, 20-year lifetime
Source: Industry Sources, NPC, IEAGHG, BCG Analysis

- Flue gas from industrial thermal combustion typically contains <10% CO2, resulting in higher carbon capture costs relative to process emissions
- *Note: Cost of CO_2 capture ($/ton) is independent of emissions intensity (kg CO_2 per MMBtu) and fuel costs*

Location

Carbon capture costs increases proportionally with CO2 transportation distance, but decline with increasing pipeline capacity



- $/tCO$_2$ **declining rapidly with CO$_2$ pipeline capacity**
- At scale, **costs rise linearly with distance** transported
- **Proximity to pipeline network** is important driver of total CO$_2$ transport cost

- Pipeline network development is likely necessary to unlock CCS potential for a wider set of industrial players.
- Joint or national development of CO$_2$ pipeline will accelerate CCS for industrials, who may be currently geographically challenged to deploy CCS

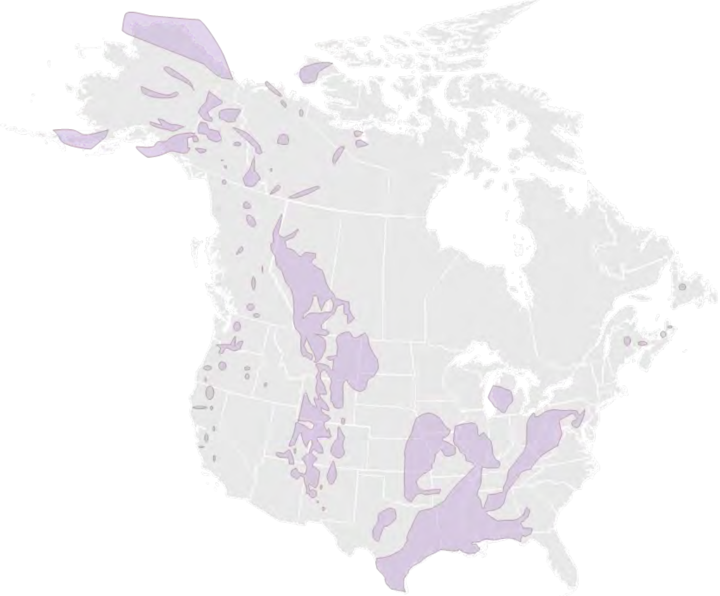
Source: Zero Emissions Platform (ZEP); Global CCS institute; BCG analysis

Location

Viable geologies for CO2 sequestration available in large portions of North America, providing potential sites for carbon capture and storage

▨ Saline aquifers

Proven technology, likely solution for short to medium term



▨ Coal/O&G

Uncertain storage durability

▨ Basalt deposits[1]

Emerging technology

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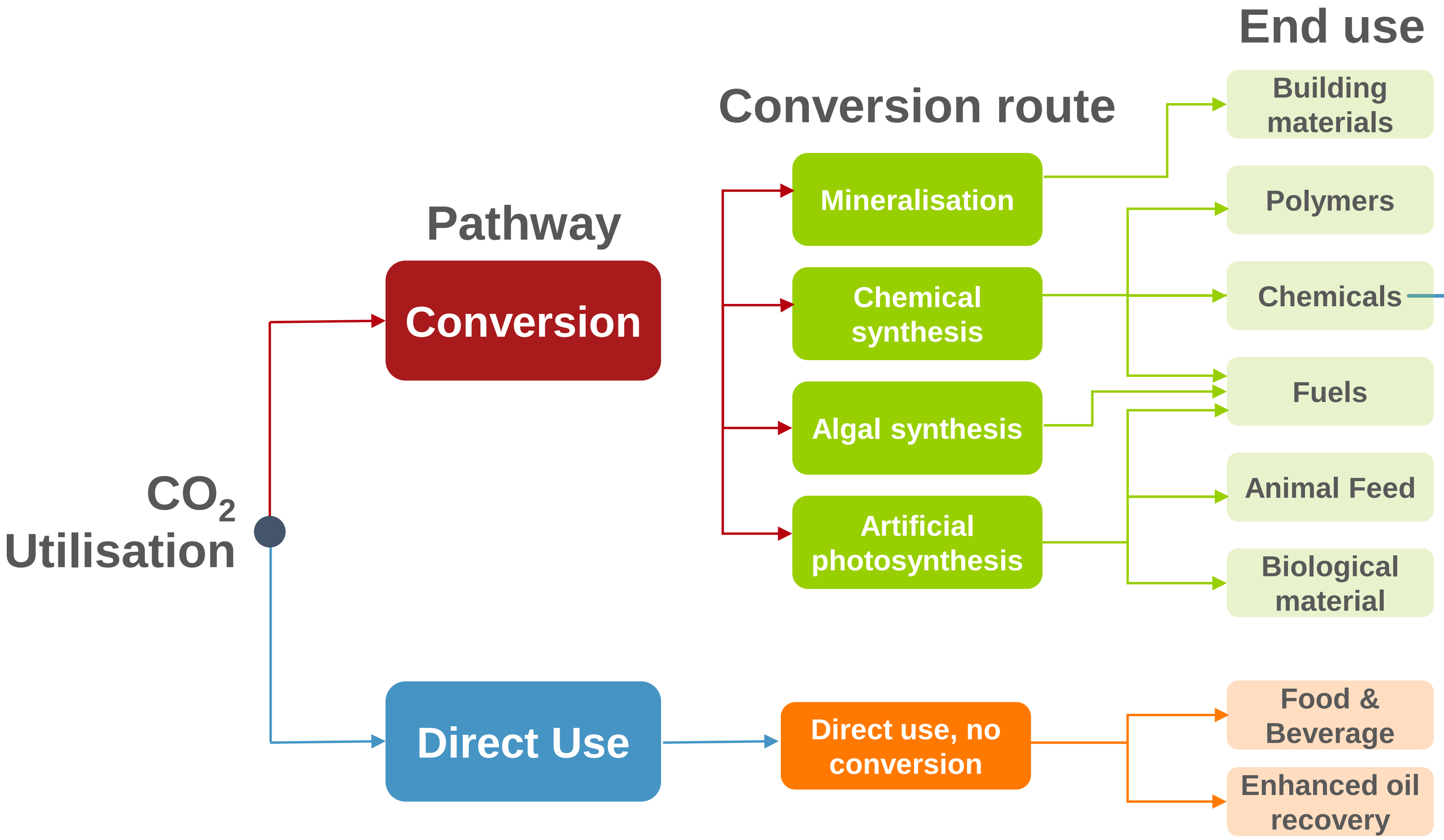
[1] Not yet fully proven but with high expectation as a form of permanent CO2 sequestration given the chemical reactions within basalt to form solid carbonates

Source: USGS, NETL NATCAB

Location

Similar to storage, utilization of captured CO2 also depends on proximity between source of emissions and end use location



End use

Conversion route

Pathway

CO_2
Utilisation

Conversion

Direct Use

Mineralisation

Chemical synthesis

Algal synthesis

Artificial photosynthesis

Direct use, no conversion

Building materials

Polymers

Chemicals

Fuels

Animal Feed

Biological material

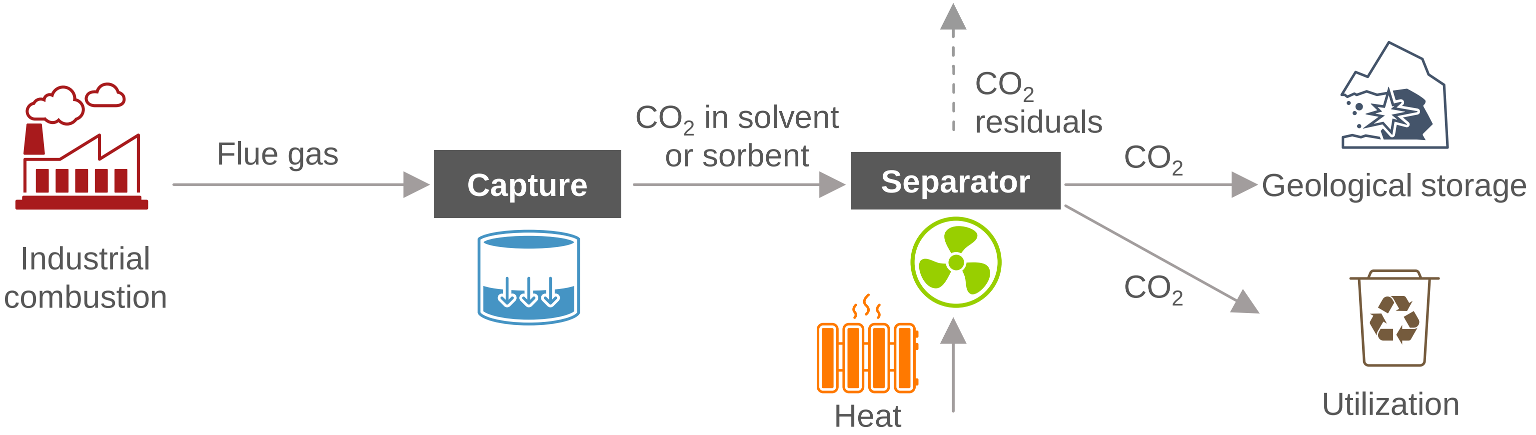
Food & Beverage

Enhanced oil recovery

Current key pathway, synthesis of methanol, syngas, urea, ethylene, ethanol, formic acid etc

Source of Heat

Thermal energy used to drive carbon capture is a major component of CCUS cost



Industrial combustion

Flue gas

Capture

CO_2 in solvent or sorbent

Separator

CO_2 residuals

Heat

CO_2

Geological storage

CO_2

Utilization

- Existing CCUS systems typically use a solvent (e.g., MEA) to capture CO_2, while novel CCUS systems are being developed using pressure-swing or electrification processes
- Heat at approximately 120ºC is applied to the solvent to release CO_2
- Depending on flue gas CO_2 concentrations, source of heat, and other factors, cost of solvent regeneration heat can constitute 20-50% of total carbon capture costs per ton of CO_2
- Waste heat streams is the most effective way to provide heat to drive the carbon capture process

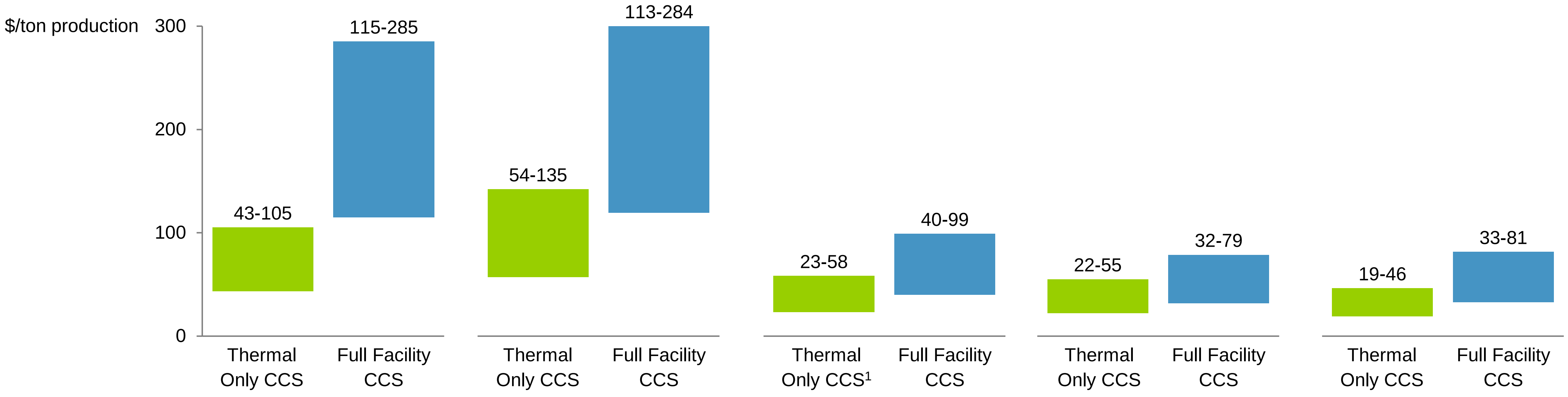
Source: Global CCS Institute

Forms of regeneration heat (in order of descending cost)

- Electric resistance
- Low temperature steam
- Hot water
- Waste heat streams

Beyond thermal-related CO2 capture, CCS is likely required to decarbonize process emissions in various hard to abate sectors

Range of cost increase per ton of material produced, with coal or natural gas as original heat source

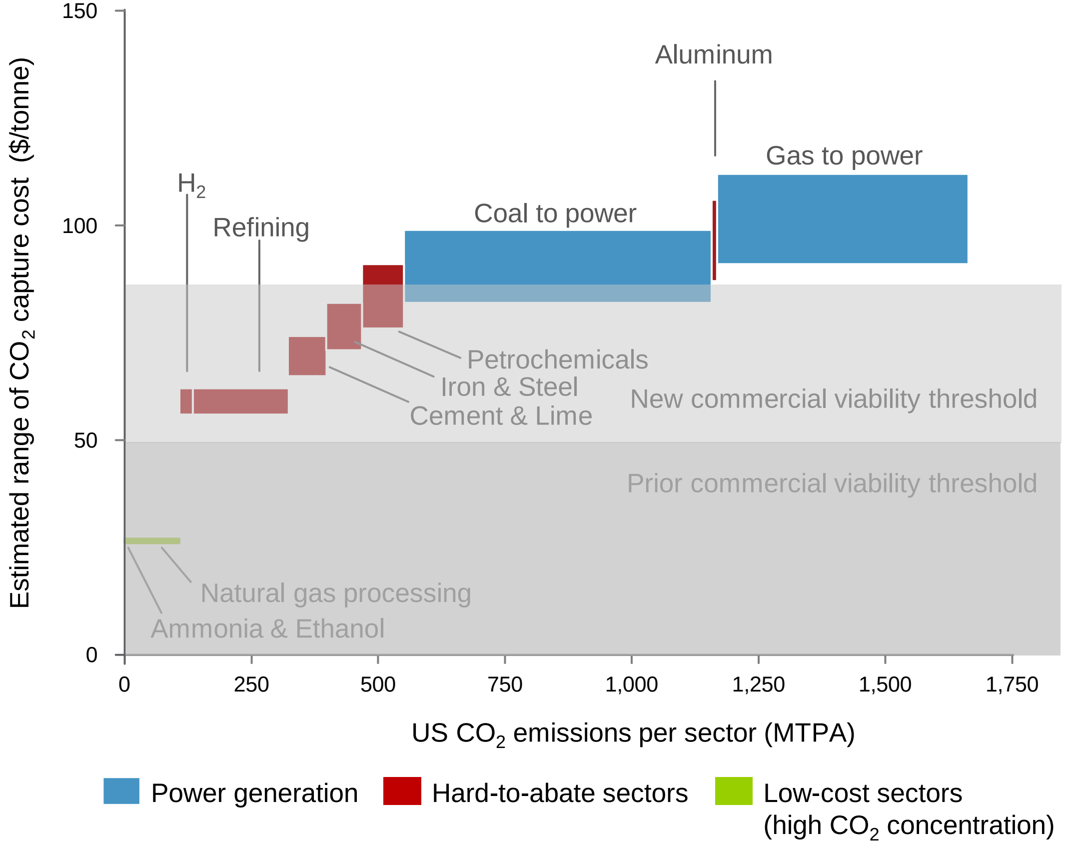


	Ammonia	Steel	Cement clinker	Glass	Methanol
Baseline commodity cost ($/ton)	500	400	100	300	430
Original heat source	Natural gas	Coal	Coal	Natural gas	Natural gas
CCUS as part of sector decarbonization	Required in short term	Required in short to medium term	Required	Low requirement	Low requirement

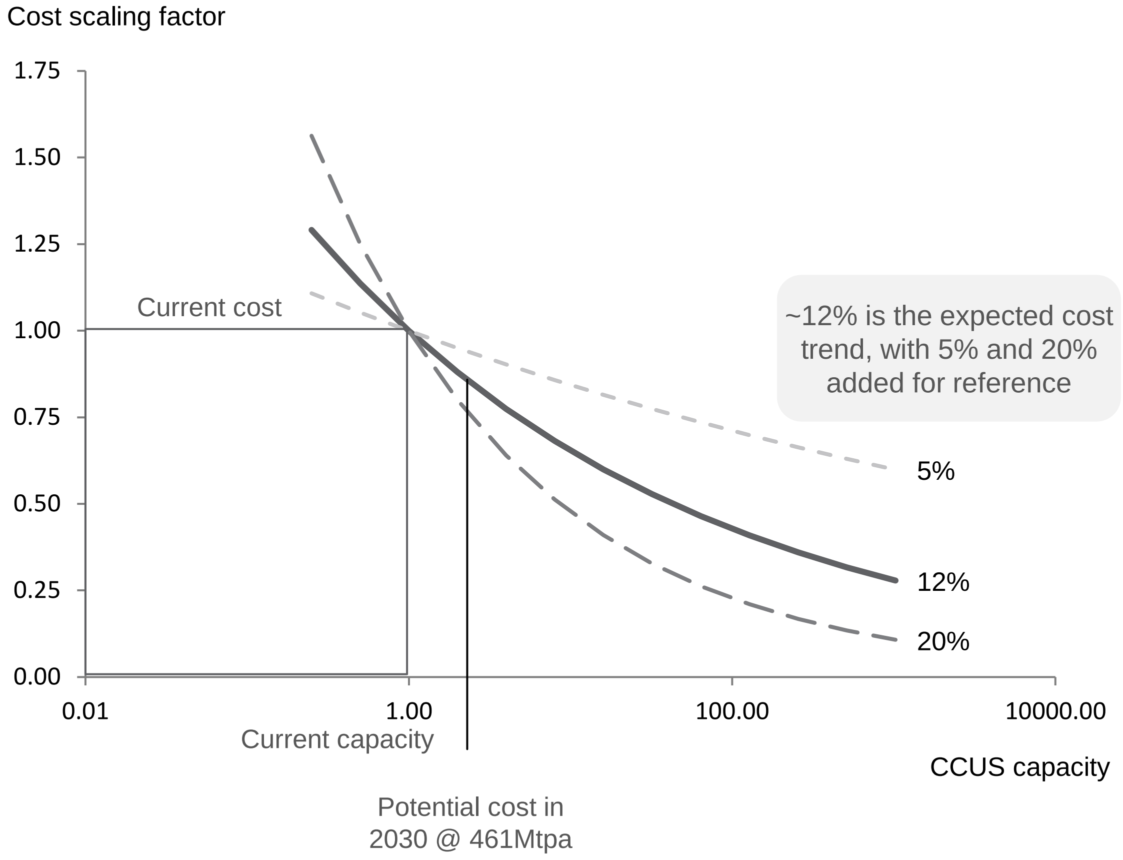
1. Cement clinker production likely not able to separate thermal vs full facility emissions in kiln | Source: Columbia University

Inflation Reduction Act increases 45Q tax credits to $85/t making CCUS potentially viable for refining, hydrogen, cement, & steel sectors

$85/ton incentives significantly expand CCUS commercial viability

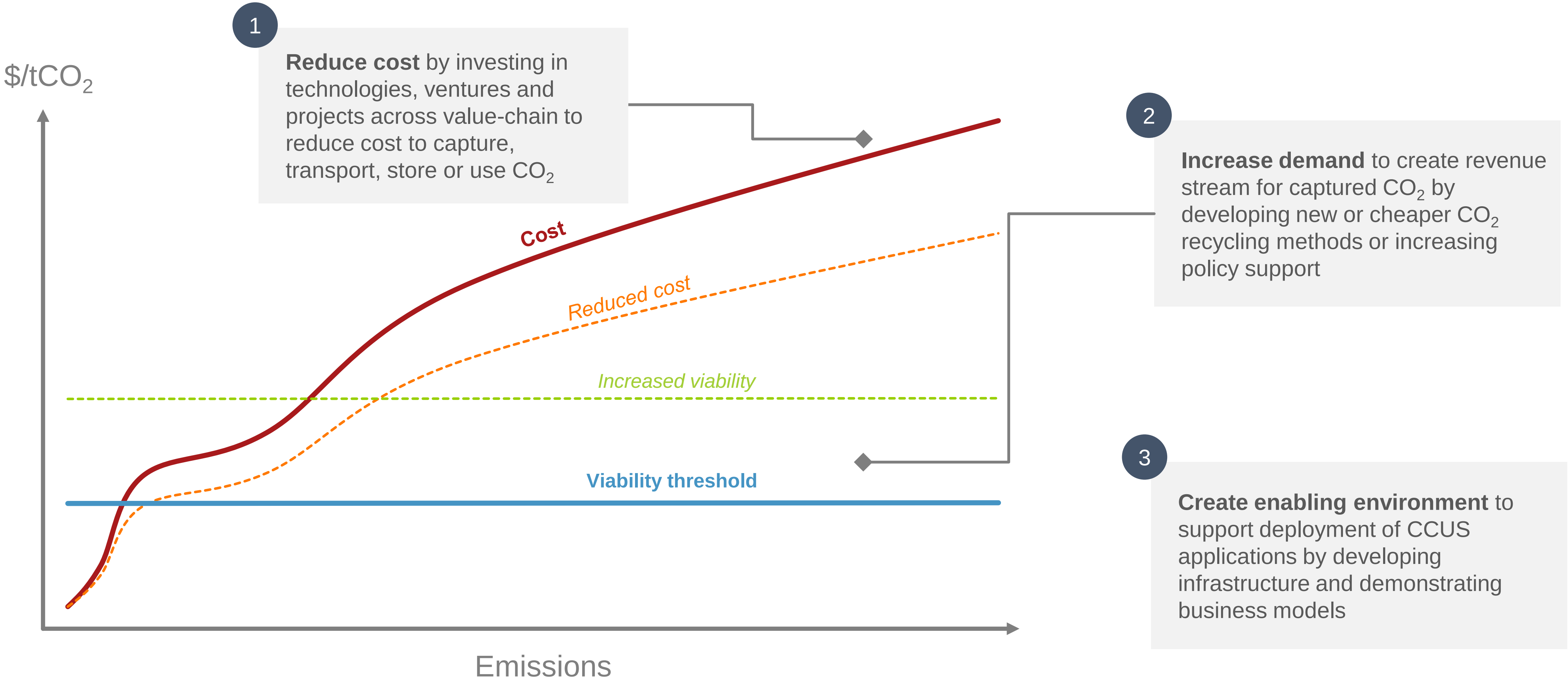


…and further cost reductions of ~12% are expected as deployment doubles, making coal+CCUS potentially viable



Source: BCG Analysis

Three broad strategies can increase the viability of CCUS for industrial heating decarbonization



1. **Reduce cost** by investing in technologies, ventures and projects across value-chain to reduce cost to capture, transport, store or use CO$_2$

2. **Increase demand** to create revenue stream for captured CO$_2$ by developing new or cheaper CO$_2$ recycling methods or increasing policy support

3. **Create enabling environment** to support deployment of CCUS applications by developing infrastructure and demonstrating business models

CCUS for industrial heating decarbonization has many advantages and unique features, but faces several key barriers to adoption

Advantages

- No major modification required to the industrial process
- May be more cost effective than alternative renewable heating options
- Technical capacity to store CO2 underground is functionality unlimited
- Can simultaneously capture CO2 from process emissions

Barriers

- Cost can be high and does not add value unless there is a price on carbon
- Extensive supplemental infrastructure required
- Non-renewable and not a long-term solution
- Does not capture 100% of CO2 emissions

Clean Hydrogen

Renewable Thermal Technology

RENEWABLE
THERMAL
COLLABORATIVE

Clean Hydrogen Technology Overview

Description of technology

- Hydrogen is a combustible gas that can substitute for natural gas in nearly all industrial heating applications
- Green hydrogen production has no CO_2 emissions, and hydrogen combustion produces only water vapor and heat
- This analysis only considers hydrogen produced using renewable energy (green hydrogen via electrolysis), since other hydrogen production methods emit CO_2 and are non-renewable (i.e., blue and grey H_2).
- Currently, hydrogen is primarily used as feedstock in the chemicals and petroleum refining industries (e.g., ammonia production, hydrocracking)

Types of equipment

- Most gas combustion equipment can switch to hydrogen as a fuel with relatively minor equipment modifications. Hydrogen catalyzed equipment are new technologies that provide lower temperature heat via flameless combustion at high efficiencies.

Hydrogen furnaces[1]

Hydrogen combustion boilers[2]

Hydrogen catalyzed boilers[3]

Note: Example equipment not exhaustive

1. Thermal Technology LLC Hydrogen Furnace; 2. Bosch Hydrogen-ready Boiler; 3. Giacomini hydrogen-powered catalytic boiler

Technical characteristics

- **Temperature range:** Up to 2,100 ºC
  - Meets the highest temperature industrial heating applications
  - Likely applicable but not ideal heat source for lower temperature applications due to availability of alternatives heating technologies
- **Heat flux:** High
  - Similar heat transfer characteristics to natural gas combustion except for lower radiative heat transfer due to lack of soot particulate production
- **Heated materials:** Most materials are applicable
  - Hydrogen combustion eliminates potential contamination of heated materials with fuel particulates or combustion flue gases

- **Emissions:** Near zero emissions relative to natural gas combustion if hydrogen is produced using renewable electricity
  - If hydrogen is produced by electrolysis using grid electricity, hydrogen combustion will decrease emissions in only a handful of states today, and increases to around half of states by 2030

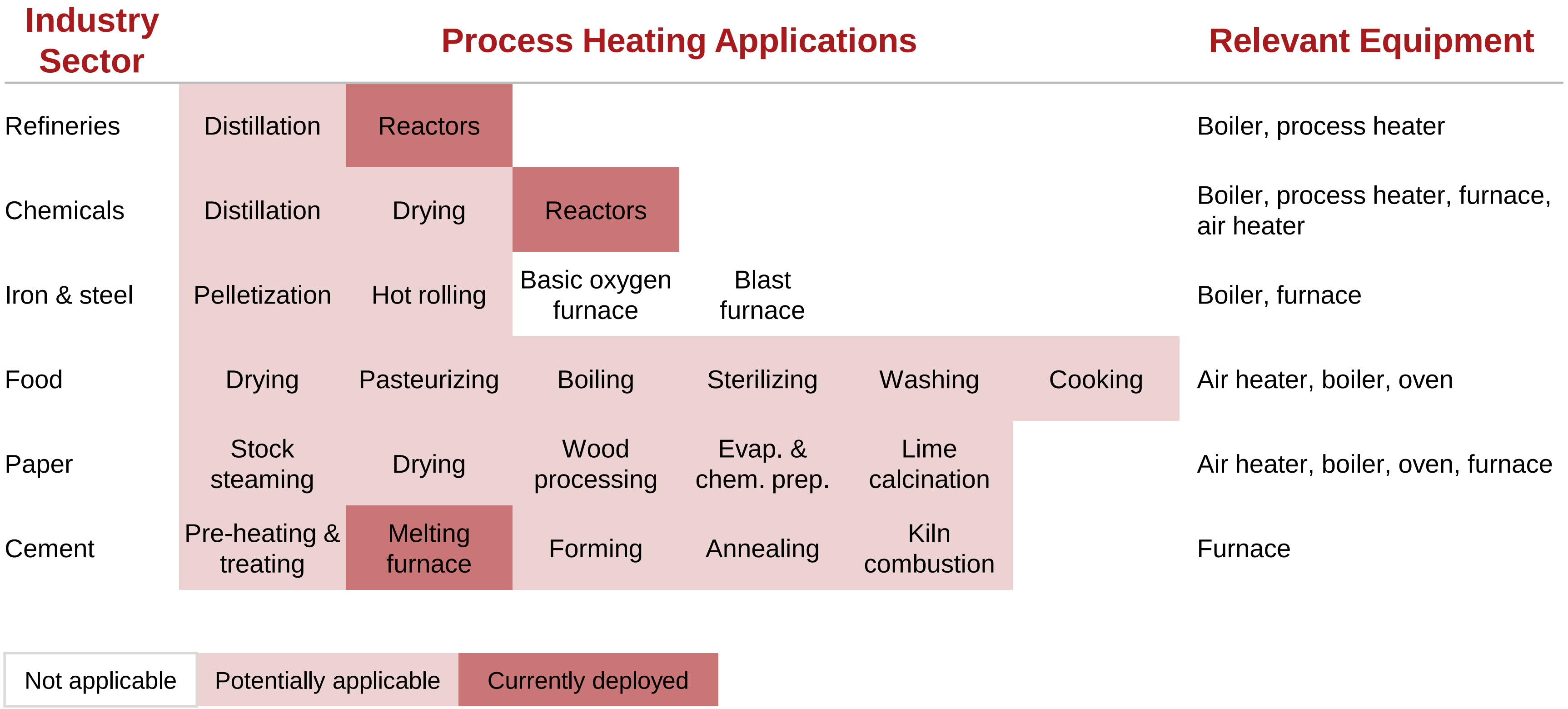
- **Technical maturity:** Low to medium maturity
  - Combustion of hydrogen as a minor constituent within fuel gas blends is widespread in refineries and chemical plants today
  - Pure hydrogen combustion is not deployed commercially beyond pilot and demonstration projects
  - Hydrogen catalyzed heating is a nascent technology

Hydrogen can provide industrial heating for all sectors and applications except for steelmaking

Key properties of RNG combustion heating include:

- 2,100 ºC max. temp.
- High heat flux
- Heats all materials

These properties align with requirements for several process heating applications.



Industry Sector	Process Heating Applications						Relevant Equipment
Refineries	Distillation	Reactors					Boiler, process heater
Chemicals	Distillation	Drying	Reactors				Boiler, process heater, furnace, air heater
Iron & steel	Pelletization	Hot rolling	Basic oxygen furnace	Blast furnace			Boiler, furnace
Food	Drying	Pasteurizing	Boiling	Sterilizing	Washing	Cooking	Air heater, boiler, oven
Paper	Stock steaming	Drying	Wood processing	Evap. & chem. prep.	Lime calcination		Air heater, boiler, oven, furnace
Cement	Pre-heating & treating	Melting furnace	Forming	Annealing	Kiln combustion		Furnace

Not applicable | Potentially applicable | Currently deployed

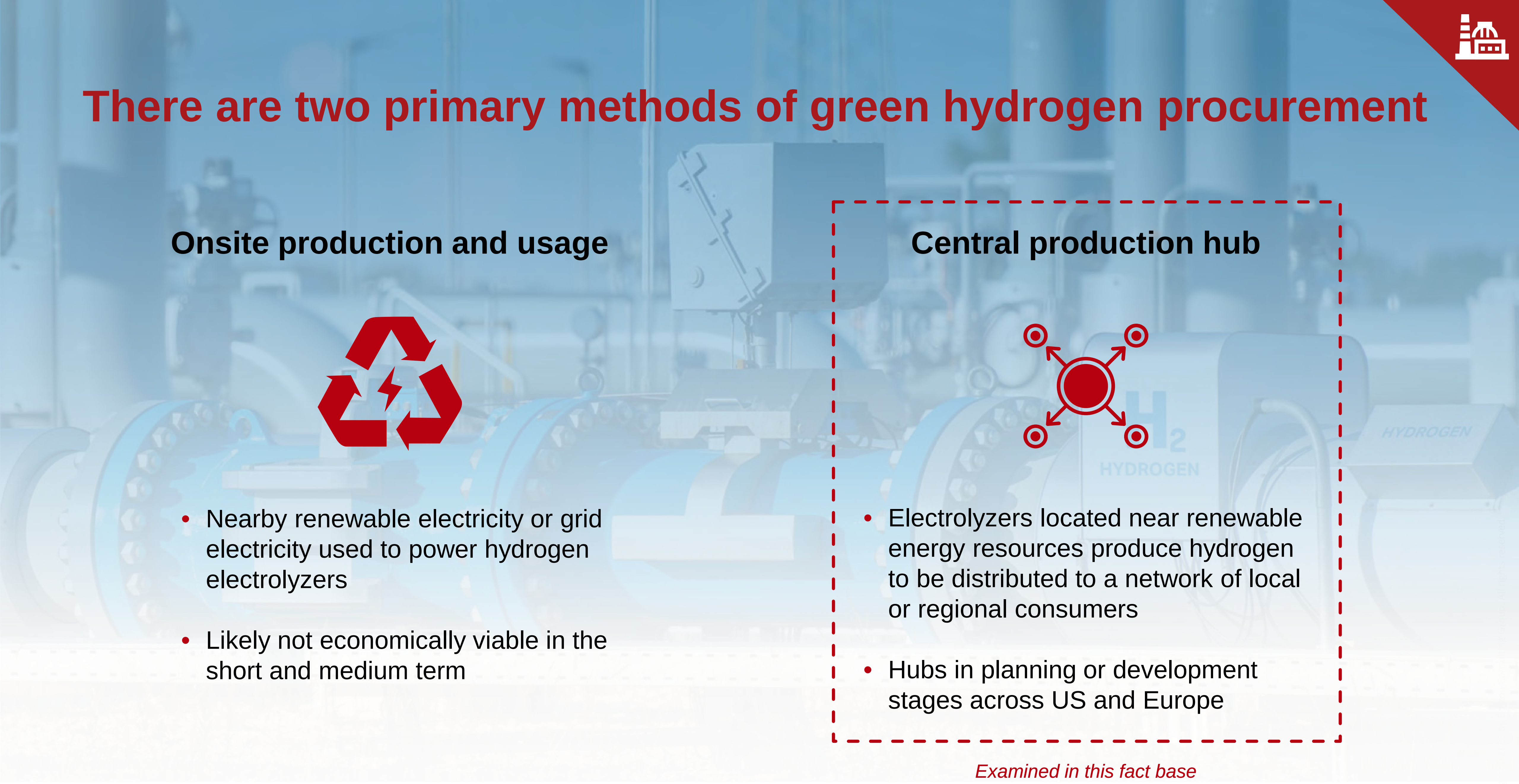
Currently, H_2 combustion heating is not widely deployed in the US

- Hydrogen combustion heating, particularly using pure hydrogen, is not used today and has significantly higher cost relative to natural gas.
- However, hydrogen combustion may have enormous industrial thermal decarbonization potential. A combination of factors may make it attractive, including:
  - **Government incentives – primarily from the Inflation Reduction Act**
    - ☆ Hydrogen production tax credit (PTC) and investment tax credits (ITC) has the potential to reduce costs by 50-70% and cost competitive with natural gas
  - **Broad applicability for industrial heating**
    - ☆ Able to reach highest required temperatures (e.g., chemical reactors, cement kilns)
    - ☆ Meets stringent particulate emissions standards
  - **Long-term sustainable net-zero fuel**
    - ☆ Only supply constraint is quantity of available renewable electricity
    - ☆ Low supply potential of other zero emissions fuels (e.g., RNG)

Practically applicable sectors & locations

- Potentially viable and applicable deployment of hydrogen combustion industrial heating include:
  - **Industry sectors**
    - Cement,
    - Iron and steel making,
    - Refining and chemicals
  - **Regions**
    - ☆ **Future H_2 hubs**
  - **Other potential application (partial decarbonization)**
    - ☆ Blending (up to 15% H_2) into natural gas network

There are two primary methods of green hydrogen procurement



Onsite production and usage

- Nearby renewable electricity or grid electricity used to power hydrogen electrolyzers
- Likely not economically viable in the short and medium term

Central production hub

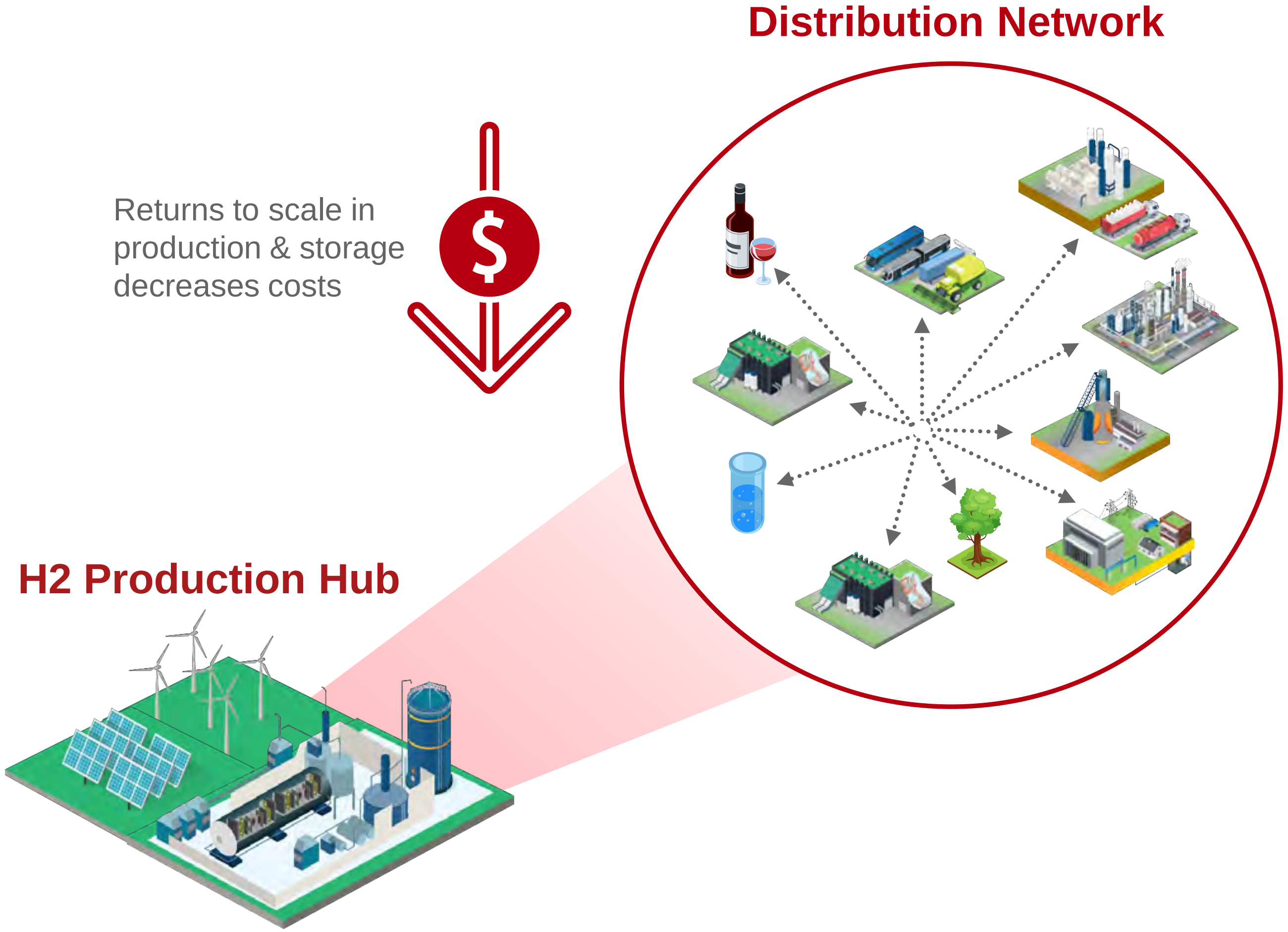
- Electrolyzers located near renewable energy resources produce hydrogen to be distributed to a network of local or regional consumers
- Hubs in planning or development stages across US and Europe

Examined in this fact base

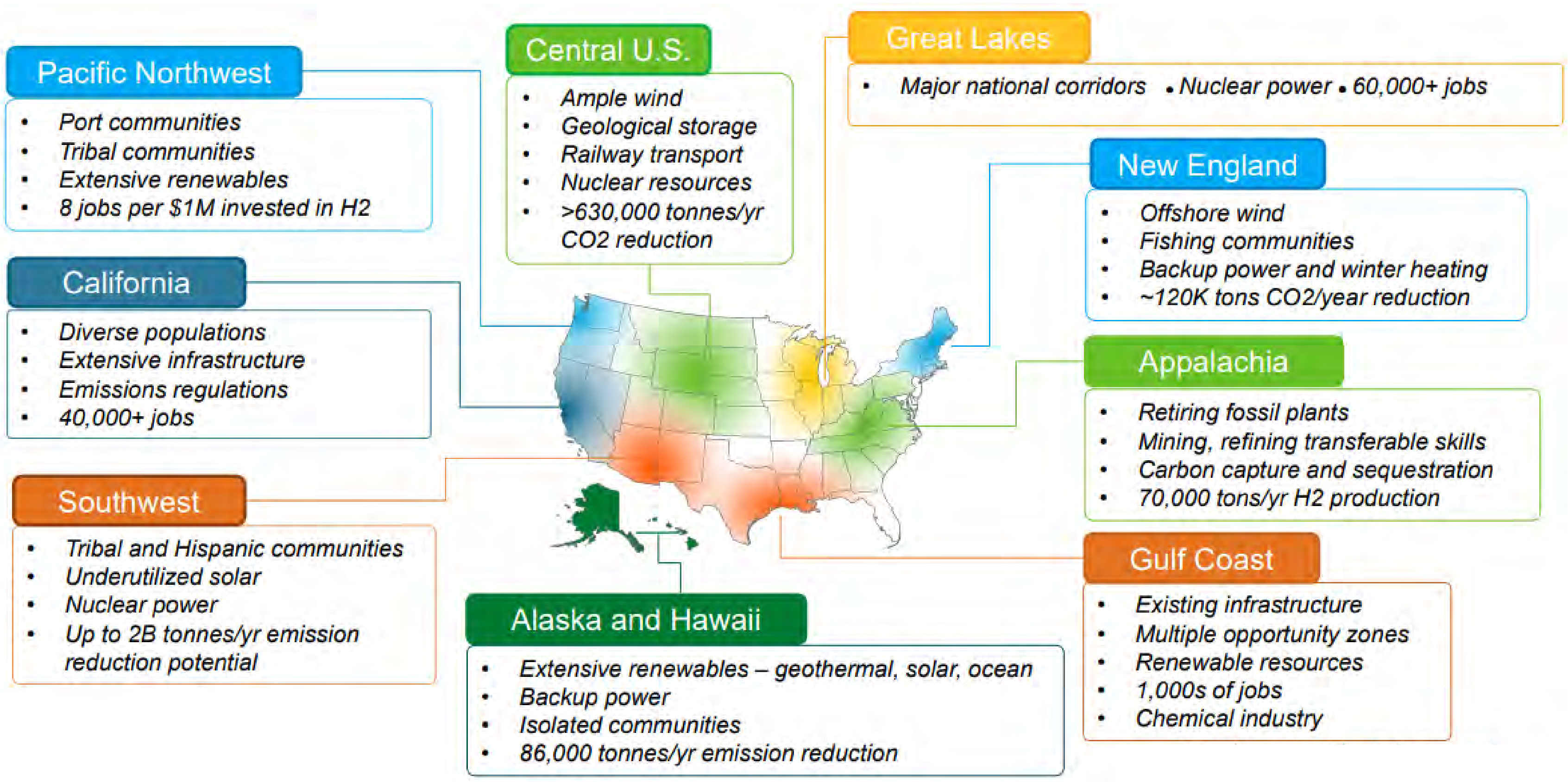
Central hubs are cost advantaged compared to onsite hydrogen production

Adding additional demand sites to the hub decreases cost through returns to scale

Hubs can tap into off-grid or wholesale electricity, which is much cheaper relative to retail industrial electricity. This can potentially lead to lower costs of from green hydrogen combustion heating compared with electric resistance heating.



DOE identified 9 potential regional hubs for clean hydrogen production to accelerate decarbonization across sectors and geographies



Pacific Northwest
- Port communities
- Tribal communities
- Extensive renewables
- 8 jobs per $1M invested in H2

California
- Diverse populations
- Extensive infrastructure
- Emissions regulations
- 40,000+ jobs

Southwest
- Tribal and Hispanic communities
- Underutilized solar
- Nuclear power
- Up to 2B tonnes/yr emission reduction potential

Central U.S.
- Ample wind
- Geological storage
- Railway transport
- Nuclear resources
- >630,000 tonnes/yr CO2 reduction

Alaska and Hawaii
- Extensive renewables – geothermal, solar, ocean
- Backup power
- Isolated communities
- 86,000 tonnes/yr emission reduction

Great Lakes
- Major national corridors
- Nuclear power
- 60,000+ jobs

New England
- Offshore wind
- Fishing communities
- Backup power and winter heating
- ~120K tons CO2/year reduction

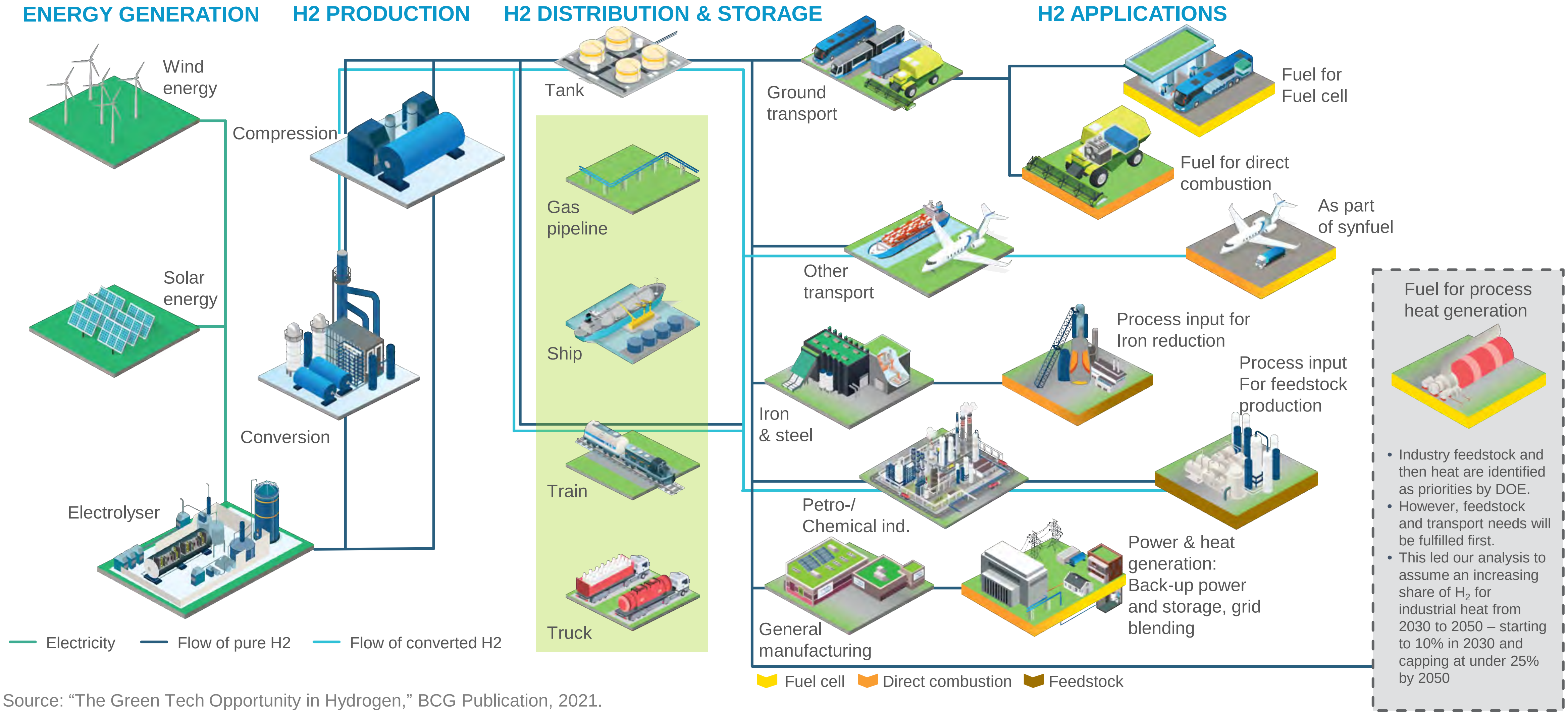
Appalachia
- Retiring fossil plants
- Mining, refining transferable skills
- Carbon capture and sequestration
- 70,000 tons/yr H2 production

Gulf Coast
- Existing infrastructure
- Multiple opportunity zones
- Renewable resources
- 1,000s of jobs
- Chemical industry

The Infrastructure Investment and Jobs Act (IIJA) passed in late 2021 appropriated $8 billion for the development of at least four Regional Clean Hydrogen Hubs (H2Hubs) across the country

Source: DOE Dec 2021 Update on Hydrogen Shot, RFI Results, and Summary of Hydrogen Provisions

Hubs centralize the production, storage & distribution of hydrogen to supply various current and emerging consumers of hydrogen



- Industry feedstock and then heat are identified as priorities by DOE.
- However, feedstock and transport needs will be fulfilled first.
- This led our analysis to assume an increasing share of H_2 for industrial heat from 2030 to 2050 – starting to 10% in 2030 and capping at under 25% by 2050

Source: "The Green Tech Opportunity in Hydrogen," BCG Publication, 2021.

Hydrogen for industrial heating is likely deprioritized vs. other applications, which may lead to strong competition for supply and increased prices

Chemicals feedstock	Refining	Power generation	Transport	Steel
NH_3 Ammonia	Hydrotreating	Power storage	Heavy road	Reducing agent
CH_3OH Methanol	Hydrocracking	Supply balancing	Shipping	
			Aviation	

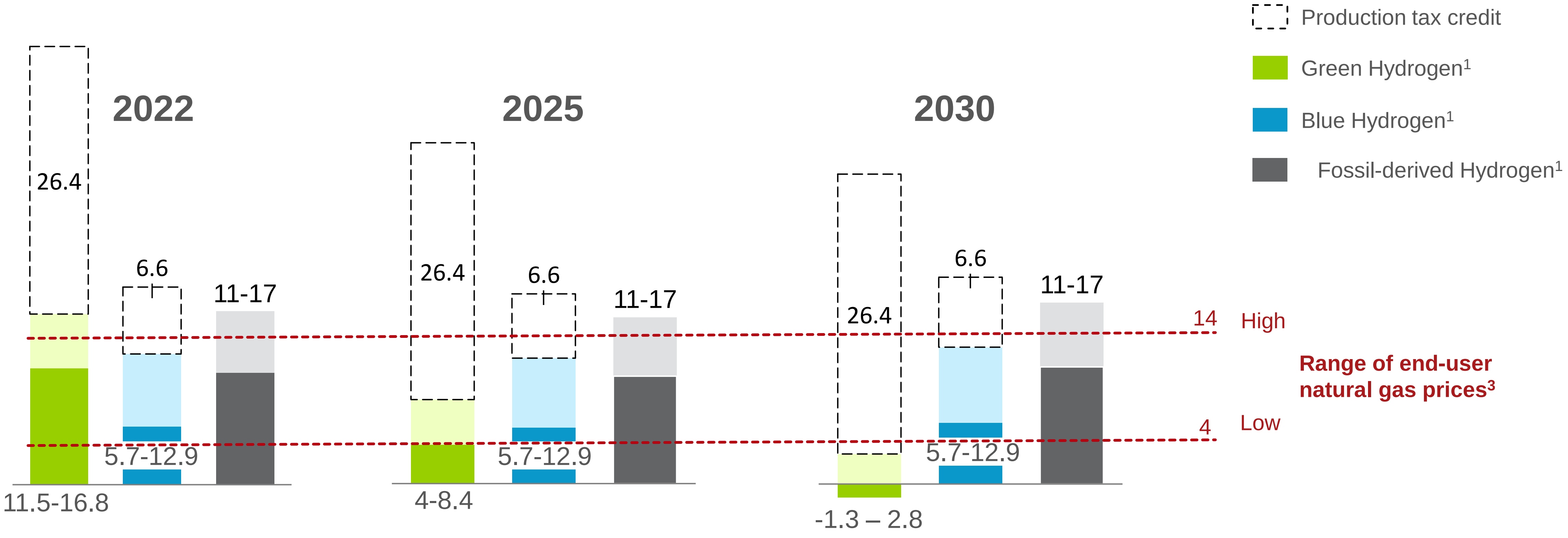
Uncertain deployment of limited clean H_2 in refining given supply constraints (for details, see refinery sector perspective)

Mature applications → *Emerging applications*

With Inflation Reduction Act subsidies, hydrogen prices are expected to be competitive relative to natural gas prices today

United States Levelized Cost of Hydrogen
($/MMBtu, production cost plus T&D costs)[1]

Lighter shades reflects range of cost uncertainty[2]



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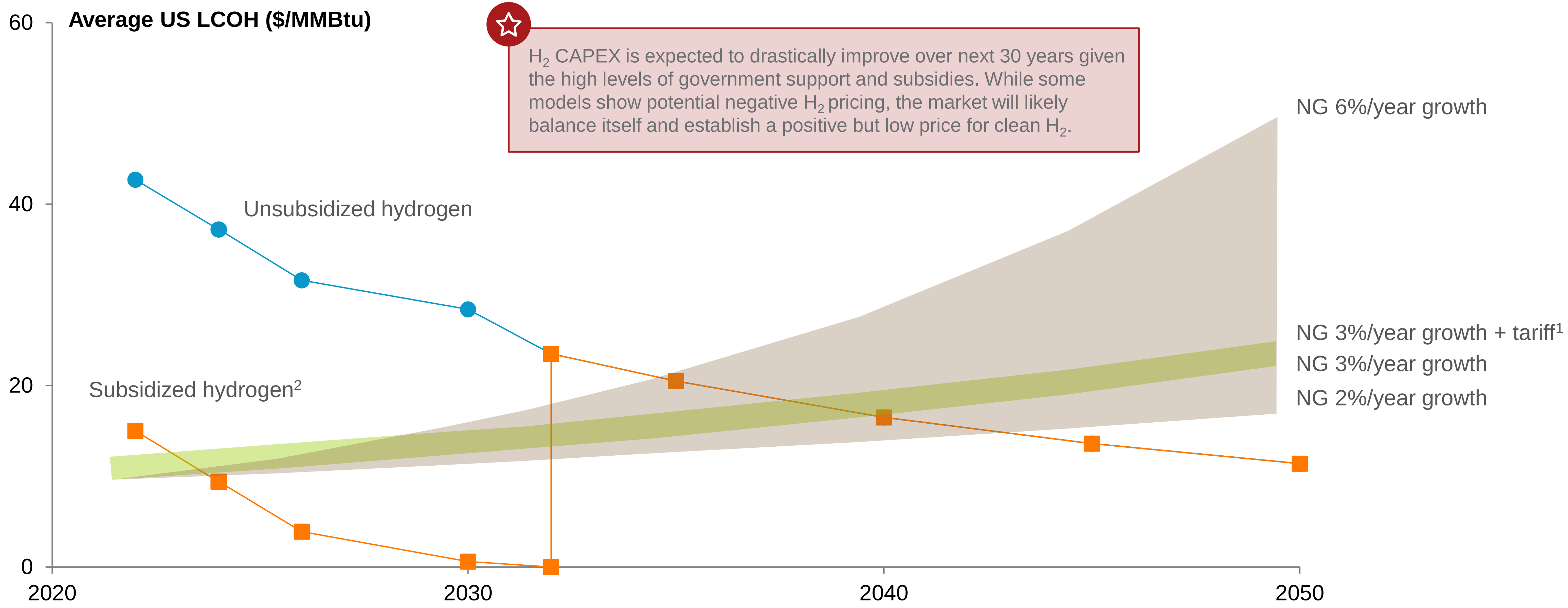
1. Lighter shade reflects pricing uncertainty regarding natural gas (lower limit $2/MMBTU, upper limit $5/MMBTU) and electricity; 2. Starts at $0.4/kg H2 for 60-75% greenhouse gas reduction vs fossil-derived hydrogen, goes up to $0.75/kg H2 for 75-85% greenhouse gas reduction; 3. US EIA May 2022
Source: BCG North America H2 Supply Model

Hydrogen prices will be reduced by government subsidies, additionally CAPEX of hydrogen equipment is also expected to fall over the next 30 years



H_2 CAPEX is expected to drastically improve over next 30 years given the high levels of government support and subsidies. While some models show potential negative H_2 pricing, the market will likely balance itself and establish a positive but low price for clean H_2.

1. Based on $51/tonne CO2 social cost of carbon; 2. Inflation Reduction Act hydrogen production tax credit and investment tax credits

Significant advancements will be required for green H_2 to become competitive for decarbonization of industrial thermal applications

Key advancements needed to achieve green H_2 feasibility

Develop H_2 hubs	Industrial players should support and invest in H_2 hubs now to secure future H_2 supplies
Reduced power price	Resulting in OPEX reduction (e.g., from wind / solar reduced costs, cost exemptions[1])
Matured technology	Increased electrolyzer and fuel cell efficiency and scale of production, reducing CAPEX
Regulatory support	Aggressive emissions targets and the legislation to support them (e.g., higher CO_2 price)
High levels of VRE	More variable renewable energy disrupting the grid & requiring new solutions (e.g., storage)

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1. E.g., Exemptions from grid fees, taxes and levies for large scale setups

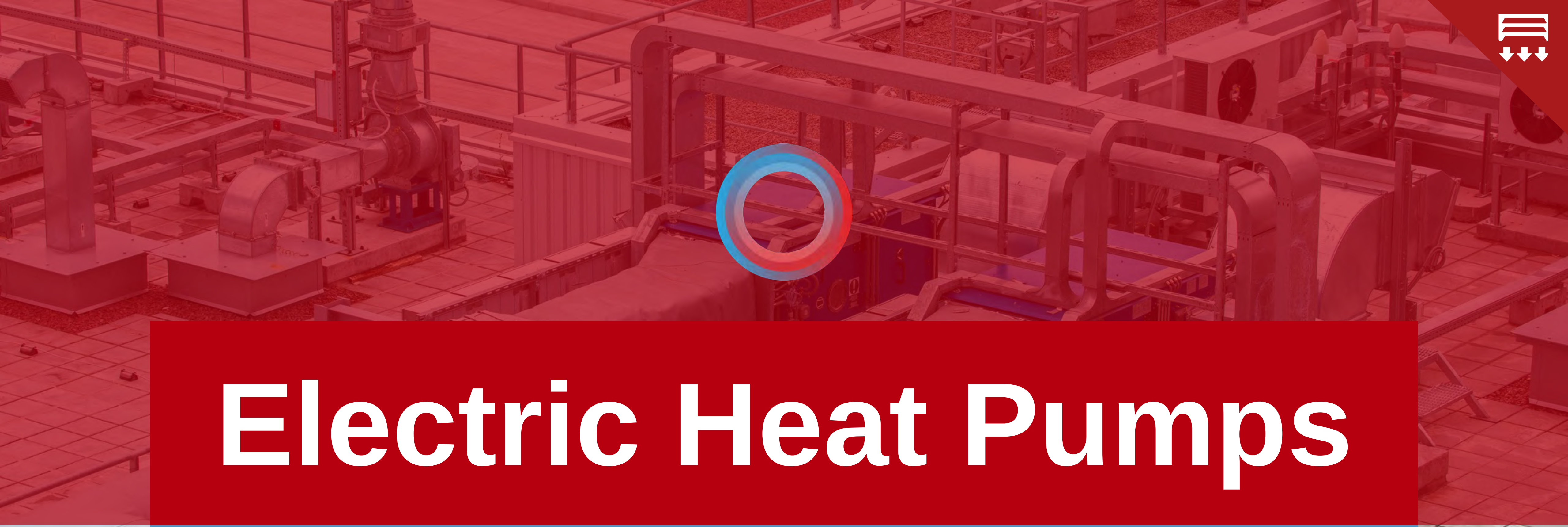
Industrial heating using H2 combustion has potential for displacing many fossil fuels if price declines are actualized, but face several high barriers to adoption

Advantages

- Able to reach highest industrial temperature requirements
- Potential cost savings with subsidies and CAPEX declines
- Relatively simple retrofit of gas combustion equipment
- Eliminates hazardous combustion particulates or emissions

Barriers

- Likely higher fuel costs compared to natural gas systems in the short term
- Difficult to store and transport hydrogen
- Competitive supply environment (i.e., chemicals feedstock, transportation)
- Combustion system full redesign needed for certain sectors



Electric Heat Pumps

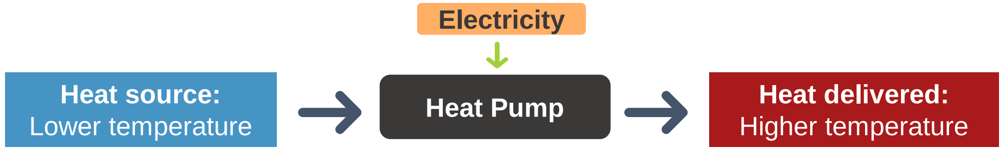
Renewable Thermal Technology

RENEWABLE
THERMAL
COLLABORATIVE

Electric Heat Pumps Technology Overview

Description of technology

- Heat pumps transfer heat from the surroundings (e.g., ground, air, water) or waste heat streams for process applications
- Electricity drives the heat pump's mechanical compression cycle to allow heat to be provided to industrial processes at desired temperatures



- The amount of heat supplied is typically greater than the amount of electricity consumed and is expressed as the Coefficient of Performance (COP), which is the ratio of heat delivered to the input electrical energy

Types of equipment

- Mechanical vapor compression (MVC) and absorption constitute the primary forms of industrial electric heat pumps. Examples include:


Air source heat pump[2]


Water source heat pump[3]


Absorption heat pump[4]

Technical characteristics

- **Temperature range:** Up to 160 ºC
  - Most heat pumps can deliver heat up to 100 ºC at high efficiency
  - Meets low temperature industrial heating requirements (e.g., drying, washing, preheating)
  - Systems capable of providing temperatures above 200 ºC are expected by 2030
- **Heat flux:** Low to medium
  - Dependent on size and configuration of mechanical compression system
- **Heated materials:** Most materials are applicable
  - Heat pump condensers may be in direct contact with the heated medium (e.g., water, process fluids, air)

- **Emissions:** Emissions savings are likely expected in nearly all states today by switching from natural gas combustion to electric heat pump heating using grid electricity

- **Technical maturity:** Medium to high maturity
  - Heat pumps are a mature technology used for building space and water heating
  - Industrial heat pumps with higher temperature ranges and heat transfer rates are nascent but growing in prevalence

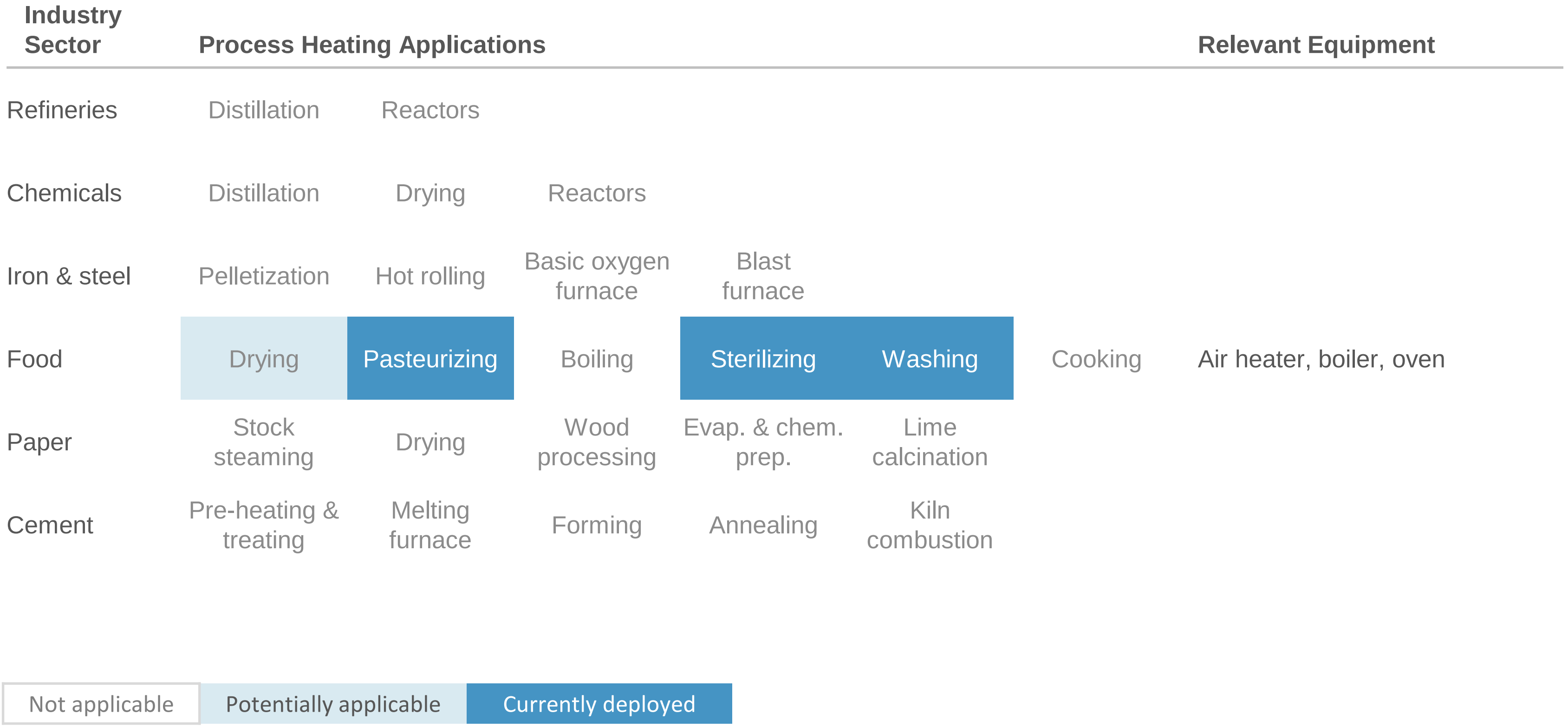
1. ARENA - Renewable energy options for industrial process heat; 2. Sprsun High Temperature Industrial Air Source Heat Pump; 3. H.Stars Group Scroll Water Source Heat Pump; 4. York YHAP-C Absorption Heat Pump. Note: Other industrial heat pumps use waste heat streams or gas combustion (e.g., mechanical vapor recompression, thermal vapor recompression). Since they use natural gas combustion or are characterized as efficiency improvements rather than stand-alone sources of heat, these systems are not discussed further in this analysis.

Due to their low temperatures, heat pumps are limited to lower temperature applications in the food sectors or preheating process streams

Key properties of solar thermal heating include:

- **160 ºC max. temp.**
- **Low to medium heat flux**
- **Heats most materials**

These properties align with requirements for several process heating applications.



Industry Sector	Process Heating Applications						Relevant Equipment
Refineries	Distillation	Reactors					
Chemicals	Distillation	Drying	Reactors				
Iron & steel	Pelletization	Hot rolling	Basic oxygen furnace	Blast furnace			
Food	Drying	Pasteurizing	Boiling	Sterilizing	Washing	Cooking	Air heater, boiler, oven
Paper	Stock steaming	Drying	Wood processing	Evap. & chem. prep.	Lime calcination		
Cement	Pre-heating & treating	Melting furnace	Forming	Annealing	Kiln combustion		

Not applicable | Potentially applicable | Currently deployed

Industrial heat pumps are primarily used for food processing, but are not currently widely deployed

A combination of factors may make electric heat pump heating attractive. These include:

Emissions and operating cost savings

- High efficiencies (i.e., COP)

Specific heating application requirements

- Precise heating controls
- Stringent health or safety standards

Resource availability

- Low electricity prices relative to natural gas prices
- Consistent and readily available source of waste heat

Practically applicable sectors & locations

- Potentially viable and applicable deployment of electric heat pump industrial heating include:
  - **Industry sectors**
    - Food & agriculture
    - Wood products
    - Pre-heating boiler feed water
    - Others with <130ºC temperature requirements, particularly with available waste heat sources
  - **Regions**
    - **Pacific Northwest** – high quantities of hydroelectric power
    - **Portions of southern Midwest** – increasing quantities of wind and solar power

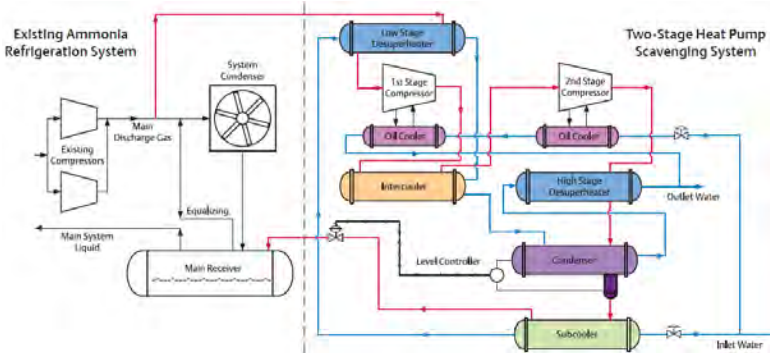
Two case studies of industrial electric heat pumps show the range from mature to emerging application areas

Case study 1: Dairy Pasteurization

- **Maturity:** Mature application area
- **Industry sector:** Food processing
- **Process heating application:** High Temperature Short Time (HTST) pasteurization
- **Location:** Wisconsin

An anonymized dairy processing facility implemented a two-staged heat pump paired with an existing ammonia refrigeration system. It heats water from 10 ºC to 88 ºC with a system COP of 4.2.

Compared to a natural gas boiler system, the project is expected to have a simple payback period of 2.7 years primarily due to operational savings from natural gas expenses.

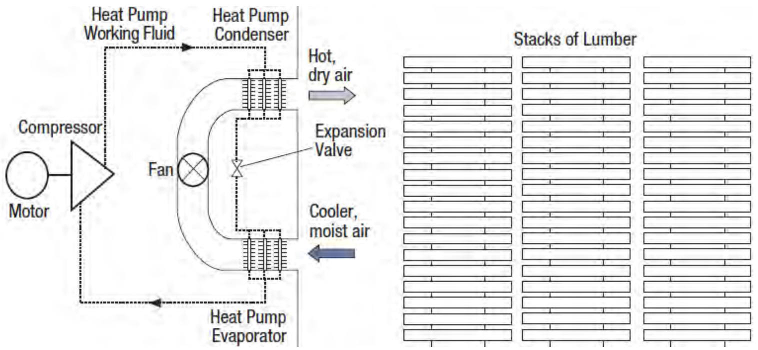


Case study 2: Lumber Drying

- **Maturity:** Emerging application area
- **Industry sector:** Wood products
- **Process heating application**: Lumber drying in wood processing
- **Location:** Quebec, Canada

Traditionally, lumber drying uses a steam-heated kiln to evaporate moisture from the wood. Instead, a closed-cycle mechanical heat pump can supply hot air to the dryer. The moist kiln exhaust air can then be passed over the heat pump evaporator coils to cool the exhaust and collect condensation.

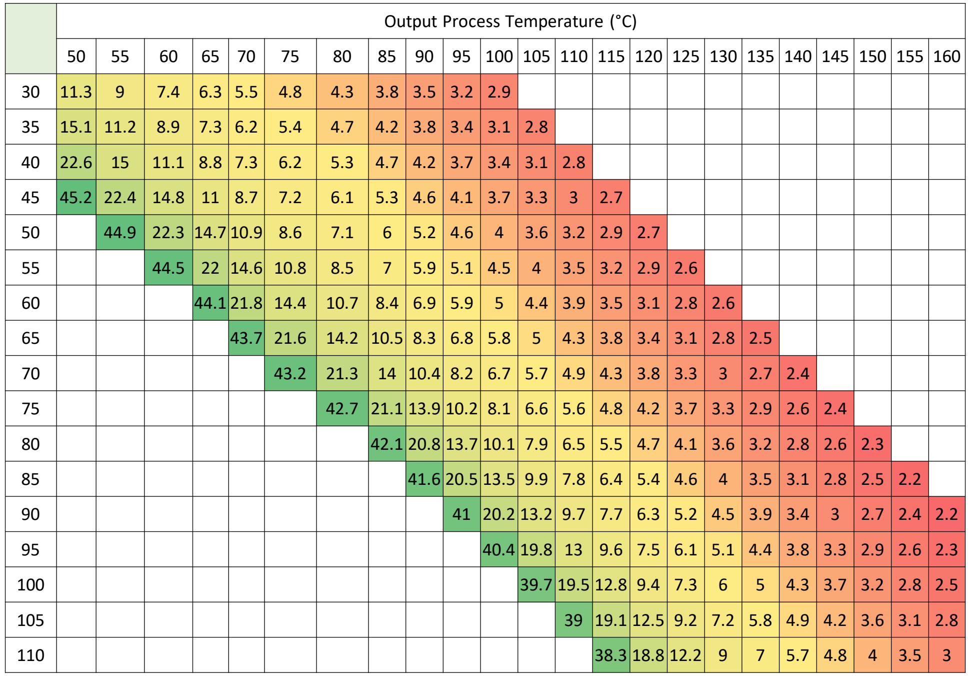
Pilot heat pump lumber drying systems have been implemented where there is relatively inexpensive electricity alongside a large forestry sector. These operations have achieved COPs of 3-4.6 with up to 57% savings in fuel consumption compared to conventional drying systems.



Sources: Industrial heat pumps – Emerson Climate Technologies, Industrial Heat Pumps for Steam and Fuel Savings – DOE, Minea, Vasile. (2012). Using industrial heat pumps in sawmills for lumber drying.

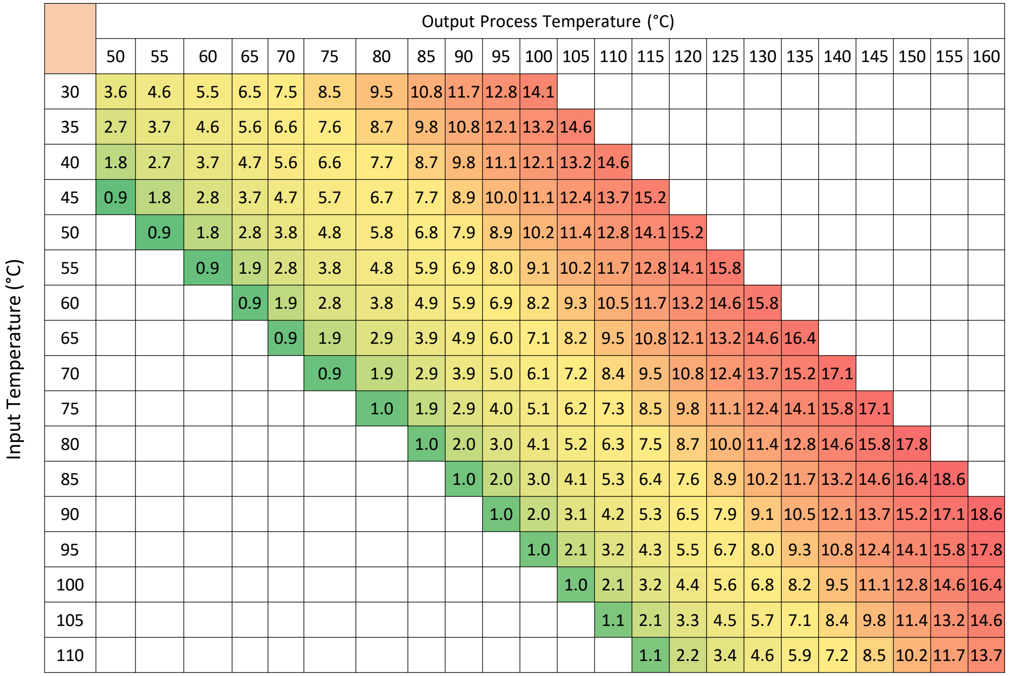
Cost of heat delivered from heat pumps is heavily impacted by the efficiency, which is in turn primarily influenced by the input and output temperatures

Coefficient of performance (COP) or efficiency



	Output Process Temperature (°C)																						
	50	55	60	65	70	75	80	85	90	95	100	105	110	115	120	125	130	135	140	145	150	155	160
30	11.3	9	7.4	6.3	5.5	4.8	4.3	3.8	3.5	3.2	2.9												
35	15.1	11.2	8.9	7.3	6.2	5.4	4.7	4.2	3.8	3.4	3.1	2.8											
40	22.6	15	11.1	8.8	7.3	6.2	5.3	4.7	4.2	3.7	3.4	3.1	2.8										
45	45.2	22.4	14.8	11	8.7	7.2	6.1	5.3	4.6	4.1	3.7	3.3	3	2.7									
50		44.9	22.3	14.7	10.9	8.6	7.1	6	5.2	4.6	4	3.6	3.2	2.9	2.7								
55			44.5	22	14.6	10.8	8.5	7	5.9	5.1	4.5	4	3.5	3.2	2.9	2.6							
60				44.1	21.8	14.4	10.7	8.4	6.9	5.9	5	4.4	3.9	3.5	3.1	2.8	2.6						
65					43.7	21.6	14.2	10.5	8.3	6.8	5.8	5	4.3	3.8	3.4	3.1	2.8	2.5					
70						43.2	21.3	14	10.4	8.2	6.7	5.7	4.9	4.3	3.8	3.3	3	2.7	2.4				
75							42.7	21.1	13.9	10.2	8.1	6.6	5.6	4.8	4.2	3.7	3.3	2.9	2.6	2.4			
80								42.1	20.8	13.7	10.1	7.9	6.5	5.5	4.7	4.1	3.6	3.2	2.8	2.6	2.3		
85									41.6	20.5	13.5	9.9	7.8	6.4	5.4	4.6	4	3.5	3.1	2.8	2.5	2.2	
90										41	20.2	13.2	9.7	7.7	6.3	5.2	4.5	3.9	3.4	3	2.7	2.4	2.2
95											40.4	19.8	13	9.6	7.5	6.1	5.1	4.4	3.8	3.3	2.9	2.6	2.3
100												39.7	19.5	12.8	9.4	7.3	6	5	4.3	3.7	3.2	2.8	2.5
105													39	19.1	12.5	9.2	7.2	5.8	4.9	4.2	3.6	3.1	2.8
110														38.3	18.8	12.2	9	7	5.7	4.8	4	3.5	3

Levelized cost of heat (LCOH) in \$/MMBtu[1]



	Output Process Temperature (°C)																						
Input Temperature (°C)	50	55	60	65	70	75	80	85	90	95	100	105	110	115	120	125	130	135	140	145	150	155	160
30	3.6	4.6	5.5	6.5	7.5	8.5	9.5	10.8	11.7	12.8	14.1												
35	2.7	3.7	4.6	5.6	6.6	7.6	8.7	9.8	10.8	12.1	13.2	14.6											
40	1.8	2.7	3.7	4.7	5.6	6.6	7.7	8.7	9.8	11.1	12.1	13.2	14.6										
45	0.9	1.8	2.8	3.7	4.7	5.7	6.7	7.7	8.9	10.0	11.1	12.4	13.7	15.2									
50		0.9	1.8	2.8	3.8	4.8	5.8	6.8	7.9	8.9	10.2	11.4	12.8	14.1	15.2								
55			0.9	1.9	2.8	3.8	4.8	5.9	6.9	8.0	9.1	10.2	11.7	12.8	14.1	15.8							
60				0.9	1.9	2.8	3.8	4.9	5.9	6.9	8.2	9.3	10.5	11.7	13.2	14.6	15.8						
65					0.9	1.9	2.9	3.9	4.9	6.0	7.1	8.2	9.5	10.8	12.1	13.2	14.6	16.4					
70						0.9	1.9	2.9	3.9	5.0	6.1	7.2	8.4	9.5	10.8	12.4	13.7	15.2	17.1				
75							1.0	1.9	2.9	4.0	5.1	6.2	7.3	8.5	9.8	11.1	12.4	14.1	15.8	17.1			
80								1.0	2.0	3.0	4.1	5.2	6.3	7.5	8.7	10.0	11.4	12.8	14.6	15.8	17.8		
85									1.0	2.0	3.0	4.1	5.3	6.4	7.6	8.9	10.2	11.7	13.2	14.6	16.4	18.6	
90										1.0	2.0	3.1	4.2	5.3	6.5	7.9	9.1	10.5	12.1	13.7	15.2	17.1	18.6
95											1.0	2.1	3.2	4.3	5.5	6.7	8.0	9.3	10.8	12.4	14.1	15.8	17.8
100												1.0	2.1	3.2	4.4	5.6	6.8	8.2	9.5	11.1	12.8	14.6	16.4
105													1.1	2.1	3.3	4.5	5.7	7.1	8.4	9.8	11.4	13.2	14.6
110														1.1	2.2	3.4	4.6	5.9	7.2	8.5	10.2	11.7	13.7

Input temperatures above ambient temperatures require waste heat streams (e.g., refrigeration condensers, vented steam)

E.g., COP of 3 indicates an efficiency of 300%, by which every unit of electricity input yields 3 units of thermal energy output

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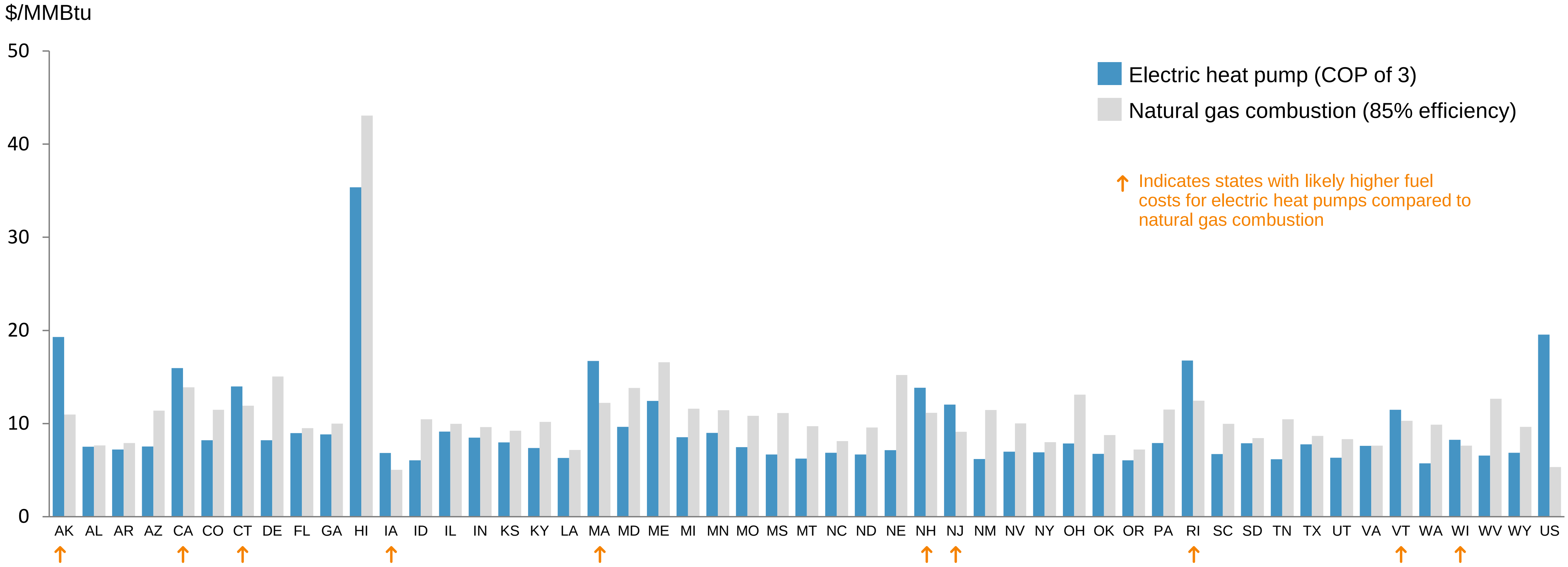
[1] Calculated using average US industrial electricity prices in May 2022

Source: US EIA Industrial Electricity Prices (May 2022), BCG analysis

All but 10 US states show likely lower fuel costs for electric heat pumps compared to natural gas heating

Relative fuel costs between electric heat pump and natural gas combustion heating in 2022

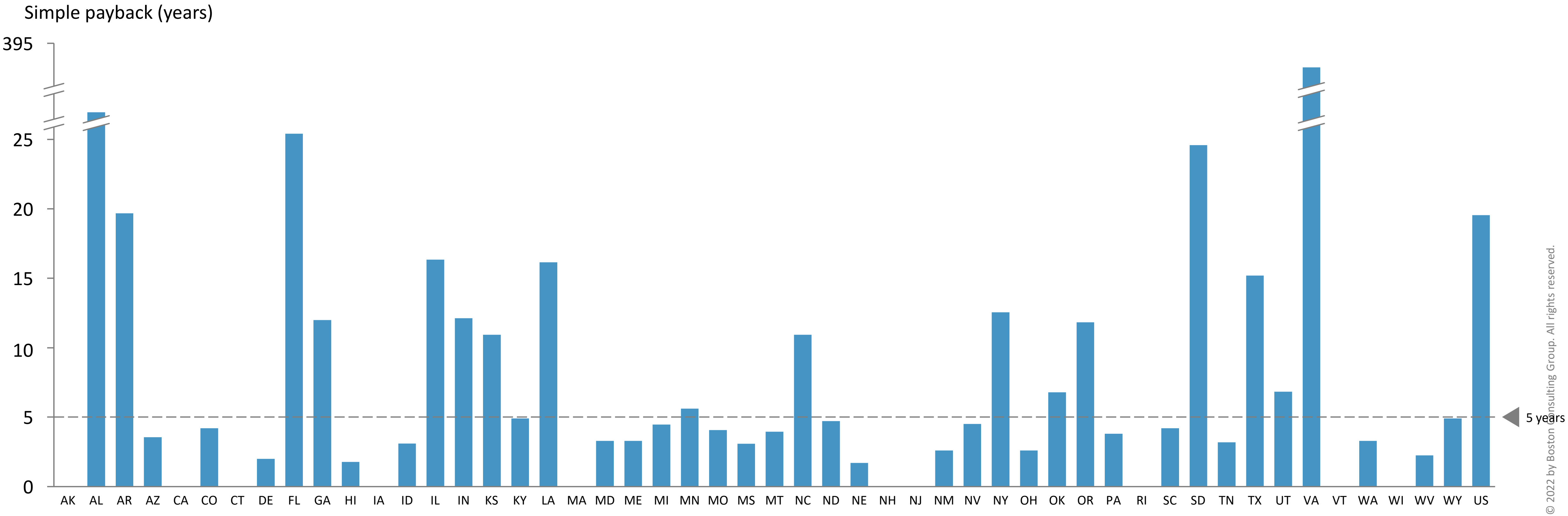


↑ Indicates states with likely higher fuel costs for electric heat pumps compared to natural gas combustion

Note: Analysis assumes a moderate natural gas combustion efficiency of 85%, and a conservative heat pump COP of 3
Source: US EIA Industrial Electricity Prices (May 2022), US EIA Industrial Natural Gas Prices (May 2022)

Transitioning from natural gas combustion to electric heat pumps likely yields payback periods under 5 years for approximately half of US states

Payback period of transitioning from natural gas combustion to electric heat pump using 2022 utility rates



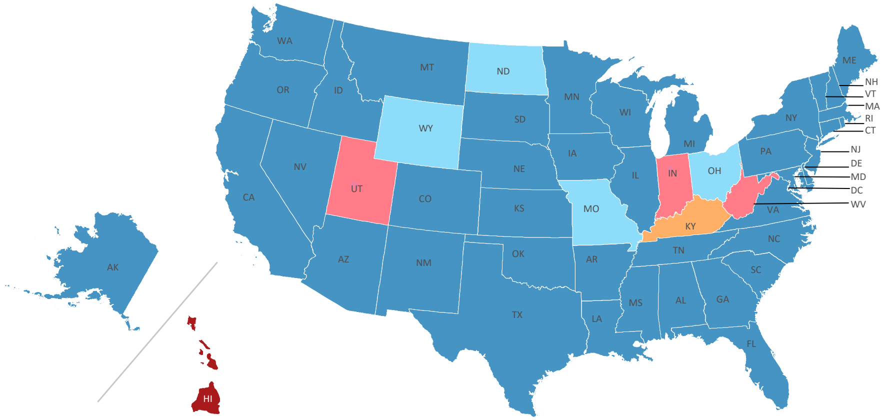
Notes: States without a payback period indicated have higher operating costs for electric heat pumps compared to natural gas combustion. Capital cost of electric heat pump was assumed to be $120,000/MMBtu from ACEEE source.
Source: US EIA Industrial Electricity Prices (May 2022), US EIA Industrial Natural Gas Prices (May 2022), Industrial Heat Pumps: Electrifying Industry's Process Heat Supply - ACEEE

Emissions savings are expected in nearly all states today by switching from natural gas combustion to electric heat pump heating

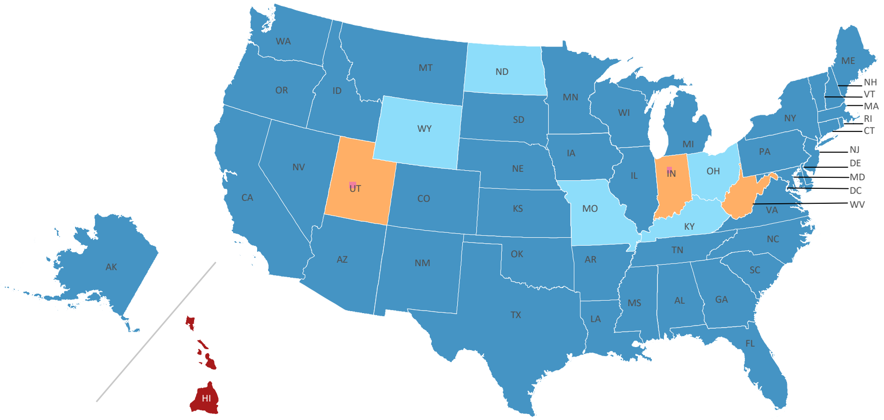
Likely reduction in emissions by switching from natural gas combustion^1 to electric heat pump^2 heating:

- ● Today (2022)
- ● By 2026
- ● By 2030
- ● By 2035
- ● Beyond 2035

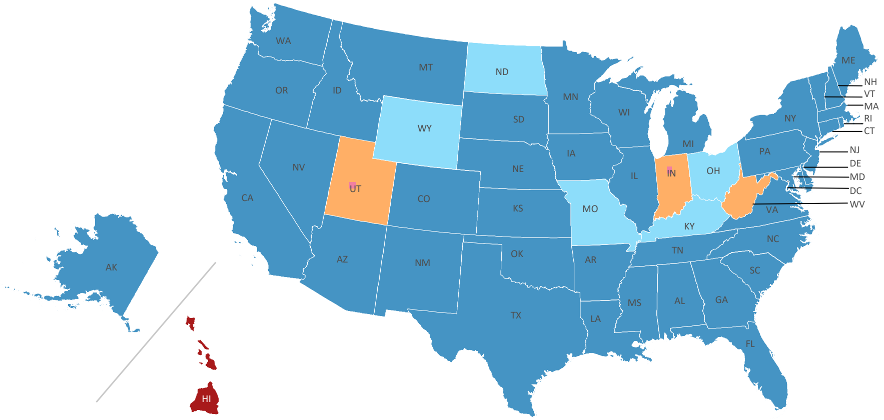
Scenario 1: 80% renewables by 2050



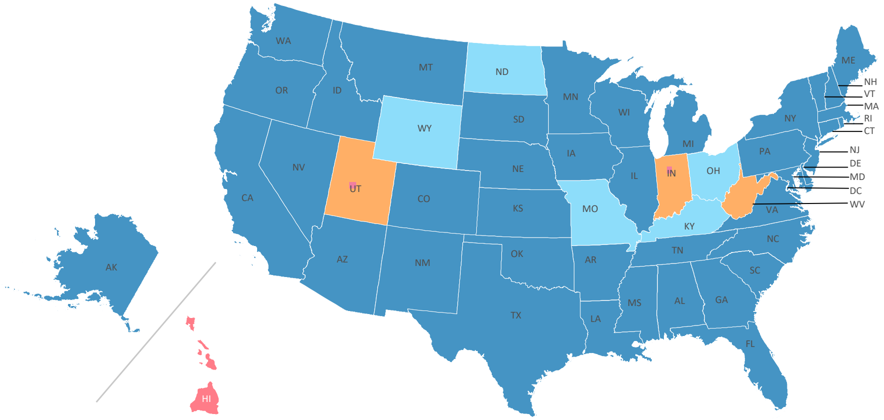
Scenario 2: 65% renewables by 2030



Scenario 3: 80% renewables by 2030



Scenario 4: Near 100% renewables by 2035



Sources: US EPA GHGRP (2019); US EIA; State Renewable Portfolio Standards; IEA ETSAP Industrial Combustion Boilers Fact Sheet; BCG analysis

1. Calculated using 85% efficiency for natural gas boiler; 2. Calculated using a conservative COP of 3

Electric heat pump industrial heating has many advantages especially for lower temperature applications, but faces several key barriers to adoption

Advantages

- May be able to achieve payback within 5 years in many parts of US
- Precise control of temperature and heat input
- Can approach 400% efficiency or beyond
- Improved health & safety due to lack of combustion

Barriers

- Higher capital costs relative to combustion equipment
- Rotating equipment leads to higher maintenance costs
- Efficiency decreases beyond 100 ºC, and cannot deliver >160 ºC
- Potential for high GWP refrigerant leaks
- Extensive electrical infrastructure upgrades may be required

Electric Resistance

Renewable Thermal Technology

RENEWABLE
THERMAL
COLLABORATIVE

Electric Resistance Technology Overview

Description of technology

- Electric resistance (ohmic) thermal equipment uses an electric current to provide heating due to a material's electrical resistivity
- There are two types of electric resistance heating:
    - Indirect – The current runs through an electrical resistor, which heats up surrounding materials through convection, conduction, or radiation. This is the primary form of electric resistance heating currently applied in industry.
    - Direct – The current runs through the material to be heated via its own electrical resistivity

Types of equipment

- Electric resistance heating is capable of directly replacing most natural gas fired industrial heating equipment without major system modifications.

Electric ovens[4]

Electric furnaces[5]

Electric boilers[6]

Electric air heaters[7]

Note: Example equipment not exhaustive

1. US EIA Electricity Data with BCG analysis (2022); 2. Renewable energy options for industrial process heat – Appendix (ARENA); 3. US EIA Electric Data – Average industrial electricity prices; 4. Industry Plaza – Industrial ovens; 5. Industry Plaza – Industrial Electric furnaces; 6. Industrial Boilers – Electric Boilers; 7. Industrial Fans Direct – Ruffneck Electric Air Heater

Technical characteristics

- **Temperature range:** Up to 1,800 ºC
    - Meets all industrial heating temperature requirements aside from highest temperature applications (e.g., cement kiln, steelmaking, metal fabrication)
- **Heat flux:** High
    - Dependent on resistive element configuration and use of convective drivers (i.e., fans)
- **Heated materials:** Most materials are applicable
    - Electric resistive heating elements are usually in direct contact with the heated medium (e.g., water, process fluids, air)
    - Electrical heating eliminates potential contamination of heated materials with fuel particulates or combustion flue gases

- **Emissions:** Higher emissions relative to natural gas combustion in all but a handful of US states currently
    - Emissions intensity ranges from 10 kg CO_2/MMBtu (VT) to 358 kg CO_2/MMBtu (HI) depending on grid mix and system efficiency [1]

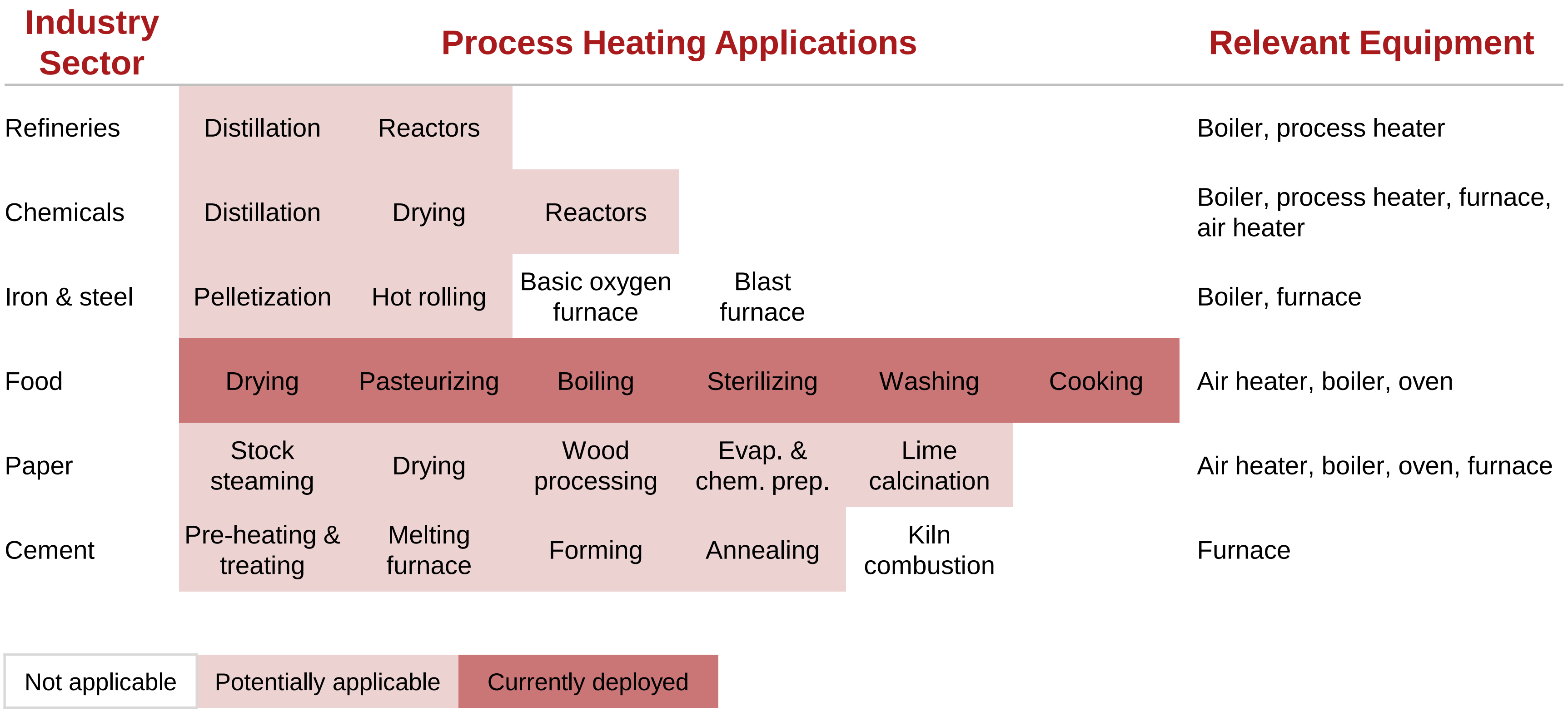
- **Technical maturity:** High maturity
    - The simplest and oldest form of electric heating

Electric resistance heating is applicable to all but the highest temperature industrial applications

Key properties of electric resistance include:

- 1,800 ºC max. temp.
- High heat flux
- Heats all materials

These properties align with requirements for several process heating applications.



Industry Sector	Process Heating Applications						Relevant Equipment
Refineries	Distillation	Reactors					Boiler, process heater
Chemicals	Distillation	Drying	Reactors				Boiler, process heater, furnace, air heater
Iron & steel	Pelletization	Hot rolling	Basic oxygen furnace	Blast furnace			Boiler, furnace
Food	Drying	Pasteurizing	Boiling	Sterilizing	Washing	Cooking	Air heater, boiler, oven
Paper	Stock steaming	Drying	Wood processing	Evap. & chem. prep.	Lime calcination		Air heater, boiler, oven, furnace
Cement	Pre-heating & treating	Melting furnace	Forming	Annealing	Kiln combustion		Furnace

Not applicable | Potentially applicable | Currently deployed

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1. US EIA Electricity Data - Detailed EIA-923 emissions survey data (2020); 2. Renewable energy options for industrial process heat – Appendix (ARENA); 3. US EIA Electric Data – Average industrial electricity prices

Industrial electric resistance heating is currently only used in niche applications and specific regions

- Currently, electric resistance heating is generally not economically viable for industrial application in the US
- However, a combination of factors may make electric resistance heating attractive. These include:
  - **Specific heating application requirements**
    - Precise heating controls
    - Stringent health or safety standards
    - Minimal maintenance
  - **Regional characteristics**
    - Low electricity prices relative to natural gas prices
    - High quantities of electricity supply

Practically applicable sectors & locations

- Potentially viable and applicable deployment of electric resistance industrial heating include:
  - **Industry sectors**
    - Food & agriculture,
    - Paper products,
    - Pharmaceuticals, and
    - Small-batch specialty chemicals production
  - **Regions**
    - **Pacific Northwest** – high quantities of hydroelectric power
    - **Portions of southern Midwest** – increasing quantities of wind and solar power

Two case studies of industrial electric resistance heating show the range from mature to emerging application areas

Case study 1: Fulton electric heating equipment

- **Maturity:** Mature application area
- **Industry sector:** Food & beverage (brewery, distillery, meat processing, etc.)
- **Process heating application:** Various (pasteurizing, boiling, sterilizing, washing, etc.)
- **Location:** Various in US

Fulton electric steam boilers and thermal fluid heaters, which are used extensively throughout the food & beverage industries. They offer a wide variety of heat transfer products and size ranges for a variety of process application requirement.

FBL electric steam boiler
Size range: 1.2-100 BHP

FBE electric steam boiler
Size range: 1.2-18 BHP

FT-N Vertical Electric Thermal Fluid Heater
Size range: 2.2-50 BHP

Case study 2: Norsk Hydro alumina refining

- **Maturity:** Emerging application area
- **Industry sector:** Metals (aluminum)
- **Process heating application:** Alumina refining
- **Location:** Brazil

Norsk Hydro ASA's Alunorte alumina refinery began using an electric boiler in March 2022. The boiler is expected to cut the plant's carbon emissions by 100,000 tonnes per year.

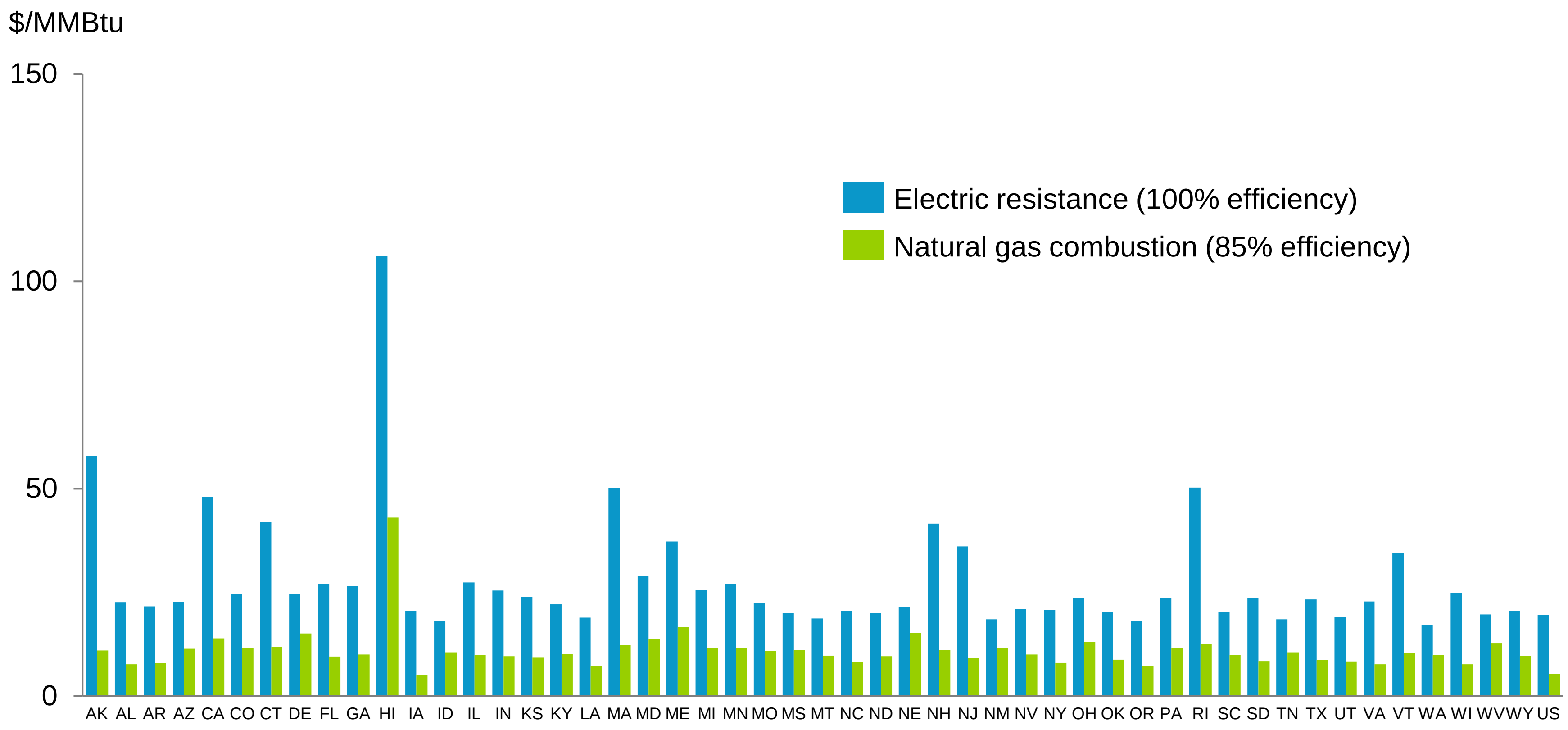
The boiler cost $7.6 million USD and can produce up to 95 tonnes of steam per hour while consuming 60 MW. The alumina refinery is planned to commission two more electric boilers within the next two years.

Initially, the boilers will operate with electricity purchased from the local grid. Norsk Hydro is examining options to acquire green electricity to power the boilers.

Source: Fulton Industries Food & Beverage Processing; Norsk Hydro Commissions New Electric Steam Boiler At Alunorte Alumina Refinery (Aluminium Insider)

All US states show significantly higher fuel costs for electric resistance compared to natural gas heating

Relative fuel costs between electric heat pump and natural gas combustion heating in May 2022



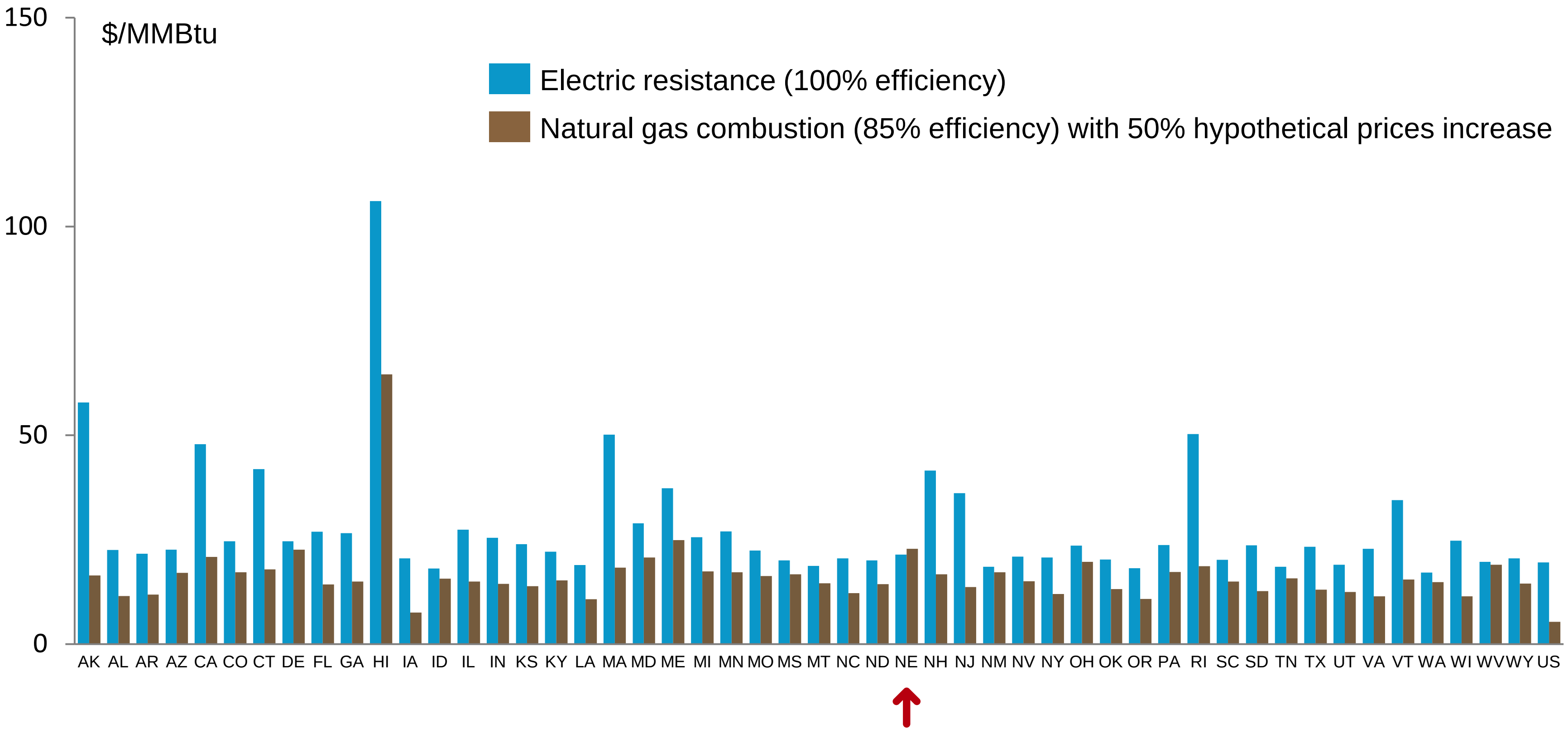
To make relative fuel costs economically viable,

- Significant incentives must be provided to users of electric heating or
- Natural gas prices or tariffs need to increase substantially

Source: US EIA Industrial Electricity Prices (May 2022), US EIA Industrial Natural Gas Prices (May 2022)

All US states show significantly higher fuel costs for electric resistance compared to natural gas heating

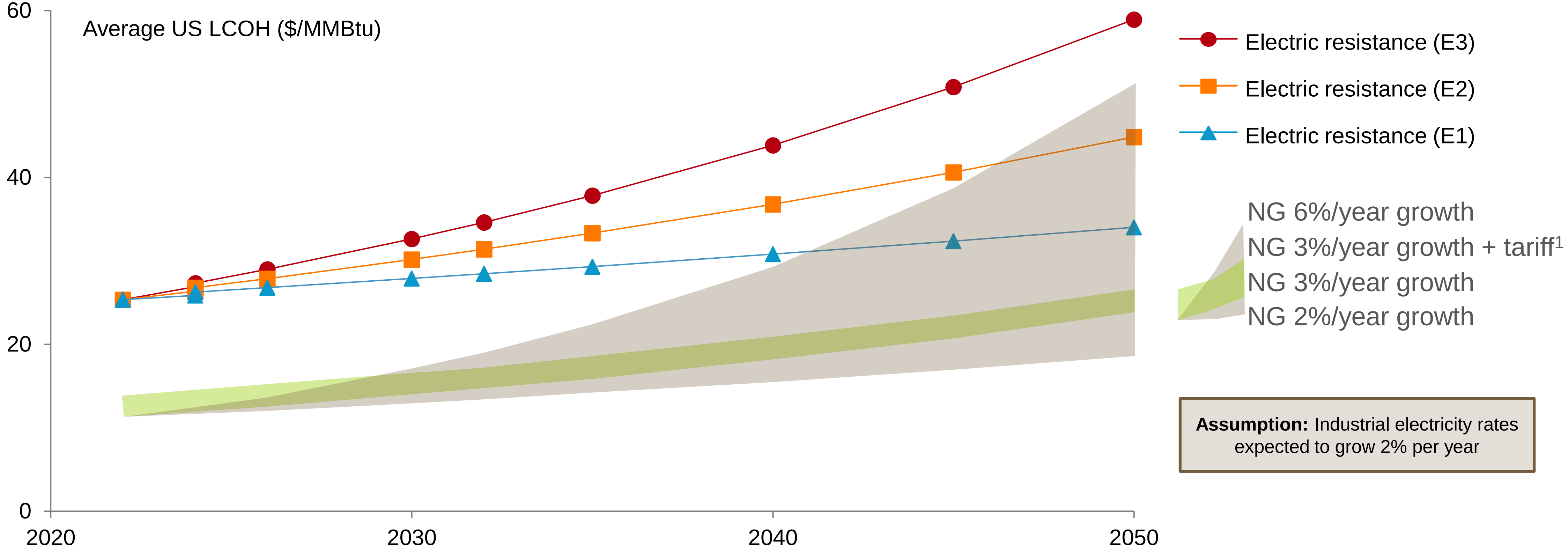
Relative fuel costs between electric heat pump and natural gas combustion heating with hypothetical 50% increase in natural gas prices



Electric resistance industrial heating using grid electricity is likely more expensive relative to natural gas

Source: US EIA Industrial Electricity Prices (May 2022), US EIA Industrial Natural Gas Prices (May 2022)

Electric resistance is not expected to be more cost effective relative to NG aside from extreme future scenarios, but better control may reduce overall heat needs



Assumption: Industrial electricity rates expected to grow 2% per year

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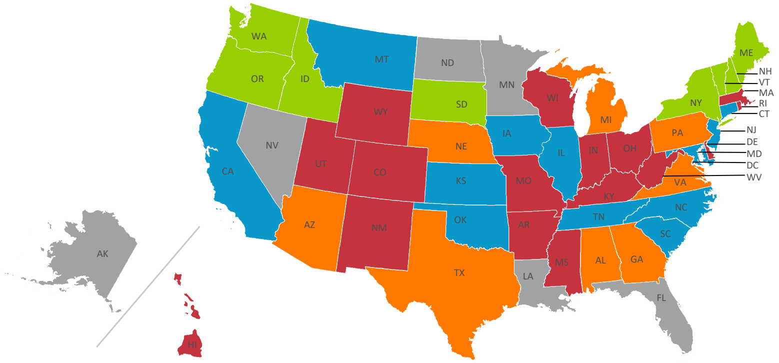
1. Based on $51/tonne CO2 social cost of carbon
Note: Subsidized are shown in plots, subsidized and unsubsidized LCOHs are within 5%

In all scenarios by 2026, more than half of states may be able to reduce emissions by switching to electric resistance heating

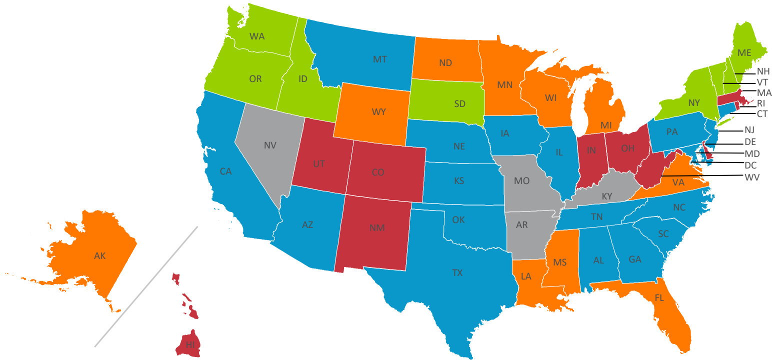
Likely reduction in emissions by switching from natural gas combustion[1] to electric resistance heating:

- 🟢 Today
- 🔵 By 2026
- 🟠 By 2030
- ⚪ By 2035
- 🔴 Beyond 2035

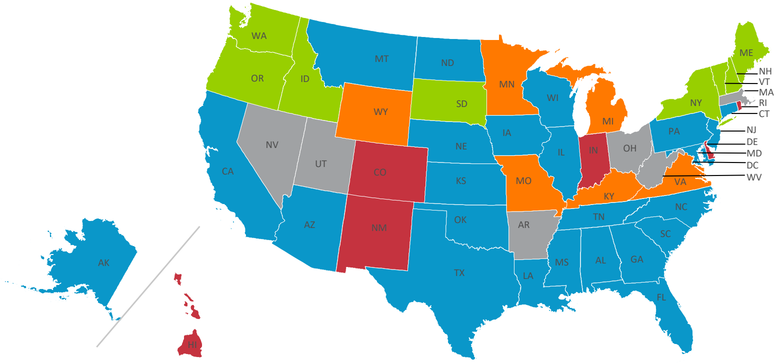
Scenario 1: 80% renewables by 2050



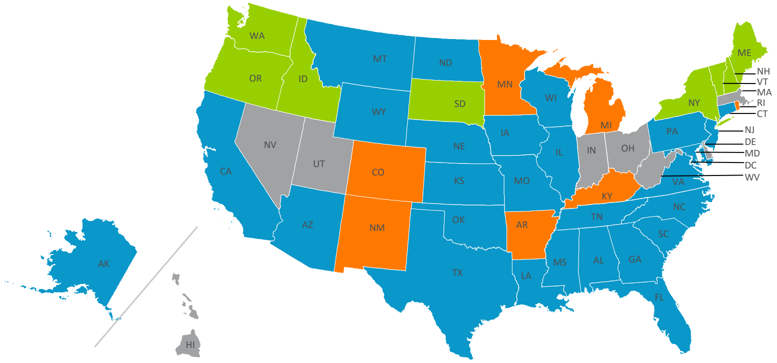
Scenario 2: 65% renewables by 2030



Scenario 3: 80% renewables by 2030



Scenario 4: Near 100% renewables by 2035



Sources: US EPA GHGRP (2019); US EIA; State Renewable Portfolio Standards; IEA ETSAP Industrial Combustion Boilers Fact Sheet; BCG analysis

[1] Calculated using 85% efficiency for natural gas boiler

Electric resistance industrial heating has many advantages, but faces several key barriers to adoption

Advantages

- Minor modifications from combustion system
- Capital costs equal to or below combustion
- Precise control of temp. and heat input
- Approaches 100% efficiency
- Low maintenance requirements
- Improved health & safety due to lack of combustion

Barriers

- Likely higher fuel costs compared to gas systems
- Limited emissions reduction potential using grid electricity in many states before 2026
- Extensive electrical infrastructure upgrades may be required

Renewable Natural Gas

Renewable Thermal Technology

RENEWABLE
THERMAL
COLLABORATIVE

Renewable Natural Gas Technology Overview

Description of technology

- Renewable natural gas (RNG), also known as biogas or biomethane is virtually identical in composition with fossil natural gas.
- RNG comes from the processing of gases captured from landfills, agricultural or food waste, wastewater treatment plants, and other sources. These facilities primarily produce methane through anaerobic digestion.
- Alternatively, synthetic natural gas, also known as power-to-gas (P2G), uses electrolysis to produce hydrogen that is then combined with CO_2 to produce methane (CH_4). P2G is not covered in this fact base due to the large differences between P2G and other RNG in terms of feedstock and economic viability.

Types of equipment

- All existing fossil natural gas equipment are compatible with RNG fuel.


Gas fired heater[1]


Gas furnaces[2]


Gas boilers[3]


Gas air heaters[4]

Note: Example equipment not exhaustive

Technical characteristics

- **Temperature range:** Up to 1,950 ºC
  - Meets all industrial heating temperature requirements aside from very highest temperature applications (i.e., steelmaking)
- **Heat flux:** High
  - Dependent on burner configuration, able to deliver high quantities of heat; identical to fossil natural gas combustion
- **Heated materials:** Most materials are applicable

- **Emissions:** Theoretically net-zero, but methane leakage and energy use during processing could lead to non-zero emissions

- **Technical maturity:** High maturity
  - RNG is produced at large scales across the US, but supply still only constitutes <0.2% of total natural gas demand

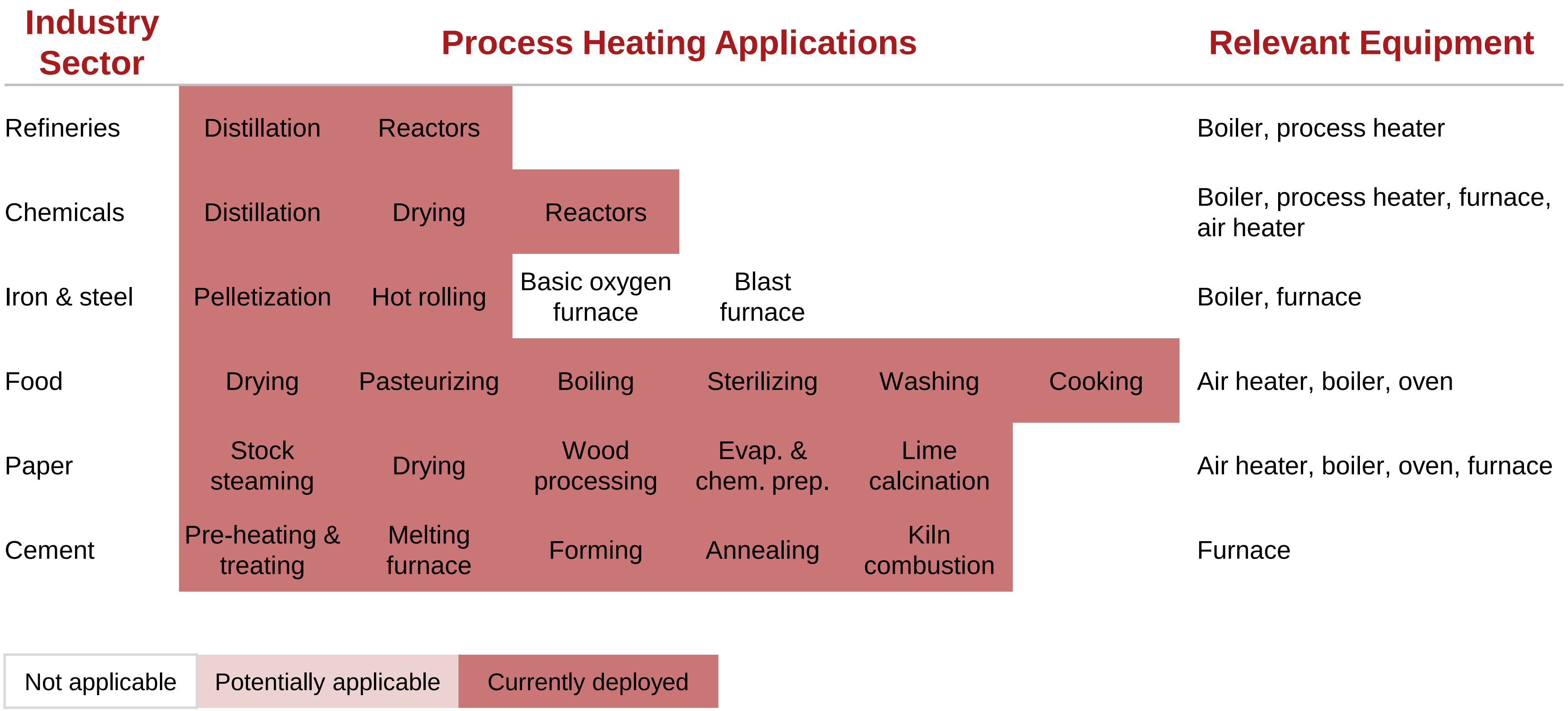
1. Sigma Thermal Direct Fired Heater; 2. Thermcraft gas fired industrial furnace; 3. Hurst Boiler industrial boiler systems; 4. Ambirad natural gas air heater unit

Since RNG is a direct substitute for fossil natural gas, it can serve nearly all industrial applications where natural gas is currently deployed

Key properties of RNG combustion heating include:

- 1,950 ºC max. temp.
- High heat flux
- Heats all materials

These properties align with requirements for several process heating applications.

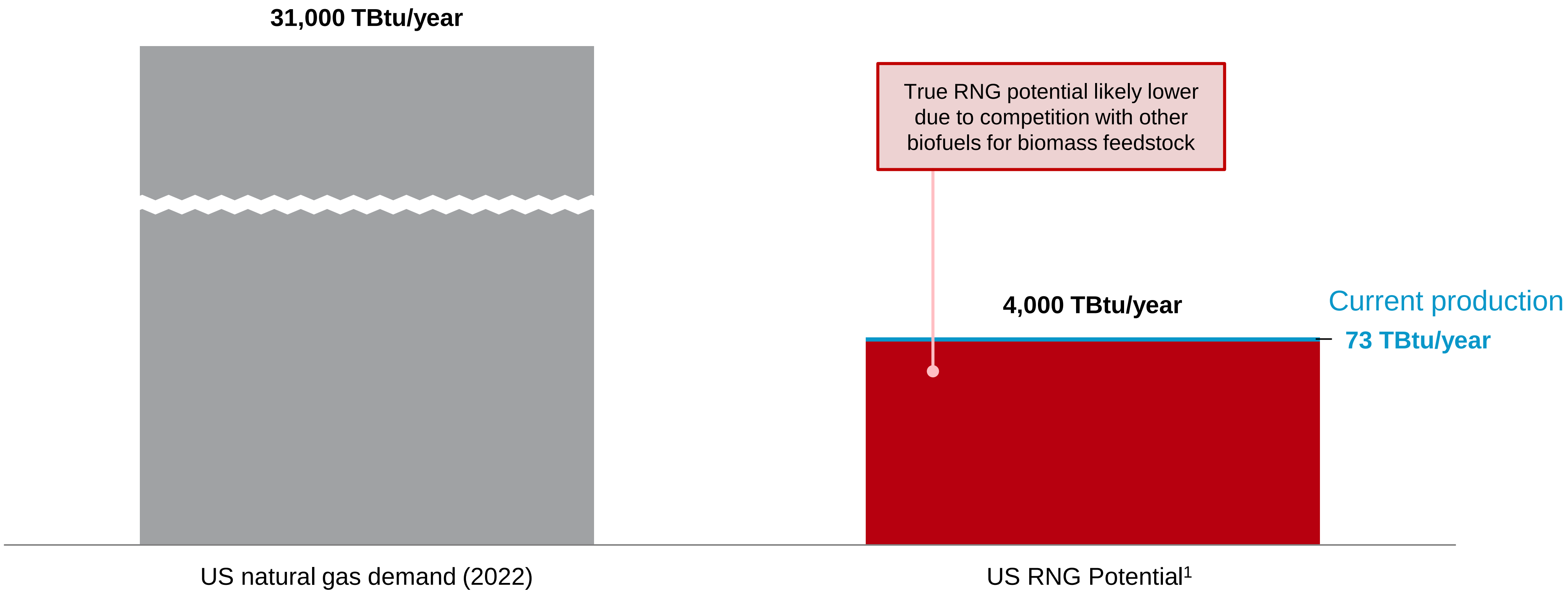


Industry Sector	**Process Heating Applications**						**Relevant Equipment**
Refineries	Distillation	Reactors					Boiler, process heater
Chemicals	Distillation	Drying	Reactors				Boiler, process heater, furnace, air heater
Iron & steel	Pelletization	Hot rolling	Basic oxygen furnace	Blast furnace			Boiler, furnace
Food	Drying	Pasteurizing	Boiling	Sterilizing	Washing	Cooking	Air heater, boiler, oven
Paper	Stock steaming	Drying	Wood processing	Evap. & chem. prep.	Lime calcination		Air heater, boiler, oven, furnace
Cement	Pre-heating & treating	Melting furnace	Forming	Annealing	Kiln combustion		Furnace

Not applicable | Potentially applicable | Currently deployed

Note: Since RNG has been blended into the existing natural gas distribution network, all potentially applicable process heating applications are denoted as "currently deployed"

Potential long-term RNG supply can meet up to 13% of US total natural gas demand, while <2% of potential supply is currently in production



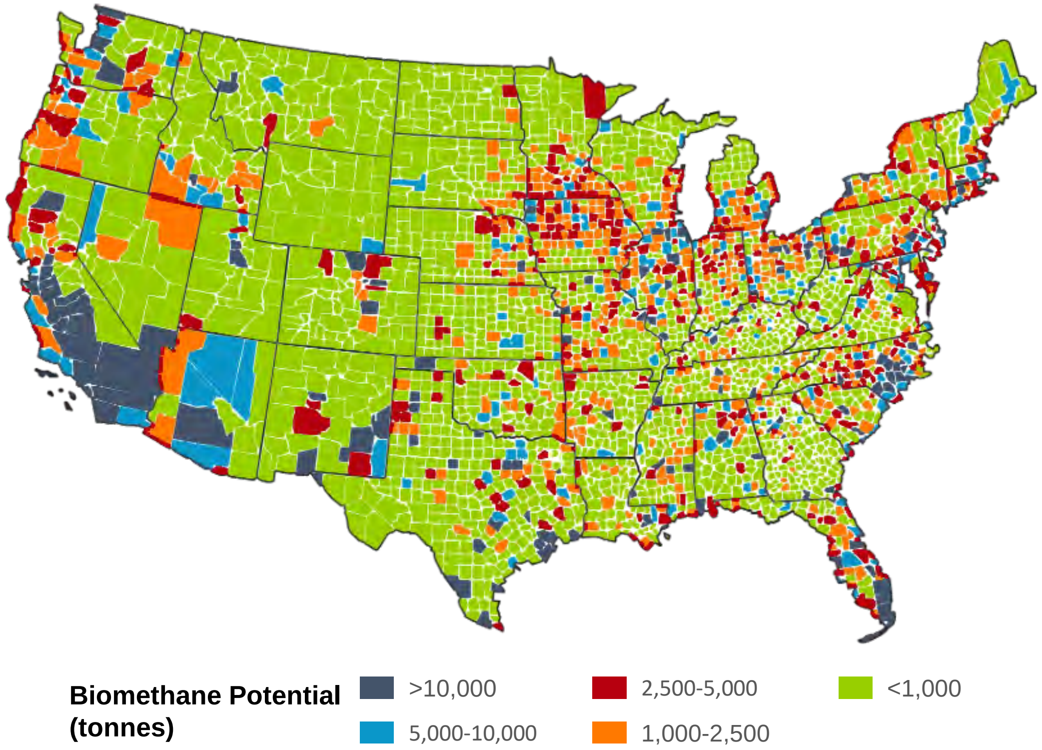
True RNG potential likely lower due to competition with other biofuels for biomass feedstock

[1] Assumes lignocellulosic biomass resources are used, does not account for competing uses (e.g., other fuels, power generation)

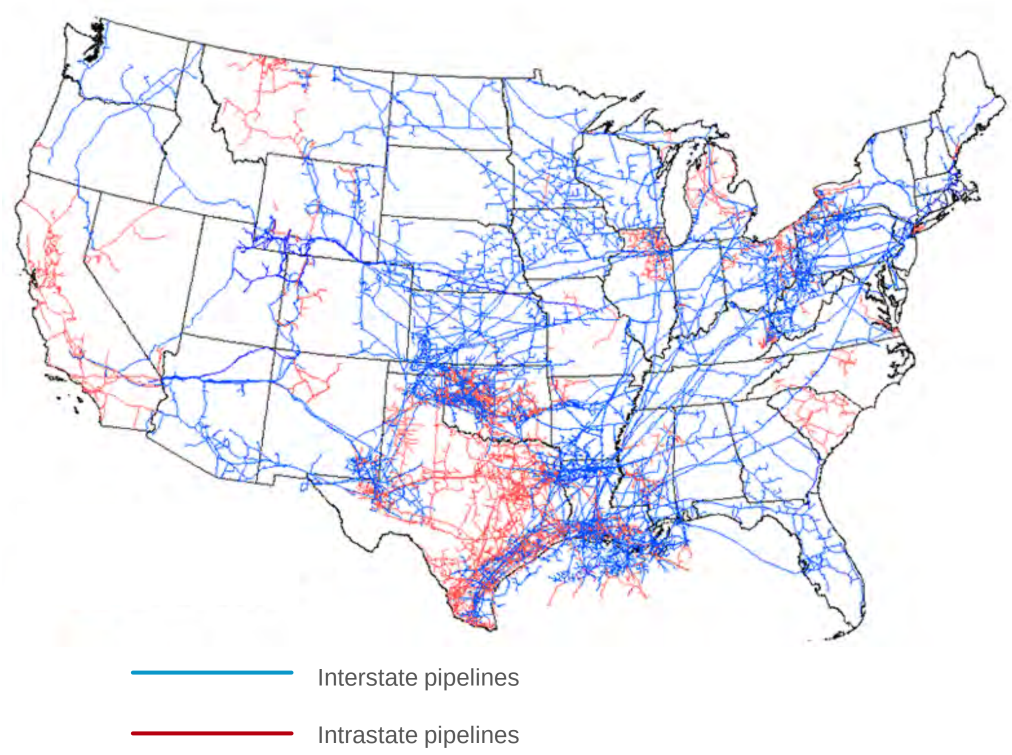
Source: EIA, IEA, EPA, Argonne National Laboratory, MJB&A, California Bioenergy, BCG analysis

RNG is likely to be consumed locally or regionally since RNG supply potentially does not directly align with existing gas pipeline infrastructure

Biomethane supply potential



Interstate and intrastate natural gas pipelines



Source: NREL, US EIA

2022 production for RNG was ~73 TBtu/year with vast majority allocated to transportation demand and nearly zero to industrial applications

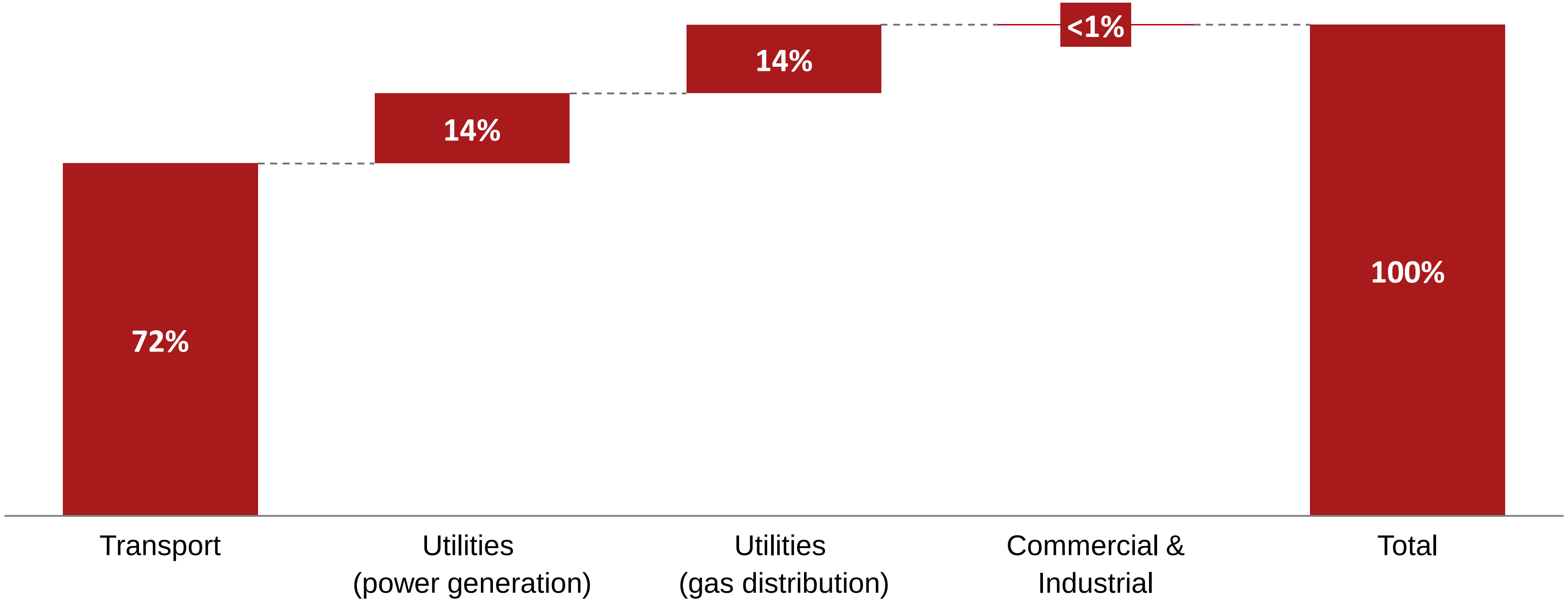
Estimated current RNG consumption in 2022

73

TBtu/year

<0.2% of total US natural gas demand

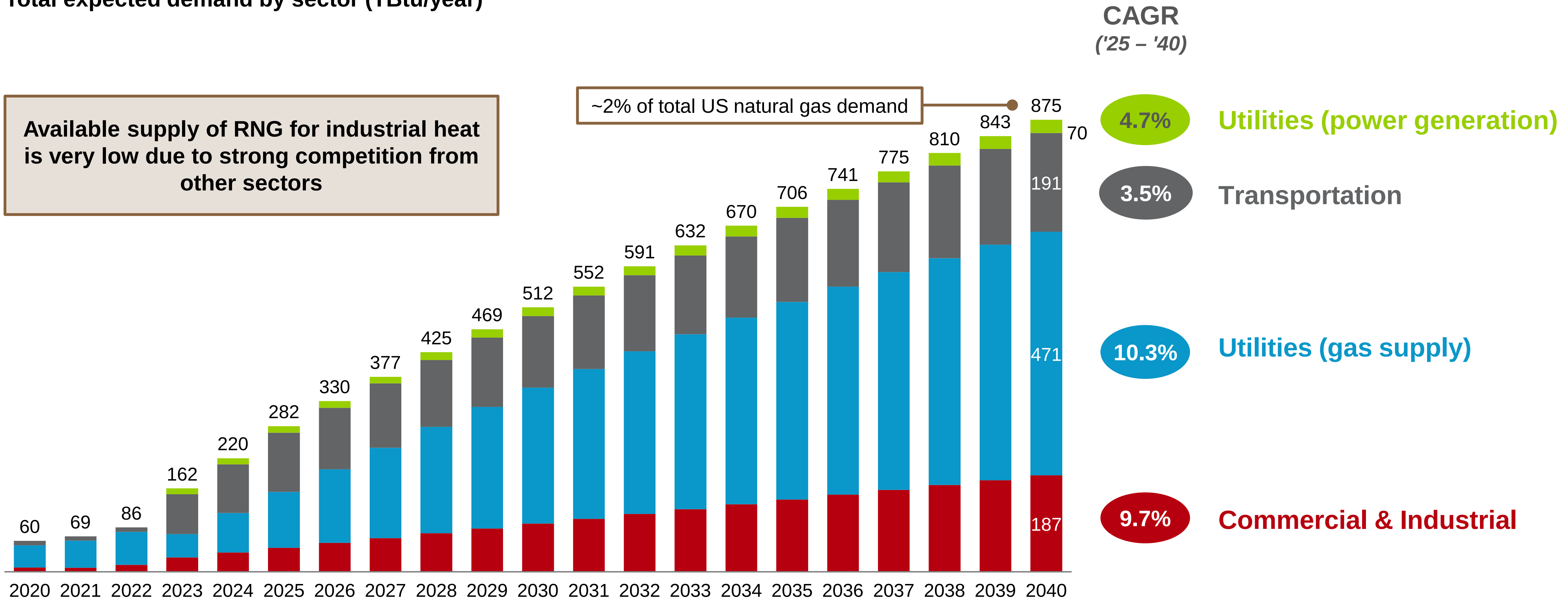
Estimated US RNG customer segment share (% of capacity allocated)



Includes LFG to RNG, agriculture sourced RNG, and wastewater sourced RNG; Projects without reported capacity estimated using benchmarks from the EPA and other sources listed below
Source: IEA, EPA, Argonne National Laboratory, MJB&A, California Bioenergy, BCG analysis

Significant demand growth across sectors expected for RNG, with largest share from gas utilities and <10% share for industrial applications by 2040

Total expected demand by sector (TBtu/year)

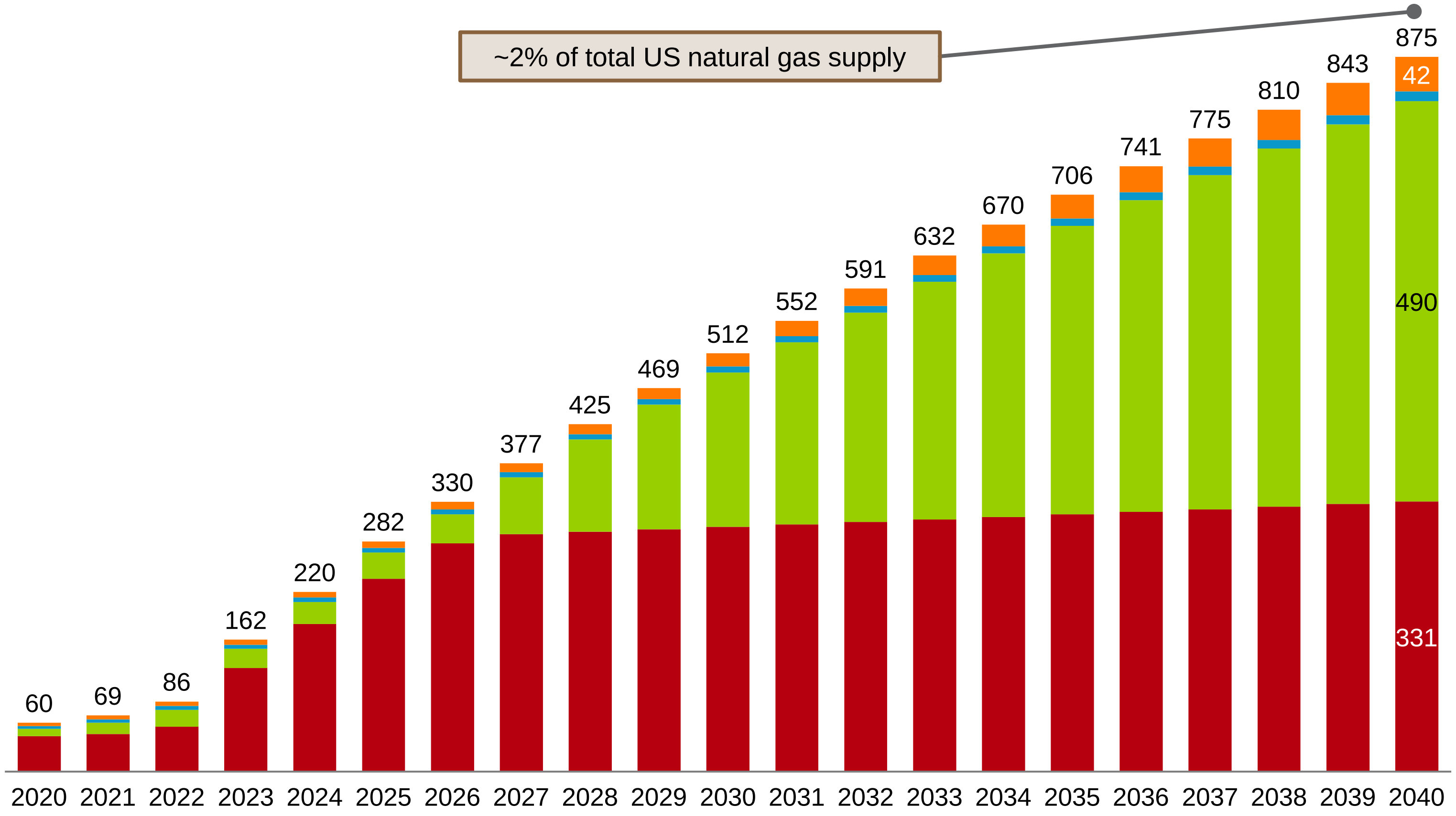


Available supply of RNG for industrial heat is very low due to strong competition from other sectors

~2% of total US natural gas demand

Source: BCG Analysis

RNG supply is expected to grow, with food waste being the largest source of growth beyond 2026



Food waste

Expected to grow to account for increasing organic waste diversion

Wastewater

Expected to grow 5% per annum to serve nominal voluntary demand

Agricultural waste

Once economic limit for landfill gas is reached, agricultural waste RNG will be used to meet voluntary demand

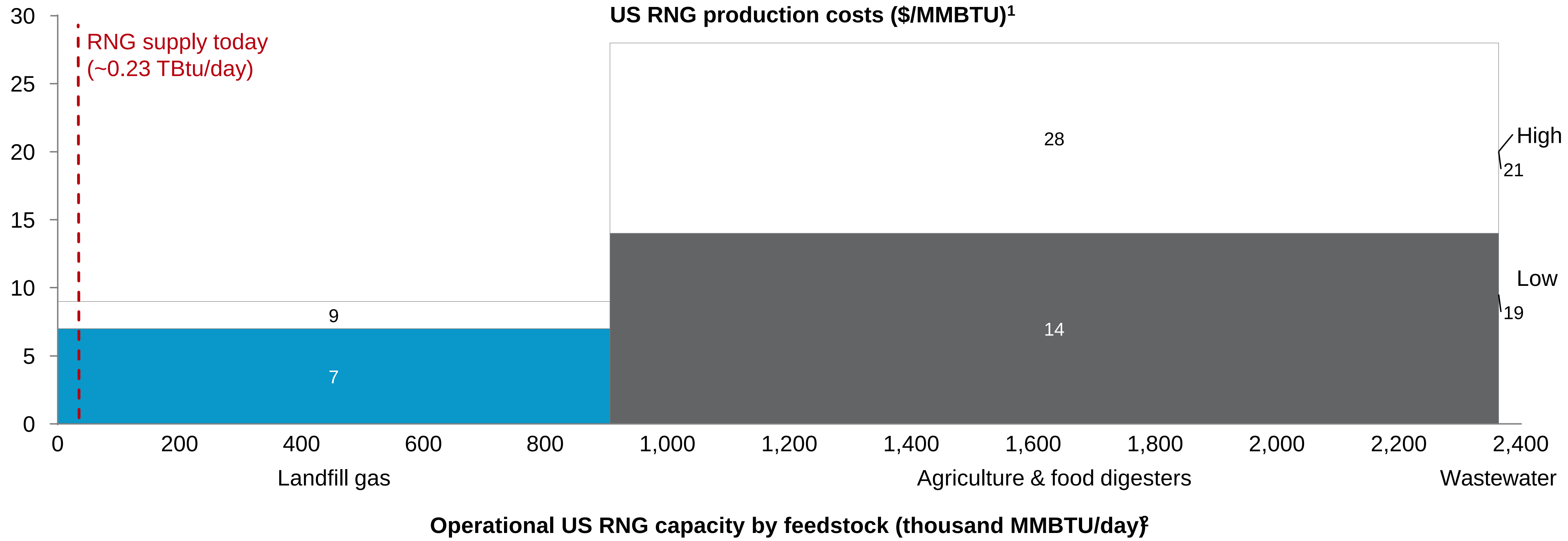
Landfill gas

Supply to grow to meet voluntary demand until economic limit is hit, after which supply expected to plateau

Source: BCG Analysis

Potential US RNG supply sources have varying cost ranges due to site-specific requirements, and differences in capital and operating costs

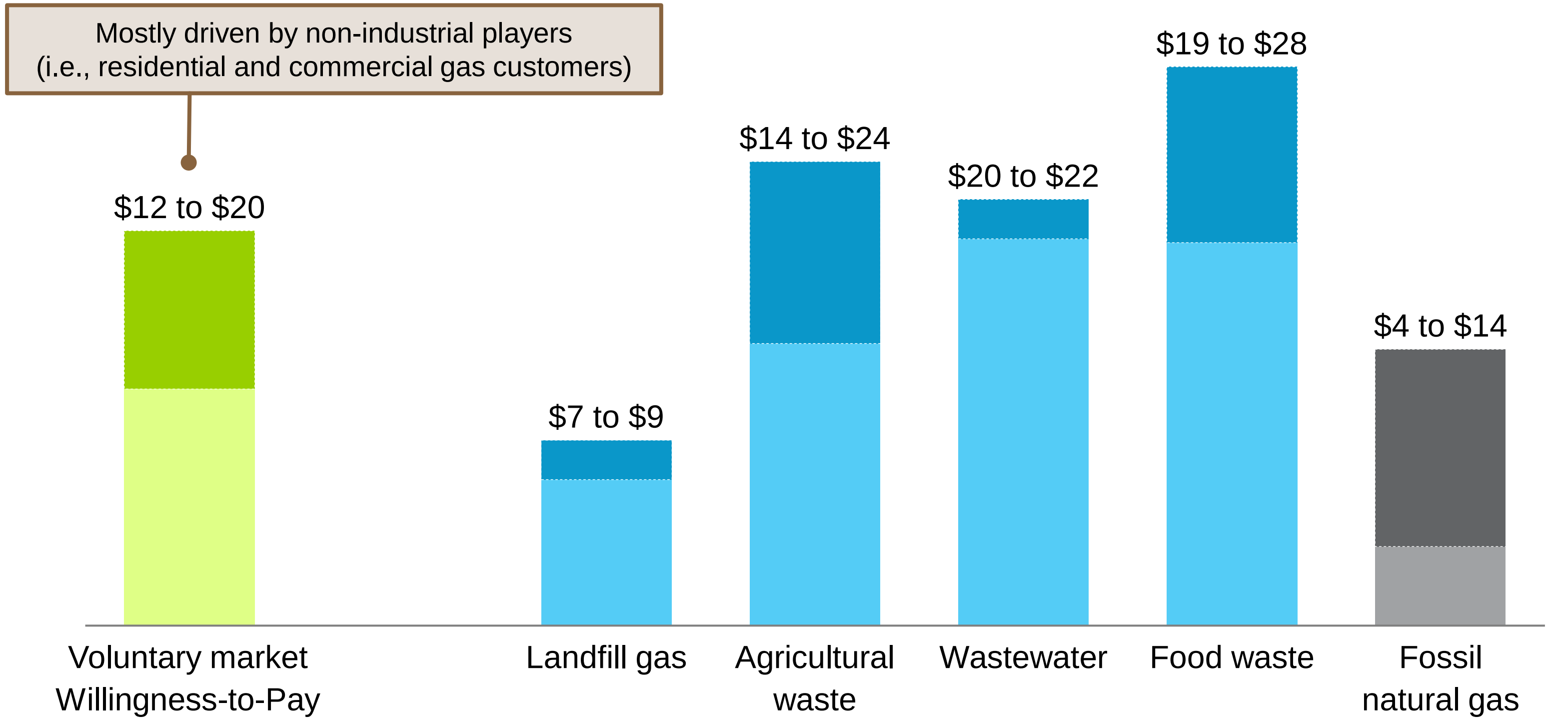
Estimated technical potential US RNG in 20 years vs. estimated supply costs



1. Cost ranges include biogas production, upgrading, and interconnection; Derived from IEA averages. 2. Includes LFG to RNG, agriculture sourced RNG, and wastewater sourced RNG; Projects without reported capacity estimated using benchmarks from the EPA and other sources listed below.
Source: IEA, EPA, ICF, BCG analysis, CBC, Federal environmental webpages

RNG from landfill gas has the lowest cost, and often falls within the voluntary market Willingness-to-Pay

RNG production costs by feedstock vs voluntary market Willingness-to-Pay ($/MMBTU) in 2020

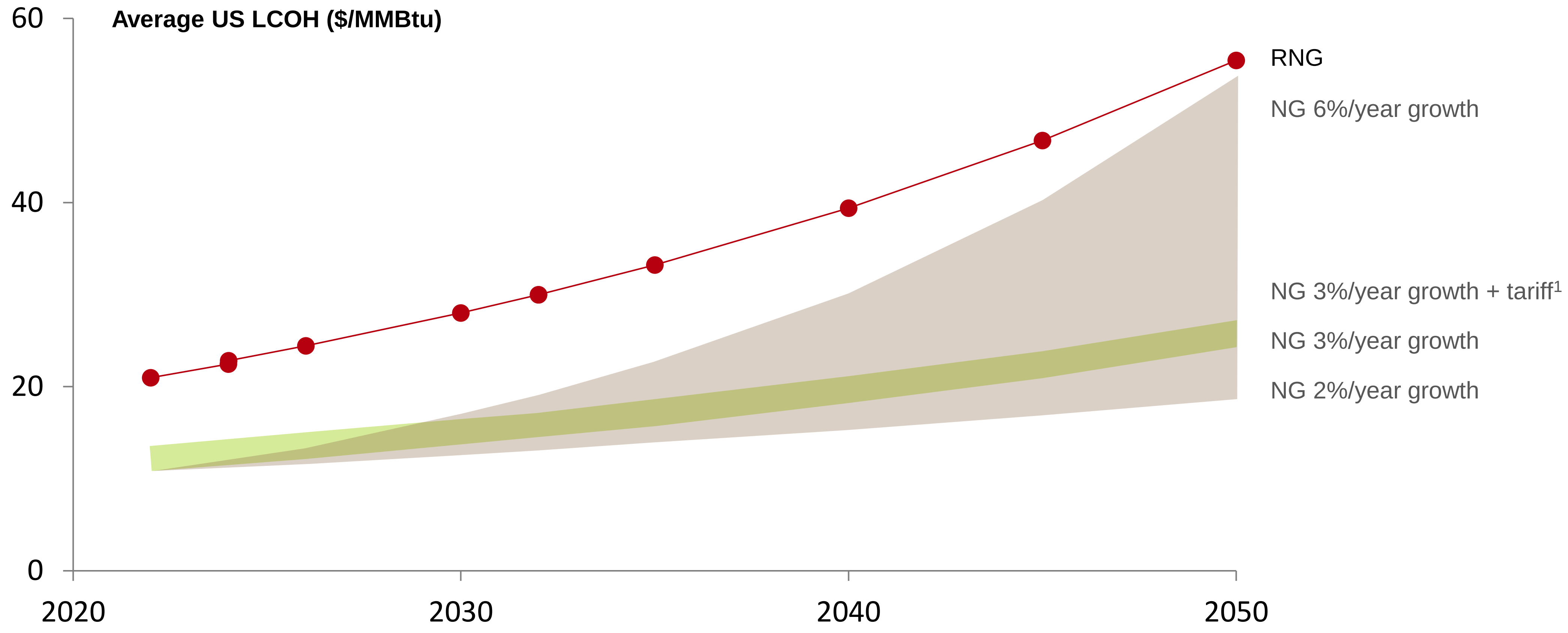


Source: ICF, EPA, USDA

Policymakers can make RNG more cost competitive by

- Providing incentives for RNG producers and purchasers
- Implementing tariffs on ambient releases of methane

RNG costs are expected to be higher than fossil natural gas in the next 30 years, especially as RNG production expands into more costly feedstocks



1. Based on $51/tonne CO2 social cost of carbon
Notes: Subsidized are shown in plots, subsidized and unsubsidized LCOHs are within 5%. Subsidies may further reduce RNG producer costs and consequently LCOH by <10%.

RNG industrial heating has many advantages, but faces supply constraints and other key barriers in gaining widespread adoption

Advantages

- Can continue using existing gas combustion equipment
- Costs for landfill RNG in some locations are in range of fossil NG
- Reduces waste and captures methane emissions
- Can continue using most existing pipeline infrastructure

Barriers

- Higher operating costs compared to fossil natural gas systems
- Limited total supply due to feedstock constraints
- Competitive supply environment (i.e., transportation, power generation)
- Gas infrastructure may require reconfiguration RNG supply locations

Solar Thermal

Renewable Thermal Technology

RENEWABLE
THERMAL
COLLABORATIVE

Solar Thermal Technology Overview

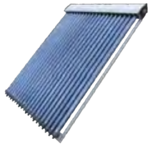
Description of technology

- Solar thermal technologies capture radiant solar energy and directly convert it to heat, which can be stored or used in industrial applications
- There are 2 main types of solar thermal technology
  - Non-concentrating
  - Concentrating
- Concentrated Solar Power (CSP) generates electricity using collected solar heat. PV-electric heating converts sunlight to electricity, which is then used to power electric heating technologies. These two adjacent technologies are not discussed in detail in this fact base but should be noted as potential competitors for solar resources.

Types of equipment

- Non-concentrating
  - Flat plate
  - Evacuated tube
  - Integral collector storage
  - Thermosiphon collector
- Concentrating
  - Parabolic trough
  - Parabolic dish
  - Power tower
  - Linear Fresnel


Flat plate collector


Evacuated tube collector


Parabolic trough


Linear fresnel

1. Onosi Solar flat plate collector; 2. Bimble Solar evacuated tube; 3. Telectronica parabolic trough; 4. US DOE linear concentrating solar

Note: Example equipment not exhaustive

Technical characteristics

- **Temperature ranges:** Practically up to 500 ºC
  - Non-concentrating: Up to 100 ºC
  - Concentrating: Theoretically up to 1,200 ºC
  - Molten salt thermal storage: Theoretically up to 560 ºC
- **Heat flux:** High heat flux
  - Dependent on scale of solar arrays and heat exchanger configuration
- **Heated materials:** Most materials are applicable

- **Emissions:** Zero emissions

- **Technical maturity:** Medium to high maturity
  - Non-concentrating low temperature solar thermal widely deployed for residential & commercial building water heating
  - Concentrating higher temperature industrial heating at pilot and demonstrating phases in US

Solar thermal is applicable to most low and medium temperature industrial heating processes

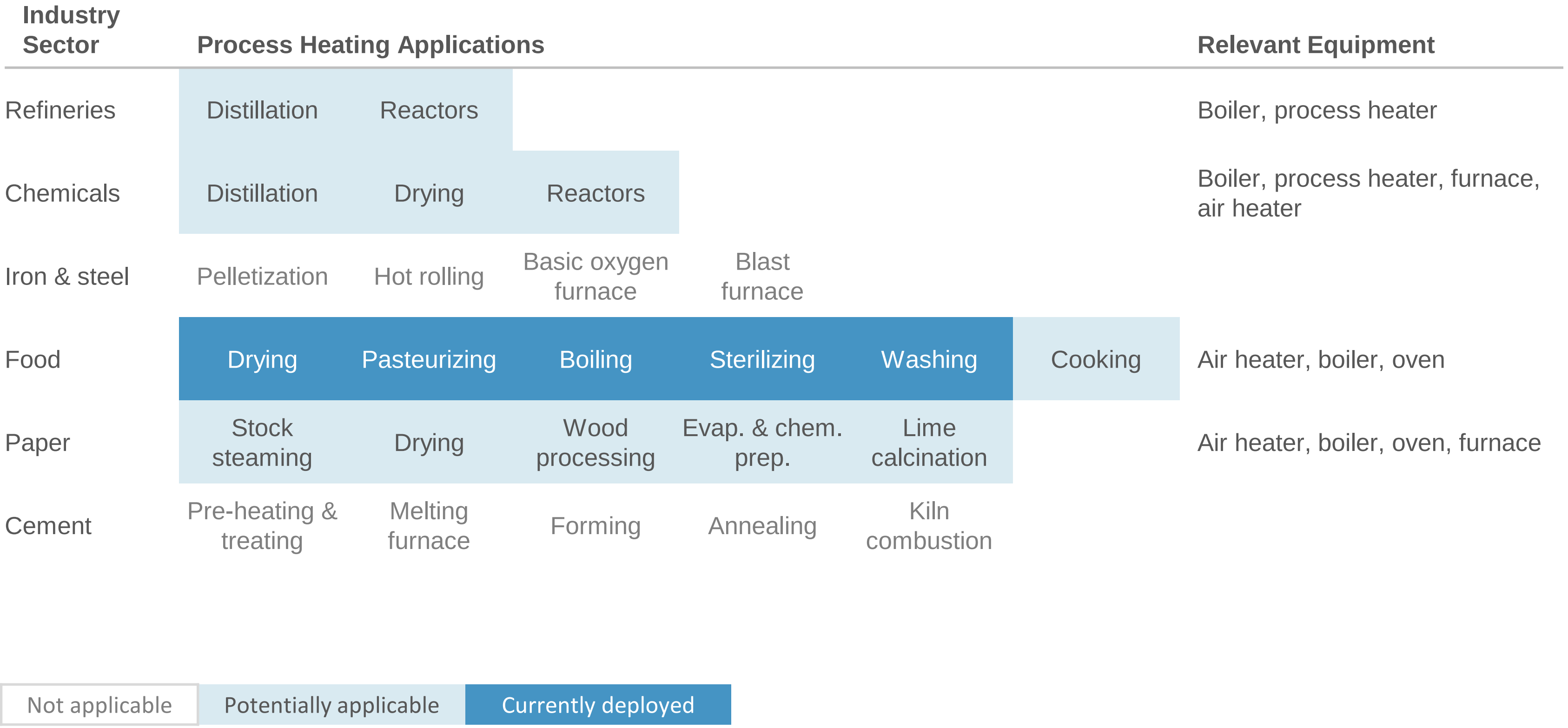
Key properties of solar thermal heating include:

1,200 ºC max. temp.

High heat flux

Heats most materials

These properties align with requirements for several process heating applications.



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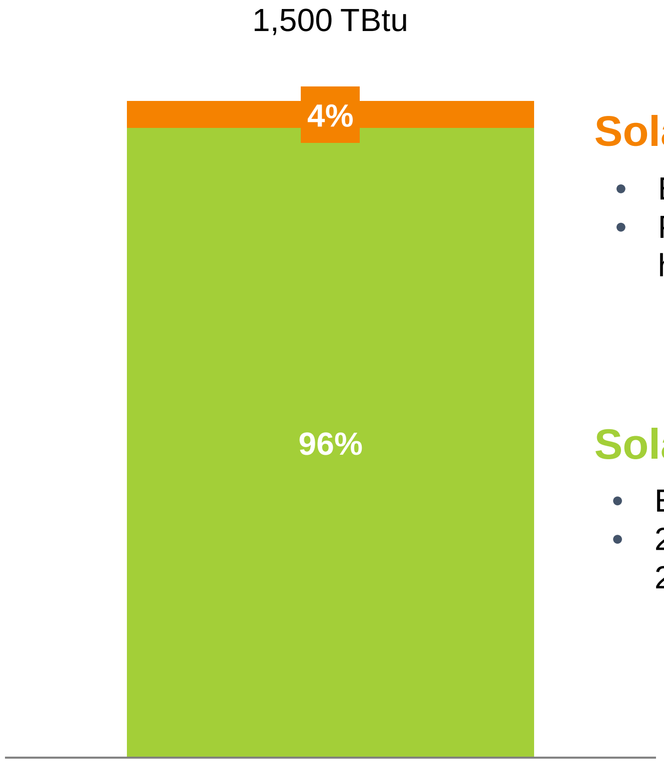
Paper	Stock steaming	Drying	Wood processing	Evap. & chem. prep.	Lime calcination		Air heater, boiler, oven, furnace
Cement	Pre-heating & treating	Melting furnace	Forming	Annealing	Kiln combustion		

Not applicable | Potentially applicable | Currently deployed

While total US solar energy use has grown rapidly in the last two decades, solar thermal currently constitutes a small proportion

Total solar energy in US (2021)



Solar thermal

- Efficiency: Can operate up to 70%
- Primarily used for domestic water heating today

Solar electricity

- Efficiency: Approaching 20%
- 2.8% of total electricity generation in 2020, and growing rapidly

Studies find that solar thermal could provide up to **25% of total US industrial heating demand**, with key constraining factors to deployment being:

- Resource potential (e.g., spatial, temporal)
- Integration of solar heat with existing industrial loads

Source: David Gardiner and Associates, US EIA, NREL

Technical viability of industrial solar thermal technologies depends on the alignment of three key factors

Spatial

Locations for process heat demand must match the supply of solar resources nearby

Temporal

Seasonal and hourly demand for process heat must align with the timing of solar thermal supply

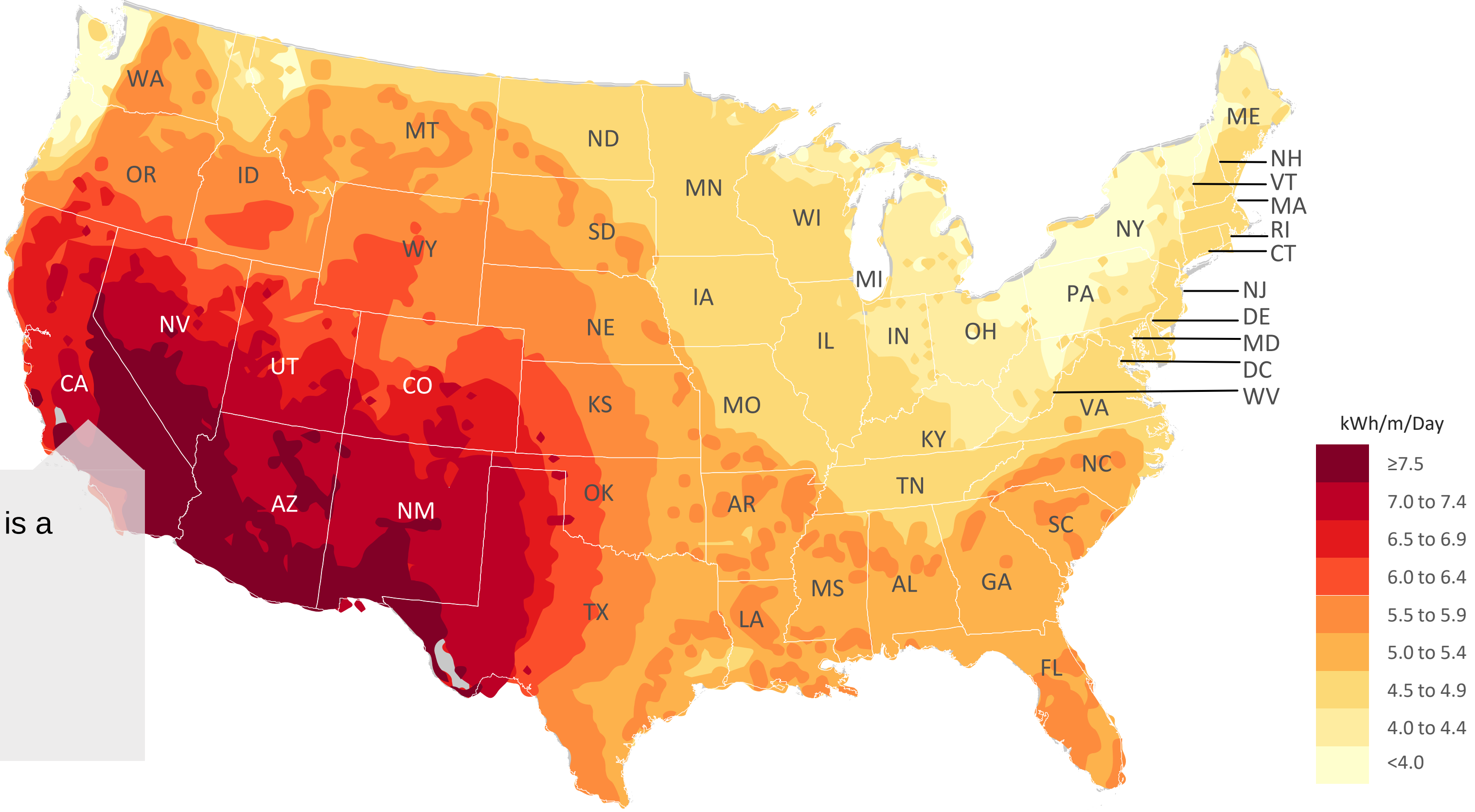
Temperature

Solar thermal technology should deliver requisite process heat temperatures and other requirements

Spatial | Within the US, the Southwest has the highest level of annual solar irradiation

Other important geographical factors to determine the viability of industrial solar thermal include:

- Matching thermal supply with demand at appropriate temperatures
- Land availability



Example: California's central valley is a promising area with:

- Rich solar resources
- Potentially available land
- Thermal demand from food and agricultural sectors

Source: NREL

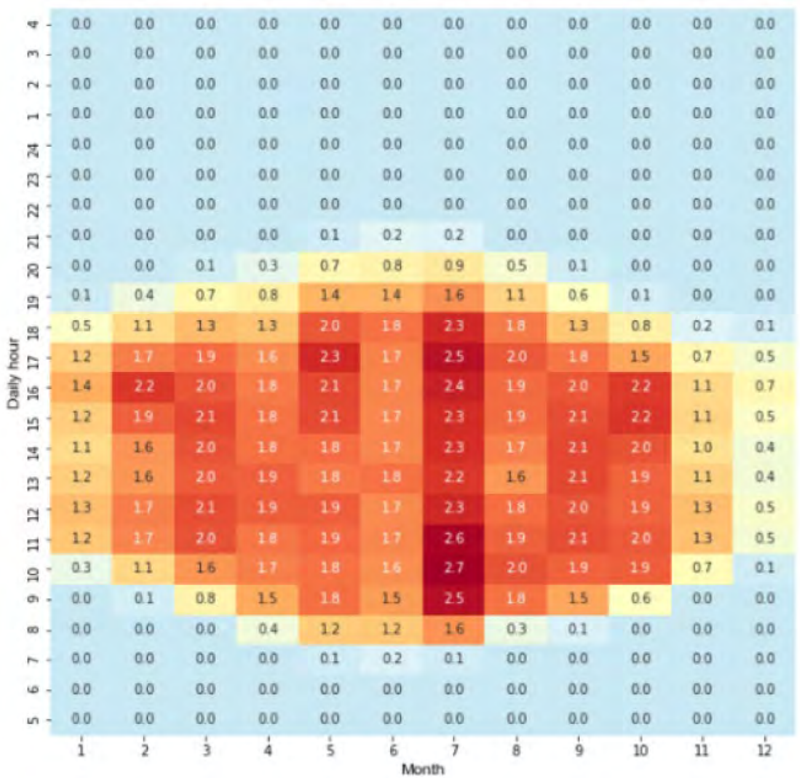
Temporal | Intermittency of heat supply is a major limitation of widespread solar thermal technology deployment in industry

To decrease the impact of solar thermal intermittency, the process operator can implement several strategies

- Design process to be compatible with irregular and low equipment utilization
- Deployment of back-up dispatchable thermal energy sources
- Deployment of thermal energy storage

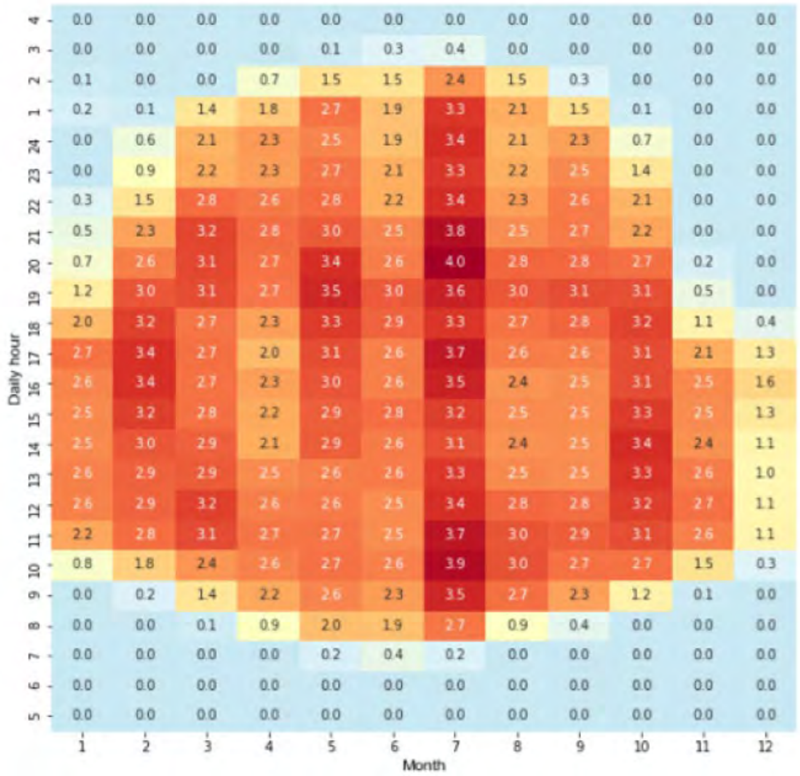
Temporal | Thermal energy storage can provide substantially more process heating potential beyond the limited hours of high solar irradiation

Example solar fraction[1] of a parabolic trough collector (PTC) system in Polk County, IA



Daily hour	1	2	3	4	5	6	7	8	9	10	11	12
4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
24	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
23	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
22	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
21	0.0	0.0	0.0	0.0	0.1	0.2	0.2	0.0	0.0	0.0	0.0	0.0
20	0.0	0.0	0.1	0.3	0.7	0.8	0.9	0.5	0.1	0.0	0.0	0.0
19	0.1	0.4	0.7	0.8	1.4	1.4	1.6	1.1	0.6	0.1	0.0	0.0
18	0.5	1.1	1.3	1.3	2.0	1.8	2.3	1.8	1.3	0.8	0.2	0.1
17	1.2	1.7	1.9	1.6	2.3	1.7	2.5	2.0	1.8	1.5	0.7	0.5
16	1.4	2.2	2.0	1.8	2.1	1.7	2.4	1.9	2.0	2.2	1.1	0.7
15	1.2	1.9	2.1	1.8	2.1	1.7	2.3	1.9	2.1	2.2	1.1	0.5
14	1.1	1.6	2.0	1.8	1.8	1.7	2.3	1.7	2.1	2.0	1.0	0.4
13	1.2	1.6	2.0	1.9	1.8	1.8	2.2	1.6	2.1	1.9	1.1	0.4
12	1.3	1.7	2.1	1.9	1.9	1.7	2.3	1.8	2.0	1.9	1.3	0.5
11	1.2	1.7	2.0	1.8	1.9	1.7	2.6	1.9	2.1	2.0	1.3	0.5
10	0.3	1.1	1.6	1.7	1.8	1.6	2.7	2.0	1.9	1.9	0.7	0.1
9	0.0	0.1	0.8	1.5	1.8	1.5	2.5	1.8	1.5	0.6	0.0	0.0
8	0.0	0.0	0.0	0.4	1.2	1.2	1.6	0.3	0.1	0.0	0.0	0.0
7	0.0	0.0	0.0	0.0	0.1	0.2	0.1	0.0	0.0	0.0	0.0	0.0
6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

PTC without thermal storage



Daily hour	1	2	3	4	5	6	7	8	9	10	11	12
4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3	0.0	0.0	0.0	0.0	0.1	0.3	0.4	0.0	0.0	0.0	0.0	0.0
2	0.1	0.0	0.0	0.7	1.5	1.5	2.4	1.5	0.3	0.0	0.0	0.0
1	0.2	0.1	1.4	1.8	2.7	1.9	3.3	2.1	1.5	0.1	0.0	0.0
24	0.0	0.6	2.1	2.3	2.5	1.9	3.4	2.1	2.3	0.7	0.0	0.0
23	0.0	0.9	2.2	2.3	2.7	2.1	3.3	2.2	2.5	1.4	0.0	0.0
22	0.3	1.5	2.8	2.6	2.8	2.2	3.4	2.3	2.6	2.1	0.0	0.0
21	0.5	2.3	3.2	2.8	3.0	2.5	3.8	2.5	2.7	2.2	0.0	0.0
20	0.7	2.6	3.1	2.7	3.4	2.6	4.0	2.8	2.8	2.7	0.2	0.0
19	1.2	3.0	3.1	2.7	3.5	3.0	3.6	3.0	3.1	3.1	0.5	0.0
18	2.0	3.2	2.7	2.3	3.3	2.9	3.3	2.7	2.8	3.2	1.1	0.4
17	2.7	3.4	2.7	2.0	3.1	2.6	3.7	2.6	2.6	3.1	2.1	1.3
16	2.6	3.4	2.7	2.3	3.0	2.6	3.5	2.4	2.5	3.1	2.5	1.6
15	2.5	3.2	2.8	2.2	2.9	2.8	3.2	2.5	2.5	3.3	2.5	1.3
14	2.5	3.0	2.9	2.1	2.9	2.6	3.1	2.4	2.5	3.4	2.4	1.1
13	2.6	2.9	2.9	2.5	2.6	2.6	3.3	2.5	2.5	3.3	2.6	1.0
12	2.6	2.9	3.2	2.6	2.6	2.5	3.4	2.8	2.8	3.2	2.7	1.1
11	2.2	2.8	3.1	2.7	2.7	2.5	3.7	3.0	2.9	3.1	2.6	1.1
10	0.8	1.8	2.4	2.6	2.7	2.6	3.9	3.0	2.7	2.7	1.5	0.3
9	0.0	0.2	1.4	2.2	2.6	2.3	3.5	2.7	2.3	1.2	0.1	0.0
8	0.0	0.0	0.1	0.9	2.0	1.9	2.7	0.9	0.4	0.0	0.0	0.0
7	0.0	0.0	0.0	0.0	0.2	0.4	0.2	0.0	0.0	0.0	0.0	0.0
6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

PTC with 6 hours thermal storage (28% greater)

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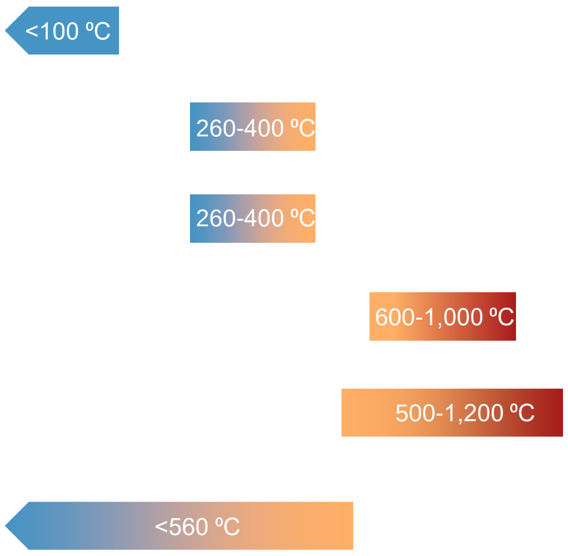
1. Potential contribution of solar energy to the total load

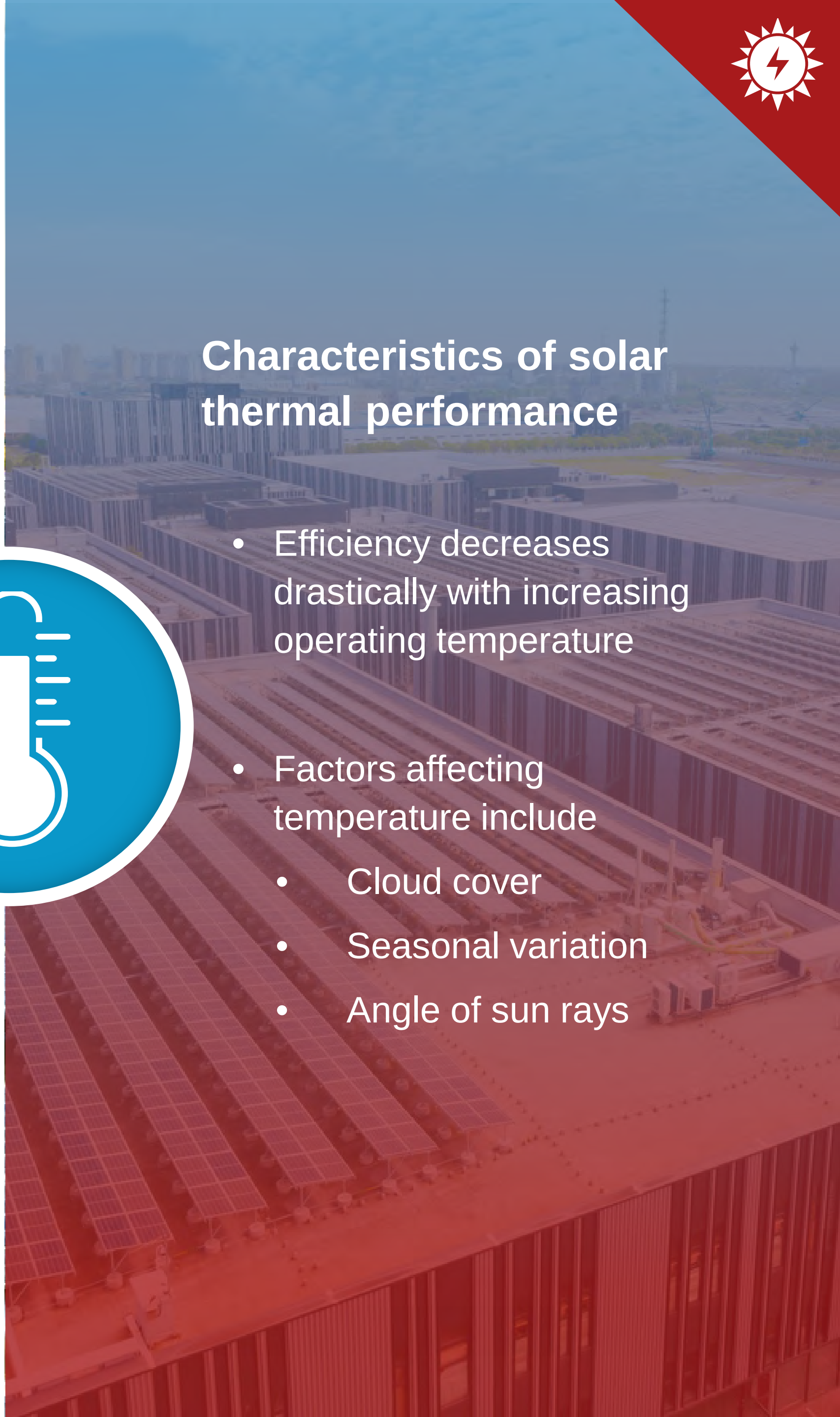
Source: NREL

Temperature | Non-concentrating solar thermal can provide up to 100ºC, while concentrating solar thermal can deliver up to 1,200 ºC



Solar thermal technology	Operating temperatures
Non-concentrating	<100 ºC
Parabolic trough	260-400 ºC
Linear Fresnel	260-400 ºC
Power tower	600-1,000 ºC
Parabolic dish	500-1,200 ºC
Molten salt storage	<560 ºC

Source: ARENA

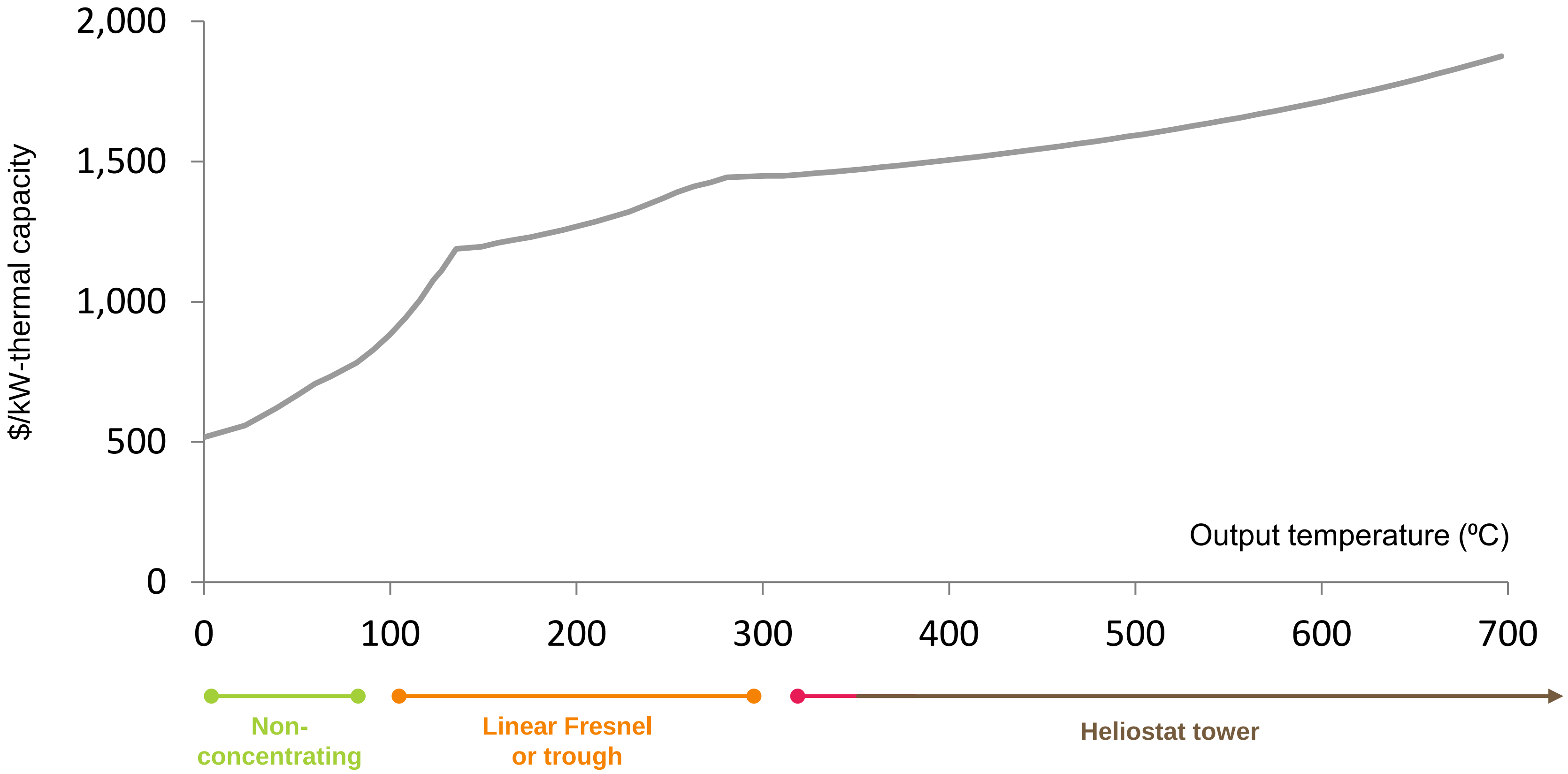


Characteristics of solar thermal performance

- Efficiency decreases drastically with increasing operating temperature
- Factors affecting temperature include
  - Cloud cover
  - Seasonal variation
  - Angle of sun rays

Two key determinates of solar thermal capital costs are the technology type and the output temperature

Lowest capital costs for solar thermal equipment in each temperature range

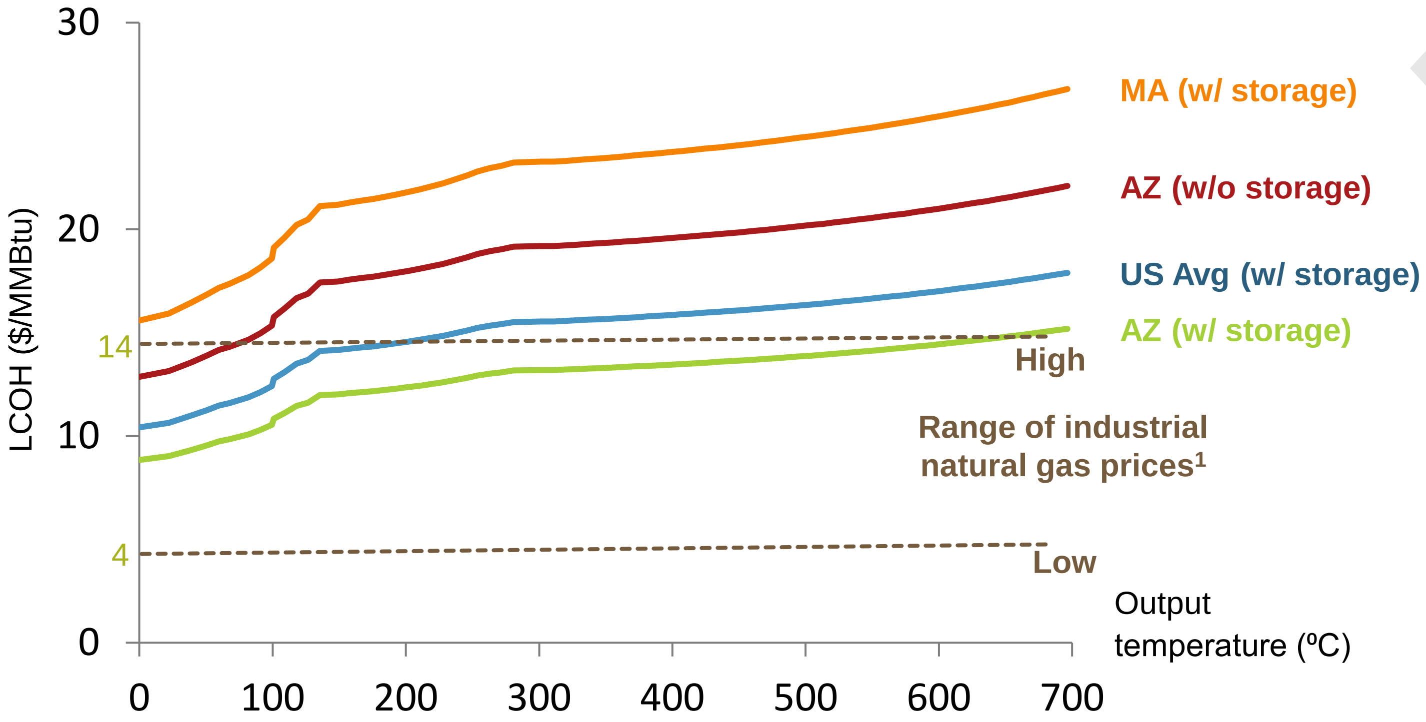


Solar thermal heating cost **increases with output temperatures**

Source: ARENA

Industrial solar heating can be cost effective depending on configuration and location

US Levelized Cost of Heat for Solar Thermal



Economic viability of solar LCOH depends on several factors

- **Process specifications**
  - Output temperature
  - Solar heating technology type
  - Deployment of thermal storage
- **Location**
  - Solar irradiance
  - Land availability
  - Proximity of heat production and use
  - Ambient temperature
- **Financial**
  - Discount rate
  - Equipment lifetime

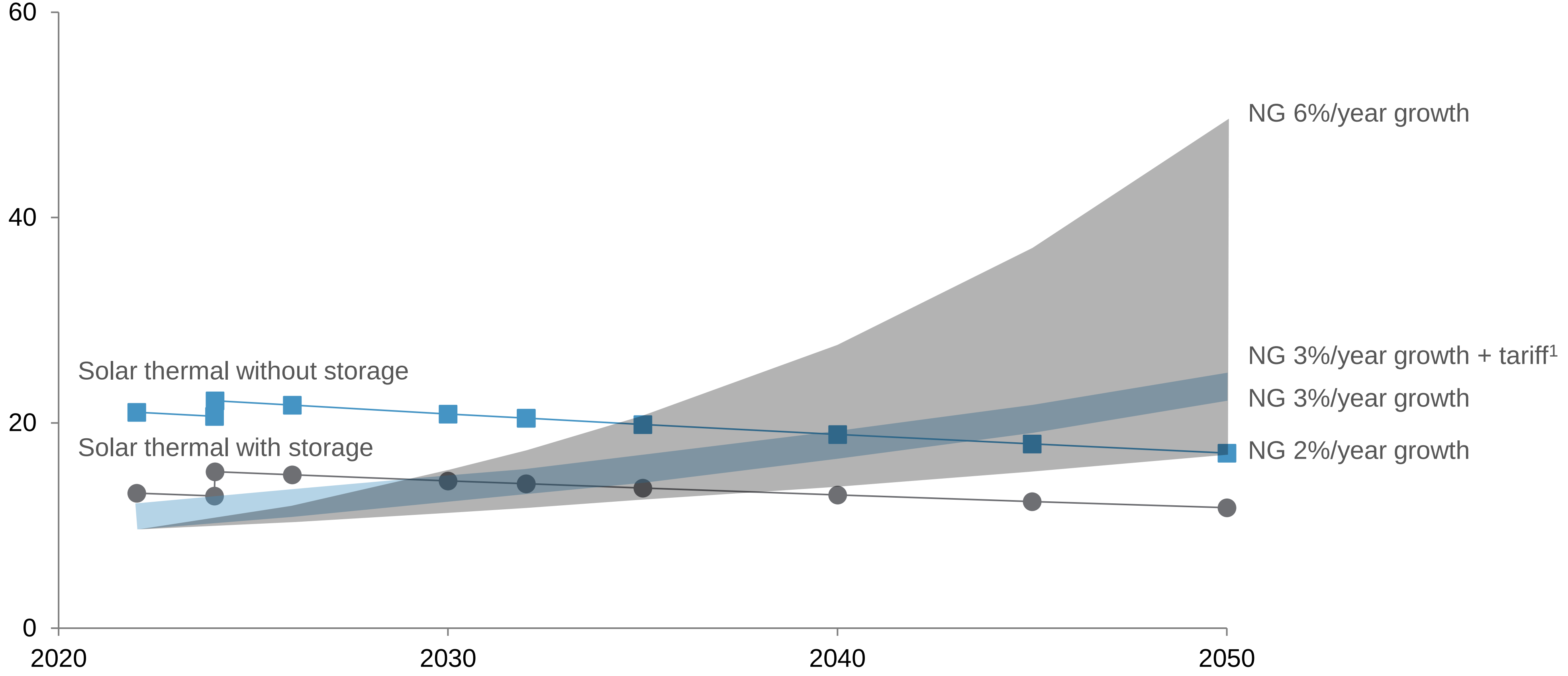
1. EIA May 2022 end-user prices

Notes: Does not include cost for land use. Uses solar thermal power plant estimates (central receiver tower with heliostats) with power generation equipment removed for LCOH calculation.

Source: NREL; Lazard; IRENA; DOE, AIP Conference Proceedings; BCG analysis

Pairing solar thermal with storage can expand geographic and sector applicability, and reach cost parity with natural gas in the medium term

Average US LCOH ($/MMBtu)



1. Based on $51/tonne CO2 social cost of carbon

Note: Subsidized are shown in plots, subsidized and unsubsidized LCOHs are within 15%

Potential consumers of industrial heat may deprioritize onsite land use for solar thermal due to competing applications

Electricity generation

Electricity generation via PV[1] or CSP[2] may provide better financial return for an equivalent level of land use

Agricultural uses

Solar thermal is most readily applicable to food and agricultural processes, but land use competes with growing crops and raising livestock

Expansion of processing facilities

Plans for expanding industrial facilities may out-compete land use for solar thermal heat collection

1. Photovoltaic; 2. Concentrated solar power

Solar thermal industrial heating has several advantages, but faces several major hurdles to adoption

Advantages

- Zero fuel costs and low operating costs
- Able to offset a portion of facility thermal demand
- Potential to pair with thermal energy storage
- Zero emissions and no combustion

Barriers

- Geographically constrained to high insolation areas
- Large footprint
- Limited to low and medium temperature applications
- Seasonal and diurnal intermittency leading to risk of process disruption

Thermal Storage

Renewable Thermal Technology

RENEWABLE
THERMAL
COLLABORATIVE

Thermal energy storage balances the mismatch in supply and demand for heating by offsetting differences in time and quantity of heat production

Source of thermal energy

Low-cost intermittent electricity or waste heat sources supply thermal energy

Thermal energy storage

Thermal battery stores heat at elevated temperatures for several hours to days

Thermal energy release

Thermal storage releases heat for useful industrial processes

Several forms of thermal energy storage are currently commercially available or under development

Sensible		Latent (phase change)	
Solid	**Liquid**	**Solid-Liquid**	**Others**
Materials: rock, sand, ceramic, metals	**Materials:** water-based, thermal oils, molten salt, molten metal	**Materials:** organic solutions, inorganic solutions	**Materials:** liquid-gas, solid-gas, solid-solid crystal
Temperature: Up to 1,500ºC delivered	**Temperature:** Up to 1,600ºC delivered	**Temperature:** Up to 120ºC delivered	**Temperature:** Up to 175ºC delivered
Cost: Low	**Cost:** Medium	**Cost:** High	**Cost:** High
Applicability: Large utility or industrial scale thermal storage	**Applicability:** Space and water heating for buildings or concentrated solar power	**Applicability:** High heat storage in limited volume or rapid heat transfer required	**Applicability:** High heat storage in limited volume or rapid heat transfer required
Maturity: High	**Maturity:** Medium high	**Maturity:** Medium low	**Maturity:** Low

Focus of this fact base

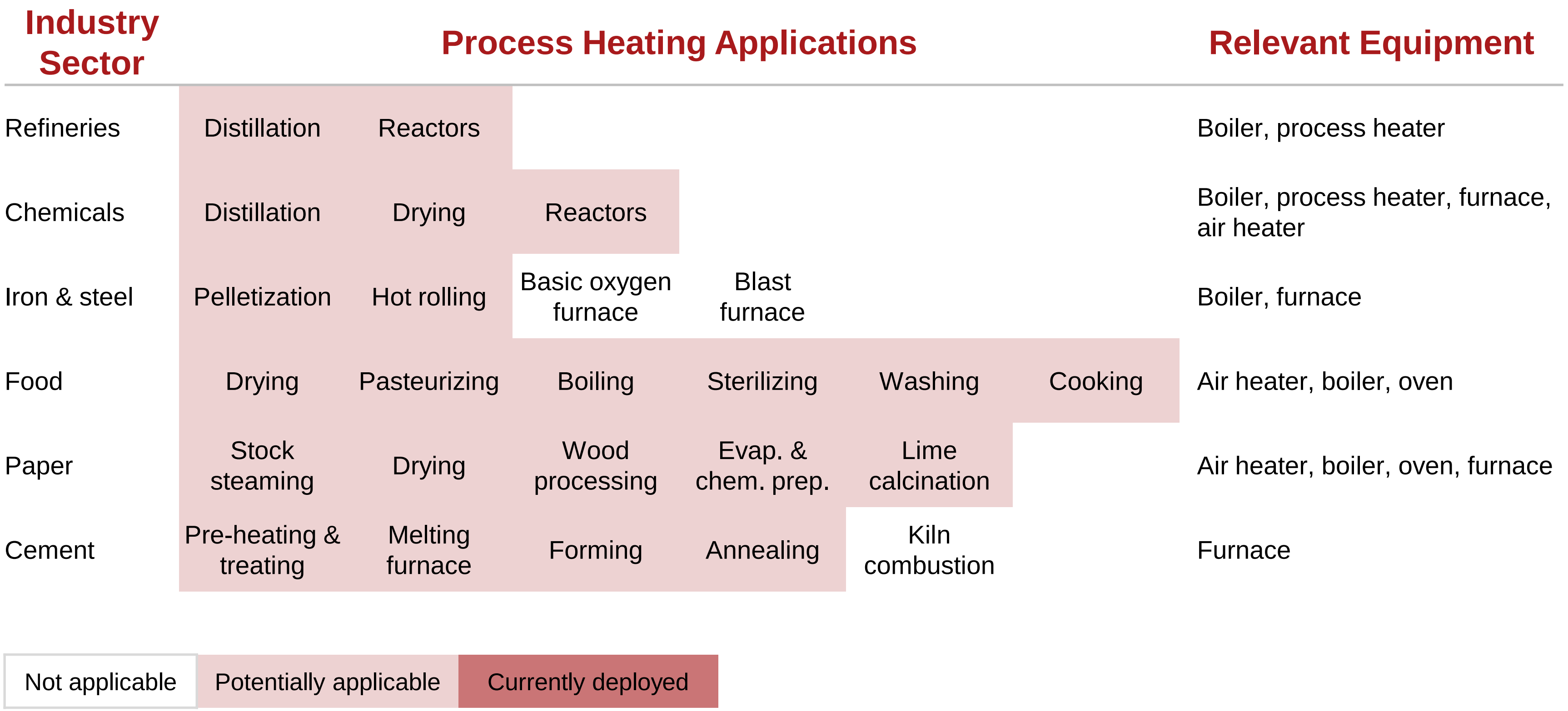
Source: Advanced cooling technologies

Heating using stored thermal energy is applicable to all but the highest temperature applications

Key properties of electric resistance plus thermal energy storage heating include:

- 1,500 ºC max. temp. delivered
- High heat flux
- Heats all materials

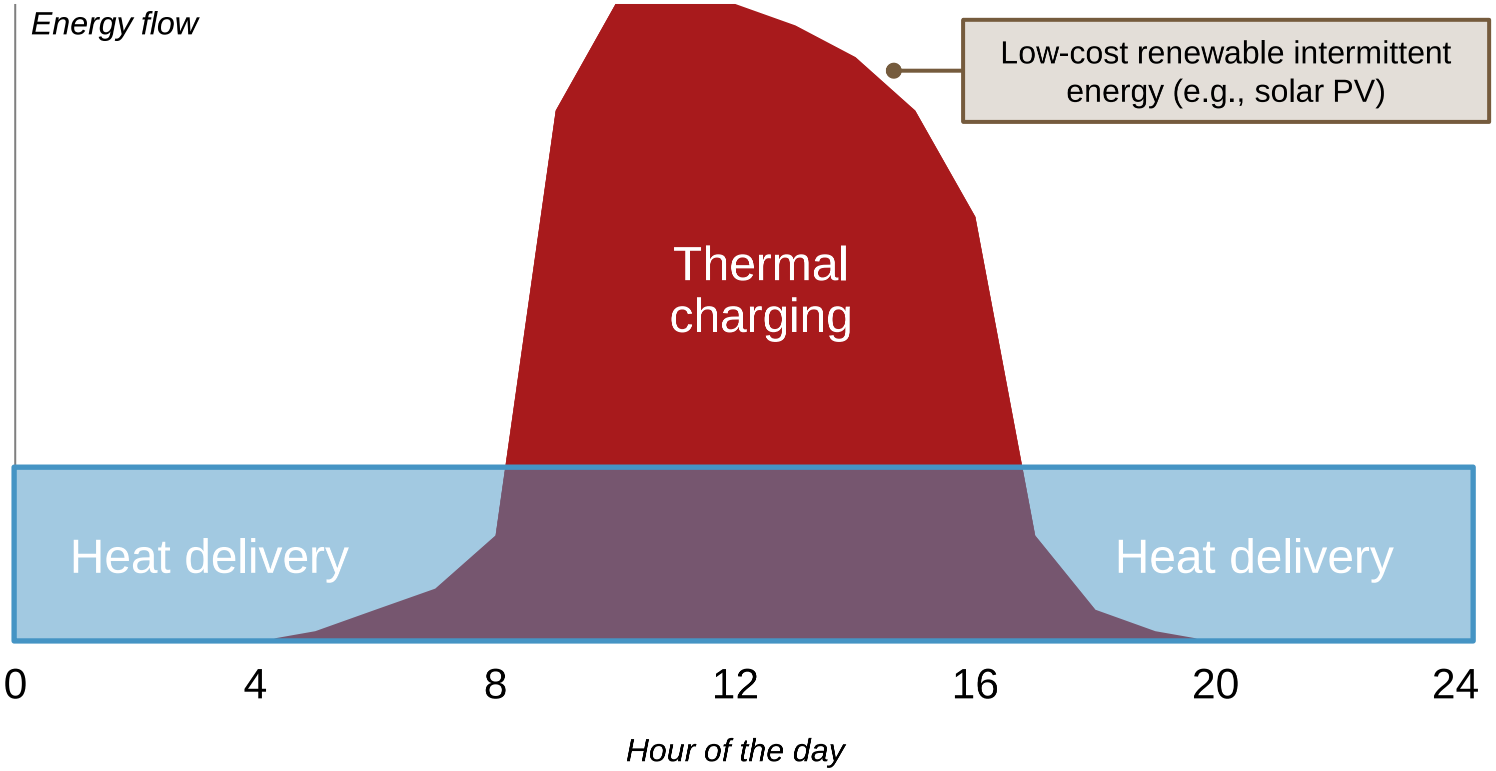
These properties align with requirements for several process heating applications.



Industry Sector	Process Heating Applications						Relevant Equipment
Refineries	Distillation	Reactors					Boiler, process heater
Chemicals	Distillation	Drying	Reactors				Boiler, process heater, furnace, air heater
Iron & steel	Pelletization	Hot rolling	Basic oxygen furnace	Blast furnace			Boiler, furnace
Food	Drying	Pasteurizing	Boiling	Sterilizing	Washing	Cooking	Air heater, boiler, oven
Paper	Stock steaming	Drying	Wood processing	Evap. & chem. prep.	Lime calcination		Air heater, boiler, oven, furnace
Cement	Pre-heating & treating	Melting furnace	Forming	Annealing	Kiln combustion		Furnace

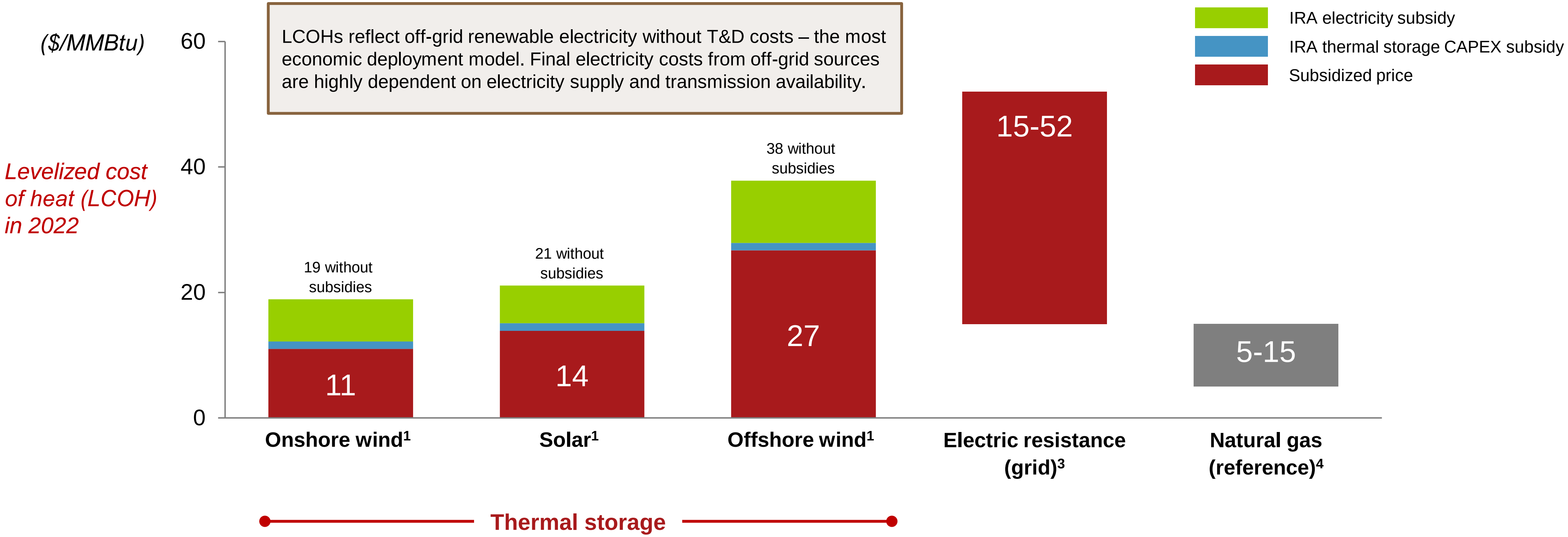
Not applicable | Potentially applicable | Currently deployed

Intermittency of low-cost renewable or waste energy is the primary driver of thermal energy storage



Time-of-use tariffs and other time shifting electricity price signals are likely required to drive the economic viability of thermal energy storage

Thermal energy storage using low-cost intermittent electricity has potential to be cost competitive with natural gas heating in many circumstances

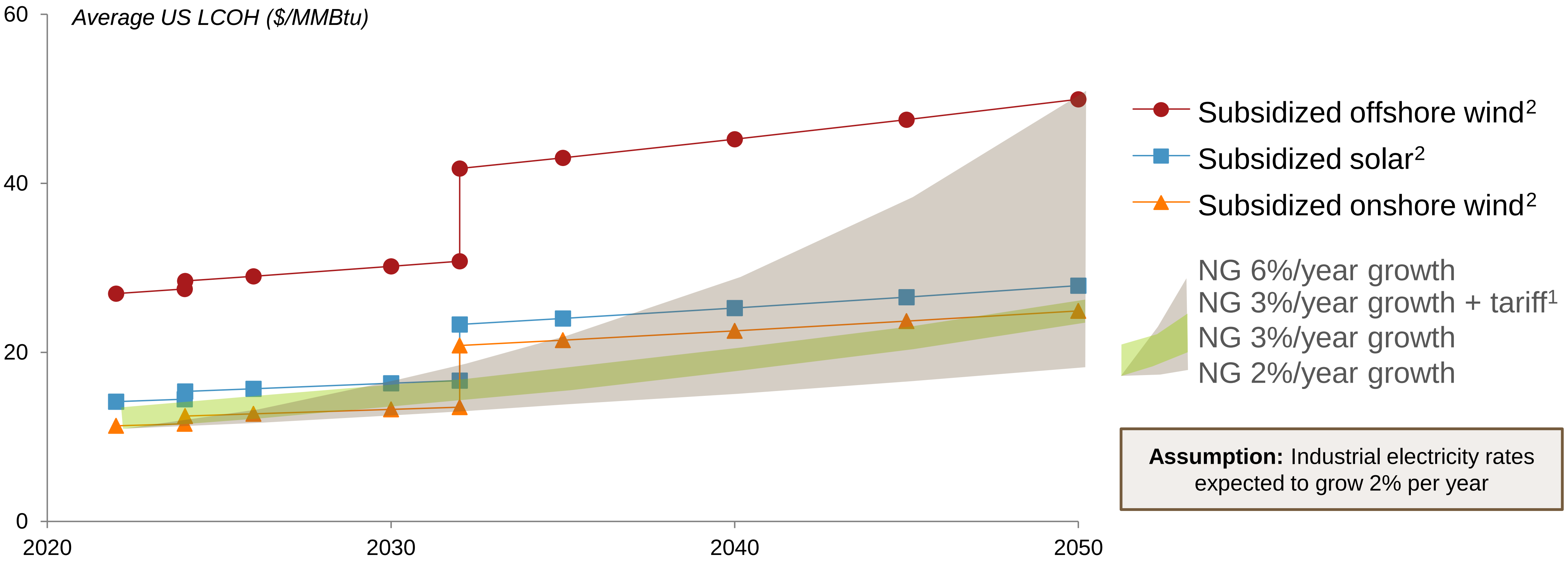


LCOHs reflect off-grid renewable electricity without T&D costs – the most economic deployment model. Final electricity costs from off-grid sources are highly dependent on electricity supply and transmission availability.

% of subsidized LCOH from fuel costs	83%	86%	93%	>95%	>95%

1. Thermal storage combined with electric resistance without T&D costs and with 30% IRA investment tax credits; 2. Thermal storage combined with grid electricity at industrial retail prices in May 2022 from EIA; 3. Range of industrial electricity prices in May 2022 from EIA; 4. Range of industrial natural gas prices in May 2022 from EIA

Thermal storage with electric resistance can be economically competitive with natural gas depending on source and cost of renewable electricity



Assumption: Industrial electricity rates expected to grow 2% per year

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1. Based on $51/tonne CO2 social cost of carbon; 2. Thermal storage combined with electric resistance without T&D costs and with 30% IRA investment tax credits

Renewable thermal collaborative (RTC) includes three thermal storage sponsor companies

BRENMILLER ENERGY

- Based in Israel, with projects worldwide include the US
- Charges thermal battery using electricity, biomass, flue-gas, heat recovery, or a combination of these inputs
- Reaches temperature up to 750ºC
- System is modular and is fully integrated with heat exchangers and a steam generator

ANTORA

- Based in California
- Uses intermittent low-cost power to charge thermal energy storage, provides on-demand industrial heat and power
- Reaches temperature up to 1,500ºC
- Rapid charging modular system

RONDO

- Based in California, with first operational customer in August 2022
- Uses intermittent low-cost power to charge thermal battery, provides on-demand industrial heat and power
- Reaches temperature up to 1,500ºC
- Achieves 98% efficiency with common insulation materials, and loses 2% energy per day

Thermal energy storage for industrial heating has many advantages, but faces several major barriers to adoption

Advantages

- Bridges gap during periods of low intermittent energy supply
- Utilizes low-cost zero-emissions intermittent energy
- Can reach most temperatures required for industrial processes
- Provides grid service as dispatchable demand source

Barriers

- Potentially high capital costs
- Not a standalone heating technology, requires heating input
- Integration of energy storage into industrial processes required
- Current low awareness and maturity of technology

Waste Biomass

Renewable Thermal Technology

RENEWABLE
THERMAL
COLLABORATIVE

Waste Biomass Technology Overview

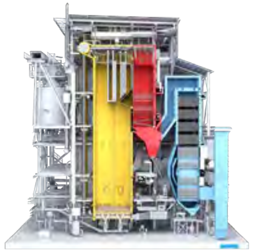
Description of technology

- Biomass is currently the largest source of renewable industrial heating in the US and worldwide, particularly in the wood, and pulp & paper sectors
- Direct combustion of solid biomass is the primary focus of this fact base, rather than conversion to liquid biofuels or gaseous fuels (i.e., pyrolysis)
- Biomass combustion typically produces steam, which drives electricity production or provides process heating
- Alternatively, air is heated by biomass combustion, which provides heat for drying applications

Types of equipment

- There are two major systems for biomass combustion heating:
  - Fixed bed combustion
  - Fluidized bed combustion

Fixed bed wood chip and pellet boiler1



Bubbling fluidized bed boiler2

Note: Example equipment not exhaustive

1. Hurll Nu Way; 2. Andritz

Technical characteristics

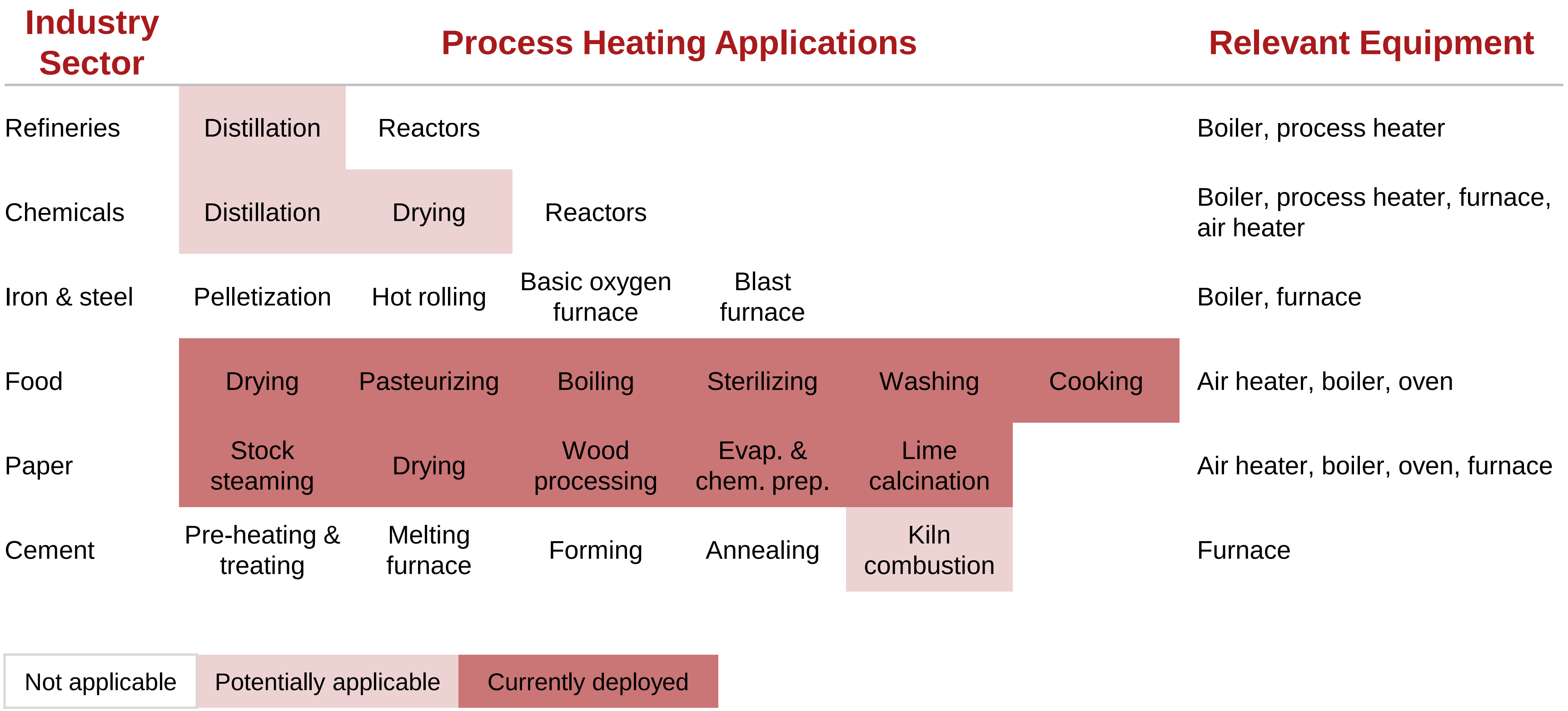
- **Temperature range:** Up to 1,000 ºC
  - Fixed bed boilers: 800-1,000 ºC
  - Fluidized bed boilers: 760-870 ºC
- **Heat flux:** High
  - Dependent on biomass combustion system and heat transfer configuration
- **Heated materials:** Most materials are applicable
- **Emissions:** CO2 and other particulate emissions at point of combustion but theoretically carbon neutral
- **Technical maturity:** High maturity
  - Biomass combustion widely deployed in wood and pulp & paper industries for power generation and process heating applications

Biomass combustion industrial heating is useful for most low to medium temperature process applications

Key properties of biomass combustion heating include:

- 1,950 ºC max. temp.
- High heat flux
- Heats all materials

These properties align with requirements for several process heating applications.



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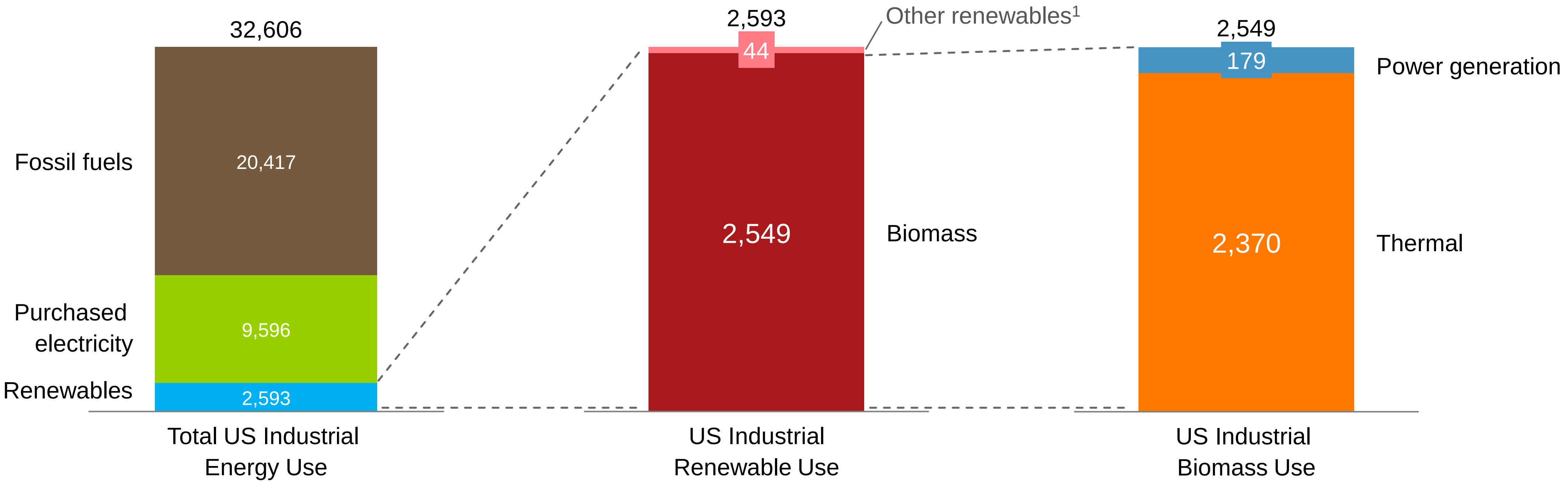
Food	Drying	Pasteurizing	Boiling	Sterilizing	Washing	Cooking	Air heater, boiler, oven
Paper	Stock steaming	Drying	Wood processing	Evap. & chem. prep.	Lime calcination		Air heater, boiler, oven, furnace
Cement	Pre-heating & treating	Melting furnace	Forming	Annealing	Kiln combustion		Furnace

Not applicable | Potentially applicable | Currently deployed

Note: Since RNG has been blended into the existing natural gas distribution network, all potentially applicable process heating applications are denoted as "currently deployed"

Biomass constitutes around 8% of US industrial energy consumption and >98% of total industrial renewable energy use – most of which is for thermal applications



1. Includes hydroelectric, solar, wind, and geothermal

Note: Fuel consumption includes non-thermal and non-combustion uses; Source: EIA Monthly Energy Review 2018

Combustion of biomass for thermal energy is currently widespread in sectors with readily available fuels from production wastes or other feedstocks

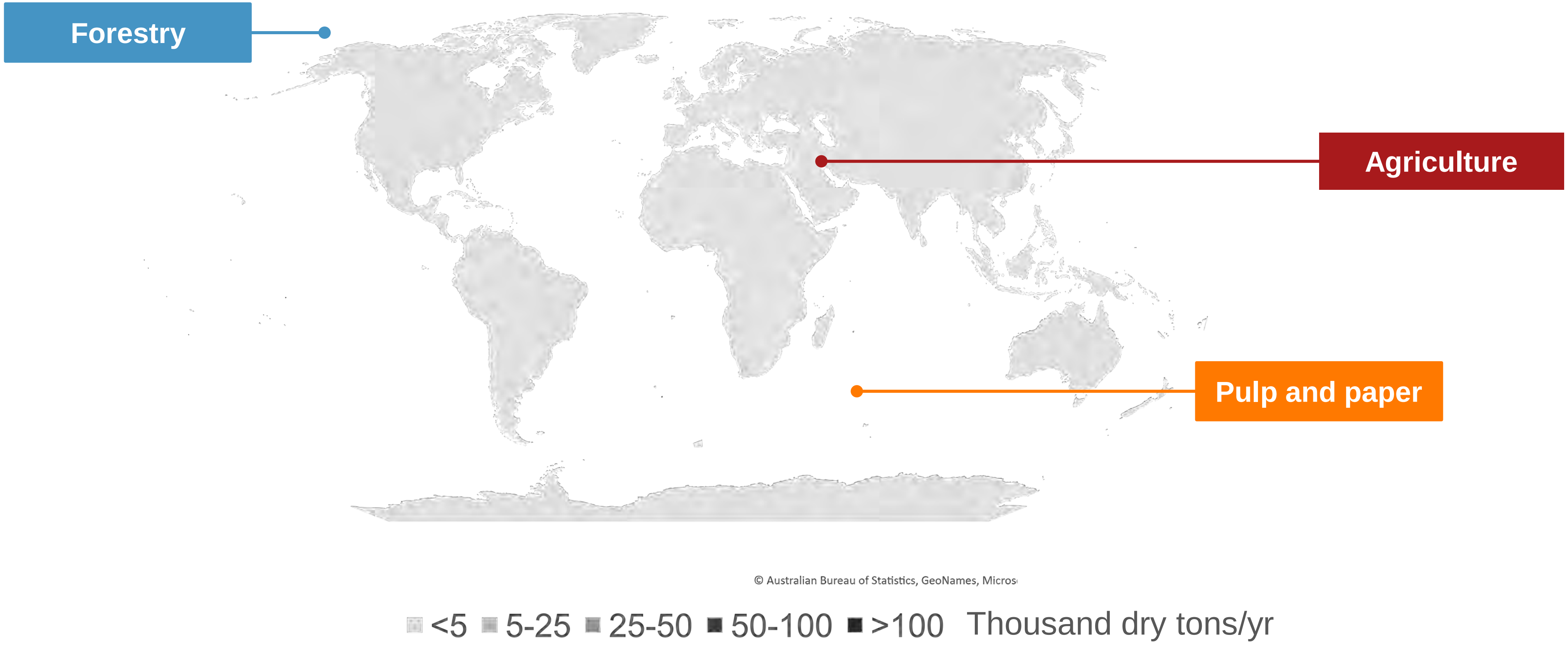
Factors for current utilization of biomass

- On-hand supplies of biomass waste or byproducts
- Low-cost fuel relative to alternatives
- Elimination of waste materials
- Potential net zero-carbon emissions

Current sectors with high biomass usage

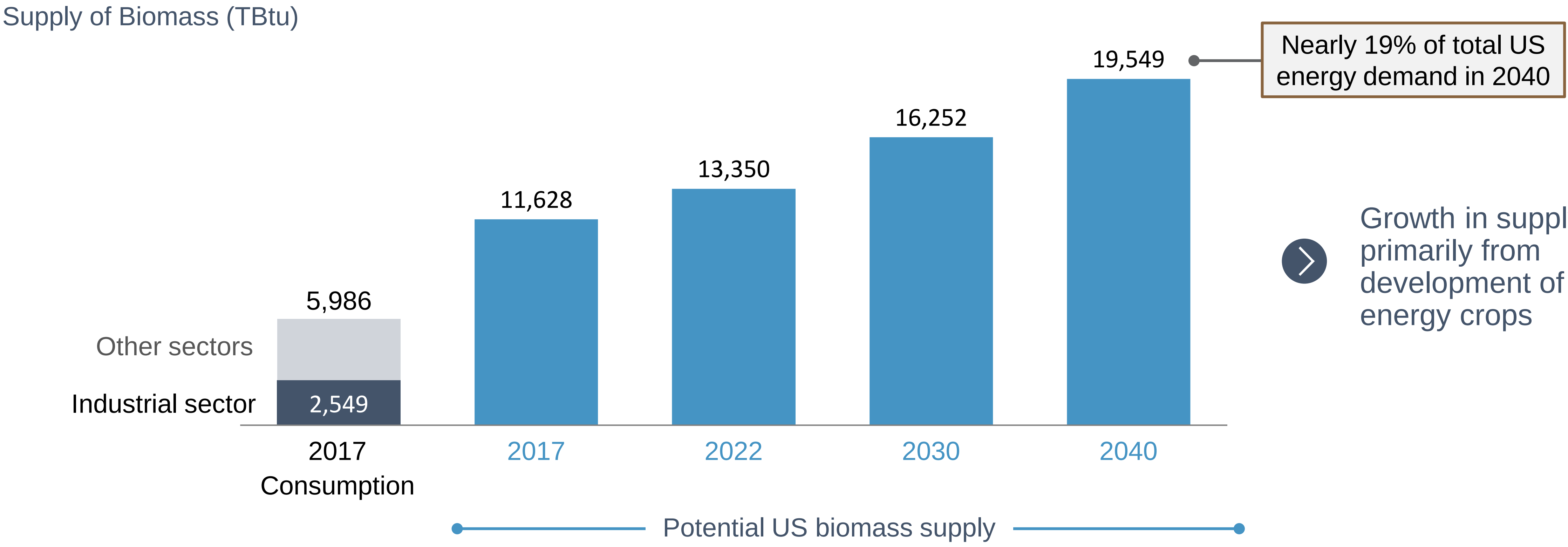
- Forestry and lumber
- Pulp and paper
- Food and agriculture

Biomass supply in the US today is predominantly concentrated in the Midwest, South, and the Pacific Northwest due to the agriculture and forestry sectors



Source: NREL Biofuels Atlas;

Current consumption of biomass is a fraction of total potential, especially with the growth of energy crop cultivation



Nearly 19% of total US energy demand in 2040

Growth in supply primarily from development of energy crops

Note: Assume biomass has average heating value of 8,200 Btu/lb (16.4 MMBtu/ton) from EIA
Source: DOE, US EIA

Biomass energy comes from four major feedstock categories

Energy crops

- Herbaceous
- Woody

Wastes

- Food processing wastes
- Wood processing wastes
- Municipal solid waste

Agricultural

- Crop residues

Forestry

- Forest residues and thinnings
- Whole-tree biomass

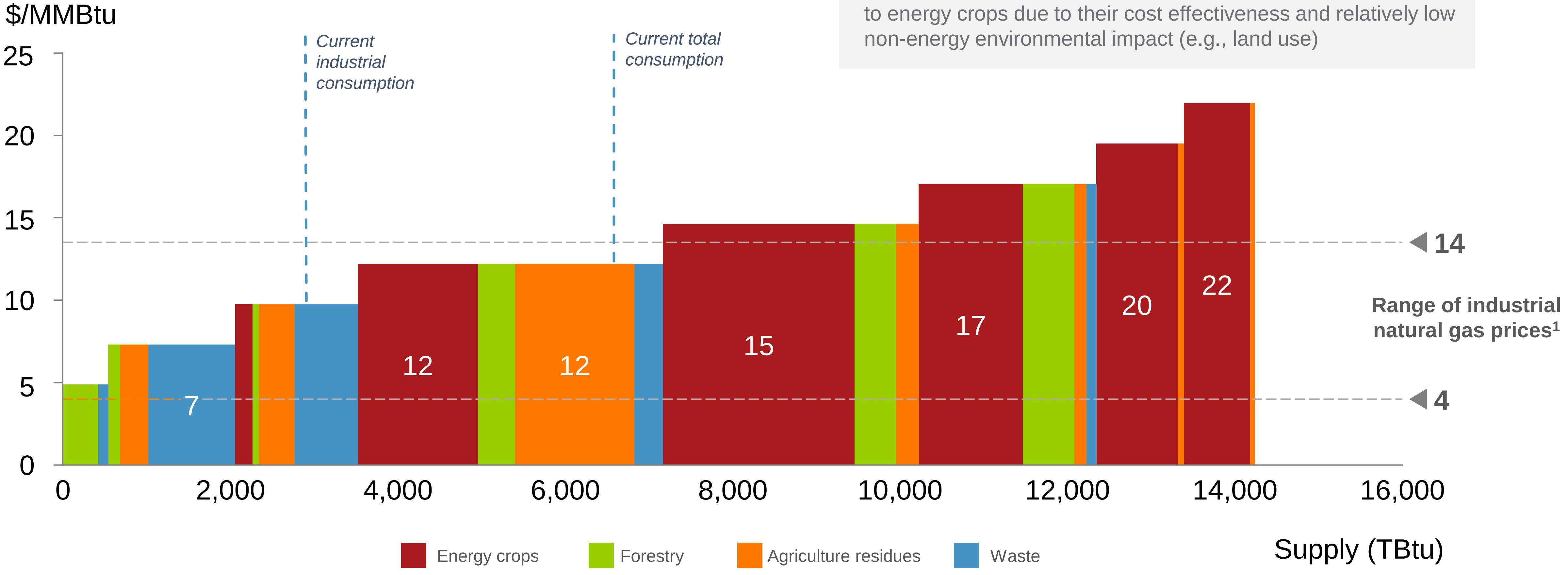
Increasing level of current usage in industrial heating →

Note: Algae is not included due to its nascent nature and primary use as a feedstock for liquid biofuels

Large supplies of biomass feedstocks in all four categories are within range of economic viability in the next decade

Potential Supply of Biomass by Feedstock Type (TBtu) in 2030

This analysis focuses on waste biomass feedstocks as opposed to energy crops due to their cost effectiveness and relatively low non-energy environmental impact (e.g., land use)



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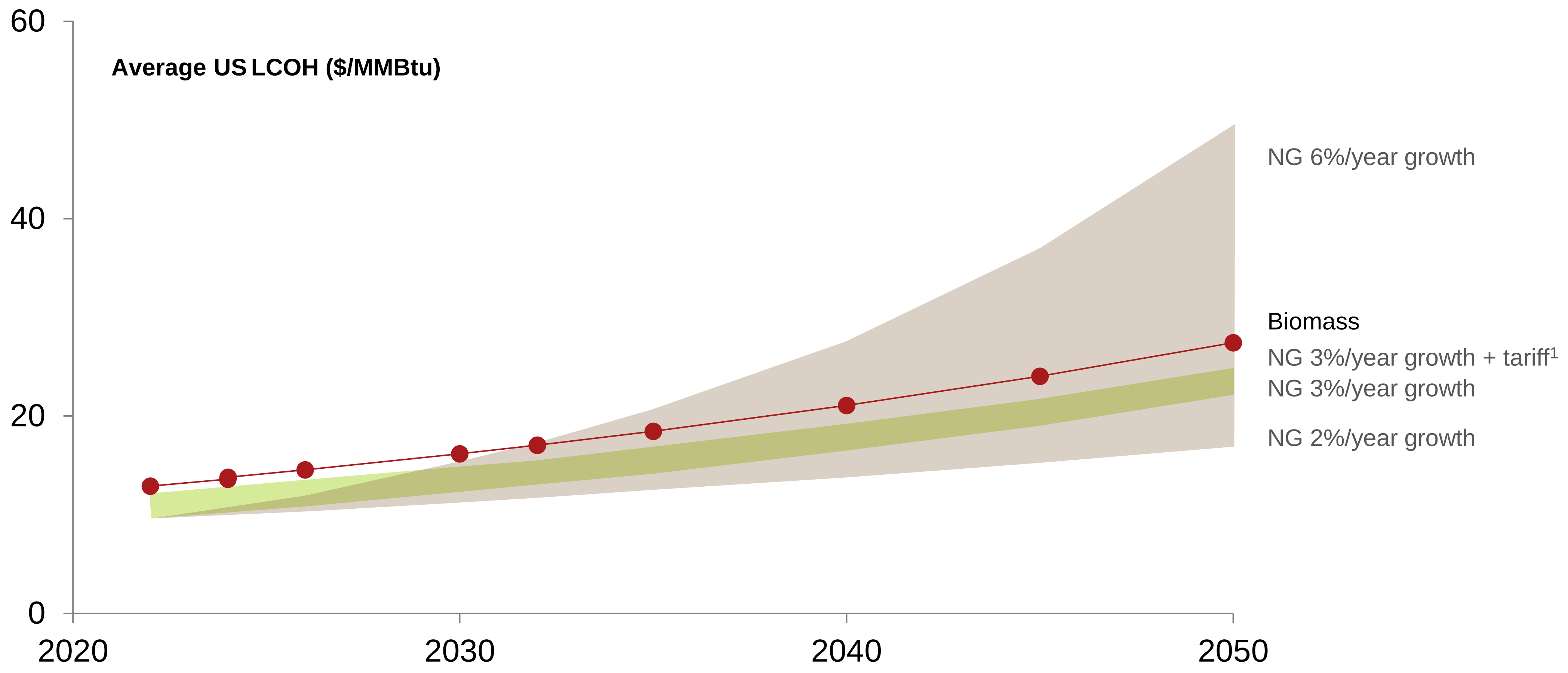
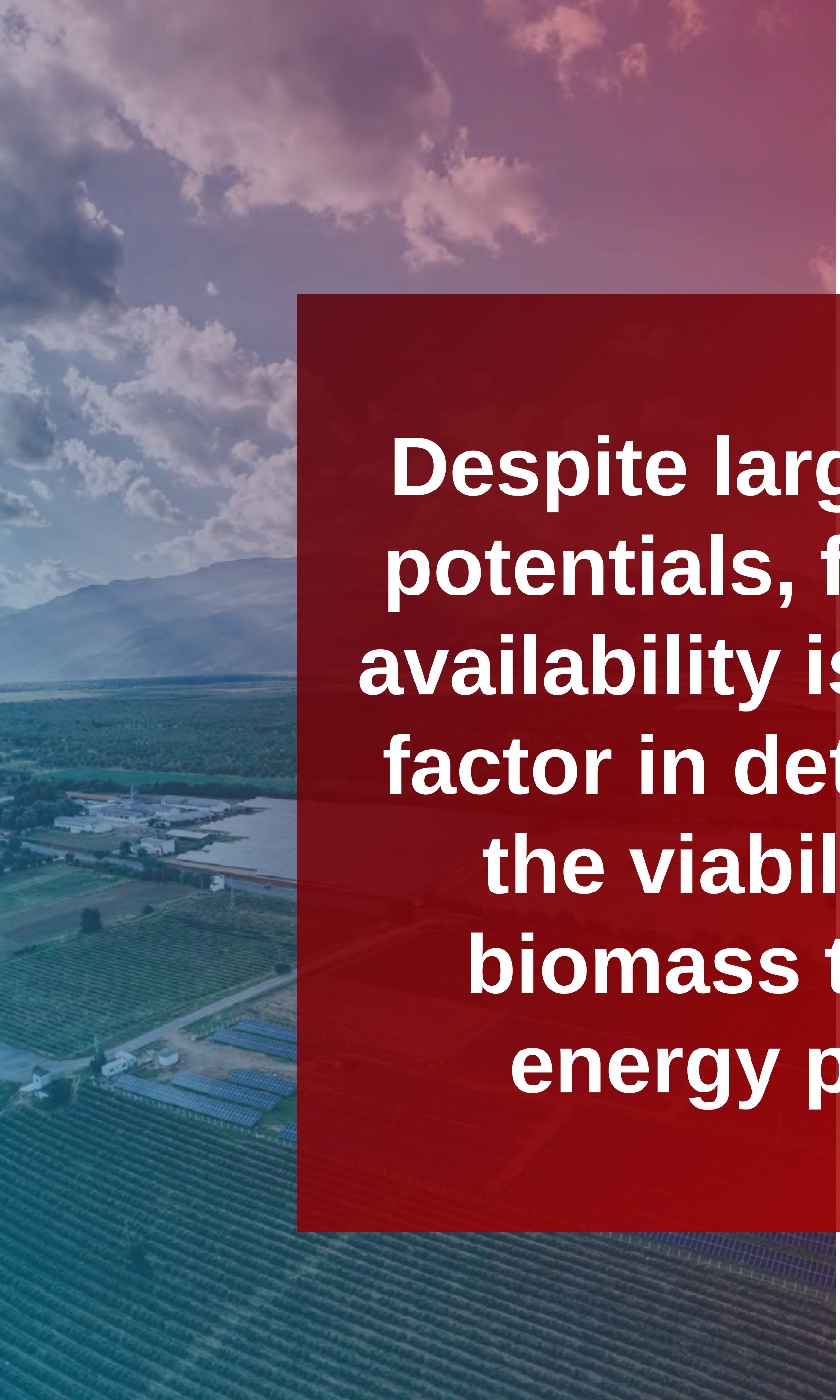
1. EIA May 2022 end-user prices; Notes: Assume biomass has average heating value of 8,200 Btu/lb (16.4 MMBtu/ton) from EIA. Biomass supplies beyond $90/ton ($5.5/MMBtu) were excluded. Prices adjusted from roadside to final sales prices; Source: DOE

Depending on feedstock constraints, biomass is expected to be comparable in cost relative to natural gas in the next 30 years



[1] Based on $51/tonne CO2 social cost of carbon

Notes: Subsidized are shown in plots, subsidized and unsubsidized LCOHs are within 5%. Subsidies may further reduce biomass producer costs and consequently LCOH by <10%.



Despite large supply potentials, feedstock availability is a critical factor in determining the viability of a biomass thermal energy project

Important questions to determine the feasibility of biomass for industrial heating include:

- What is the transportation distance and cost for the feedstock?
- Does the feedstock require collection, or is it a waste or byproduct at a processing plant?
- Is the feedstock a waste that would incur disposal costs if not used for bioenergy?
- What processing steps are required to prepare the biomass feedstock for combustion?
- What combustion technology is suitable?

Biomass for industrial heating may compete with other biomass applications, which could lead to constrained supply and increased prices

Non-energy uses

Pulp & paper feedstock

Power generation

Electricity production

Building heating

Space and water heating

Transport

Liquid biofuel production

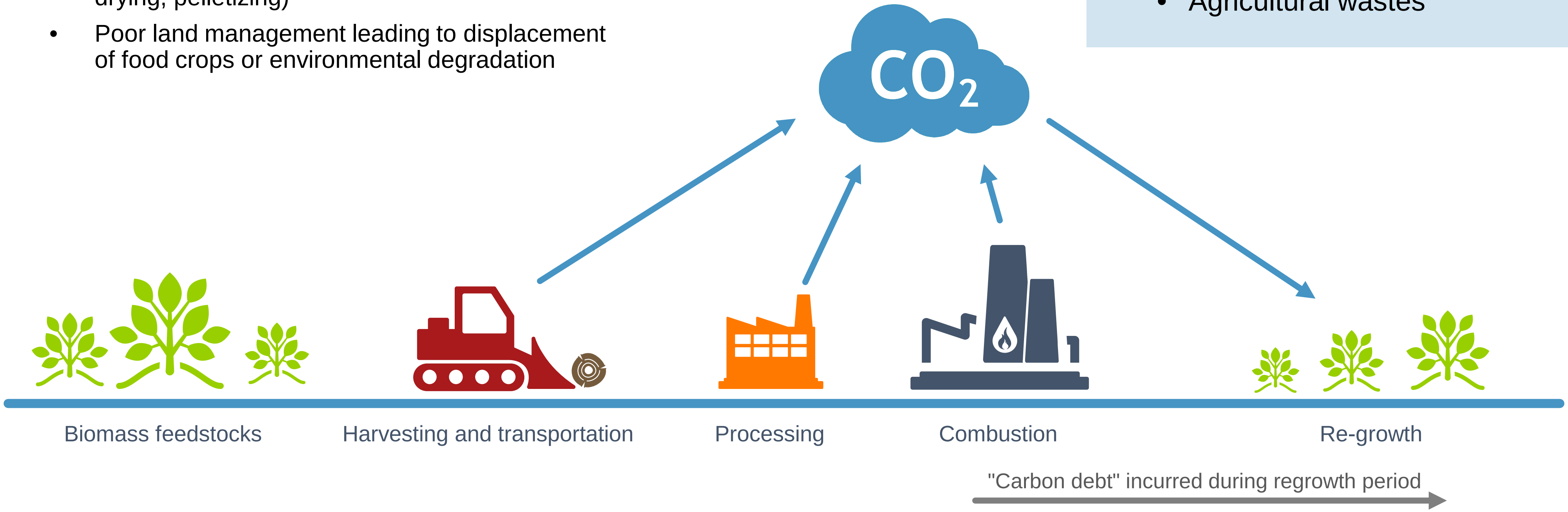
Mature applications

Emerging applications

Carbon neutrality of biomass is contentious and overall carbon footprint can range significantly depending on feedstocks, transportation, and processing

- Biomass combustion is theoretically carbon-neutral due to natural carbon sequestration during plant growth
- However, several factors may increase the overall carbon footprint
  - Emissions during harvesting and transportation
  - Emissions during processing steps (e.g., chipping, drying, pelletizing)
  - Poor land management leading to displacement of food crops or environmental degradation

The best source of biomass is **waste or byproduct biomass**
- Pulp and paper wood wastes
- Forestry residuals
- Agricultural wastes



Biomass feedstocks

Harvesting and transportation

Processing

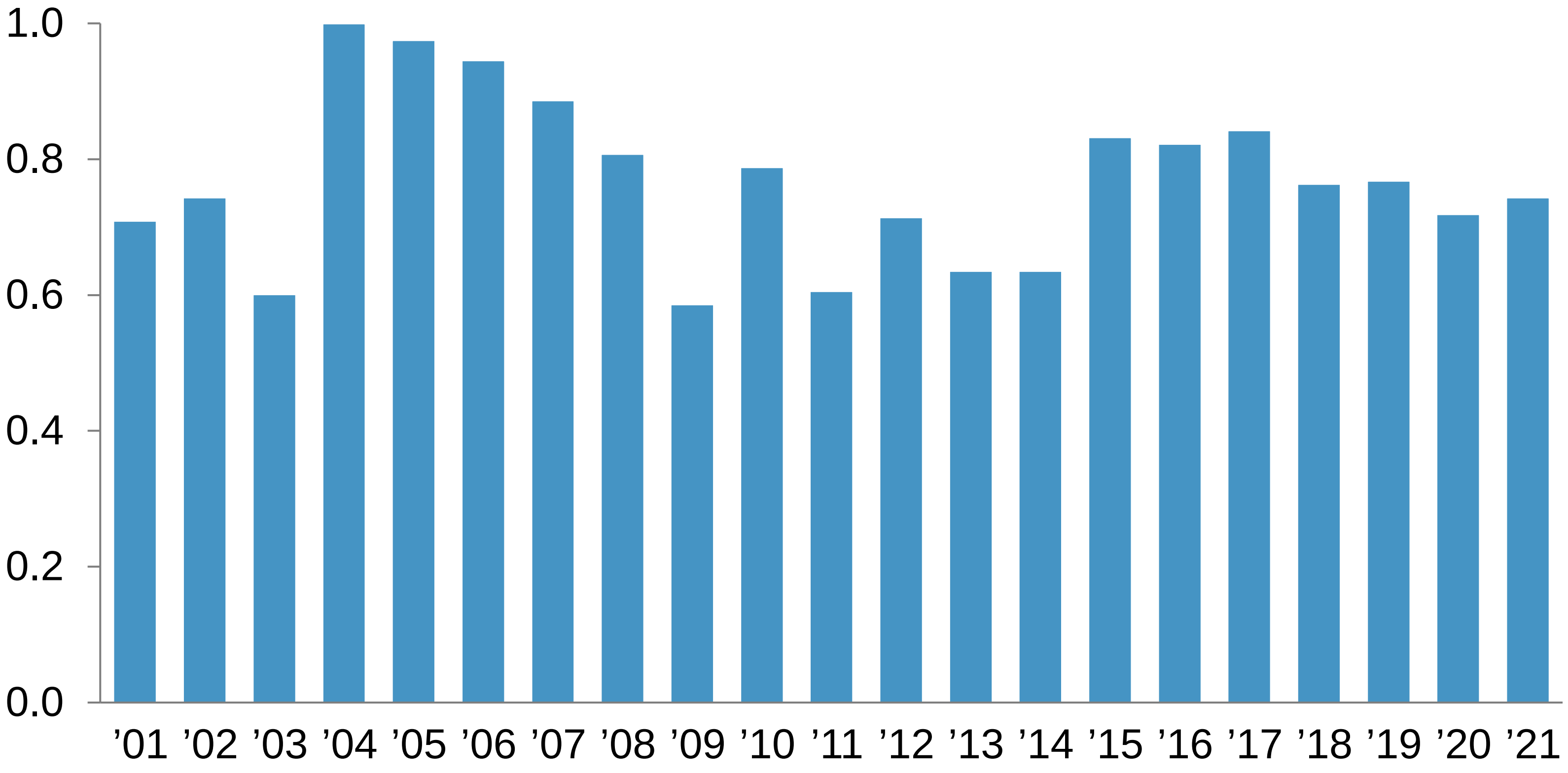
Combustion

Re-growth

"Carbon debt" incurred during regrowth period

US has lost over 16% of its tree cover in last 20 years; majority of biomass consumed by paper sector is unlikely to be sustainable or net zero

Tree cover loss (million ha/year)



- From 2001 to 2021, US lost 44.3 million ha (16%) of tree cover
- This deforestation is equivalent to 17.4Gt of CO_2e emissions
- Due to changing climate conditions, the forest sector will likely become a net emitter by 2040[1]

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1. USDA Integrated Projections for Agriculture and Forest Sector Land Use, Land-Use Change, and GHG Emissions and Removals
Source: Global Forest Watch, USDA

Biomass combustion industrial heating is a mature technology with many advantages, but faces several key barriers to adoption

Advantages

- Renewable resource and theoretically carbon neutral
- Dispatchable thermal energy supply
- Low fuel costs depending on location and feedstock type
- Can be paired with CCS for potential negative emissions

Barriers

- High transportation costs constrains geographic applicability
- Agricultural biomass displaces food production
- Biomass combustion creates air pollutants (e.g., VOCs, NOx, PM)
- Carbon released during combustion may not be recaptured for decades