

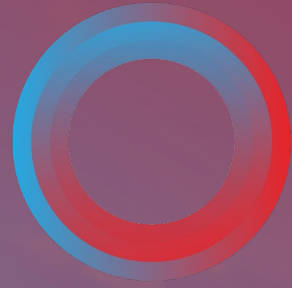
# Industrial Thermal Decarbonization Package

# Included in this Package

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# 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)

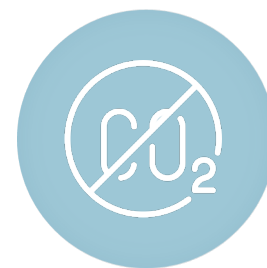




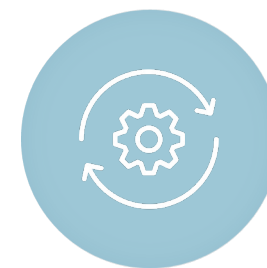
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**Industrial thermal  
emissions and  
abatement options**



**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**

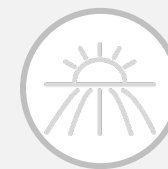
## Decarbonization Technological Pillars<sup>1</sup>



Low-carbon fuels & energy sources



CCS<sup>2</sup>



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

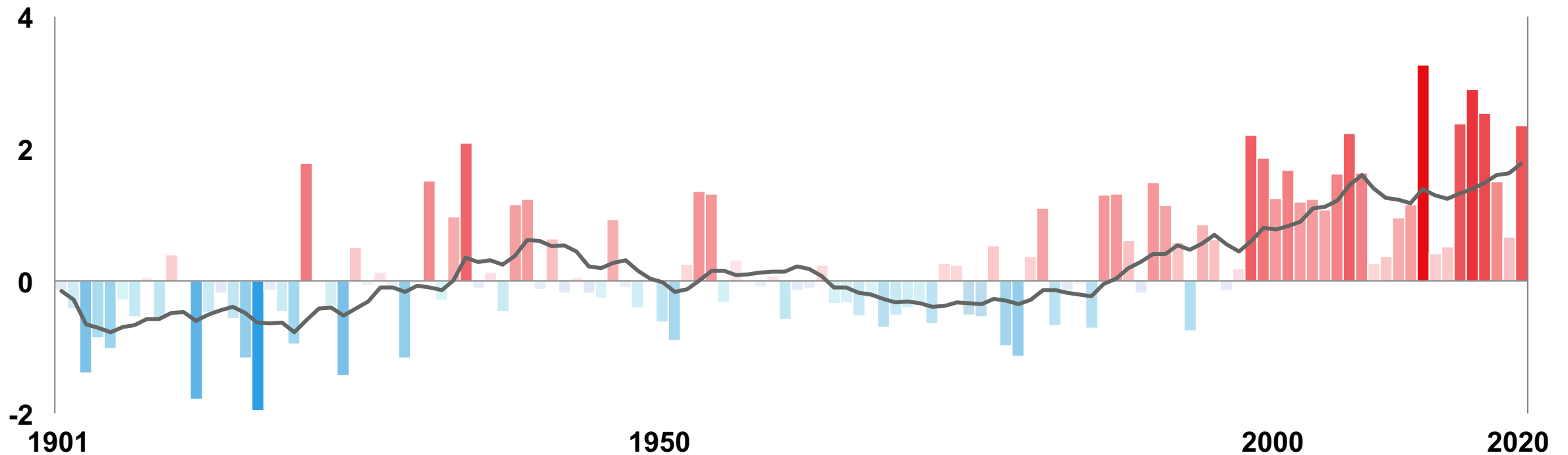
1. This roadmap focusses on growth of renewable thermal energy and related technologies; for prioritization purposes, energy efficiency has not been modeled (except for electric heat pumps and EAF); please refer to the DOE industrial decarbonization roadmap for information on energy efficiency 2. CCS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





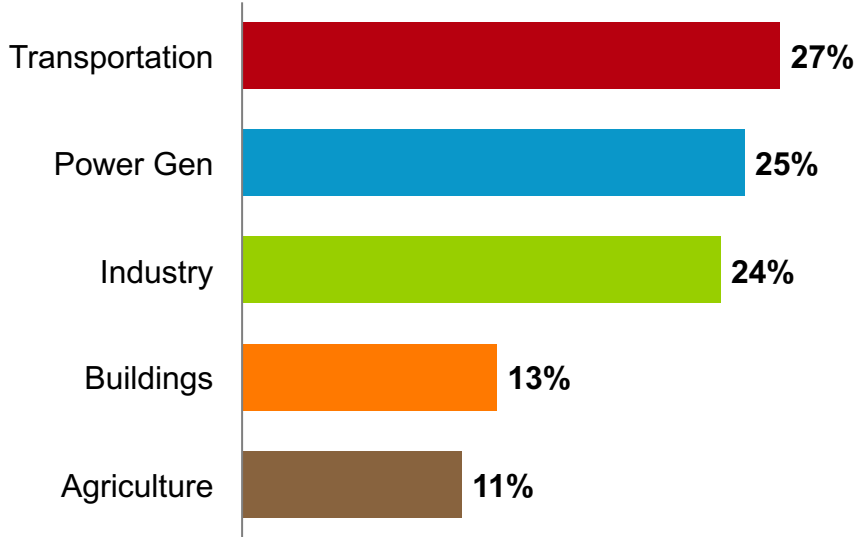
# The US is already facing the impacts of a 1.5°C world

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

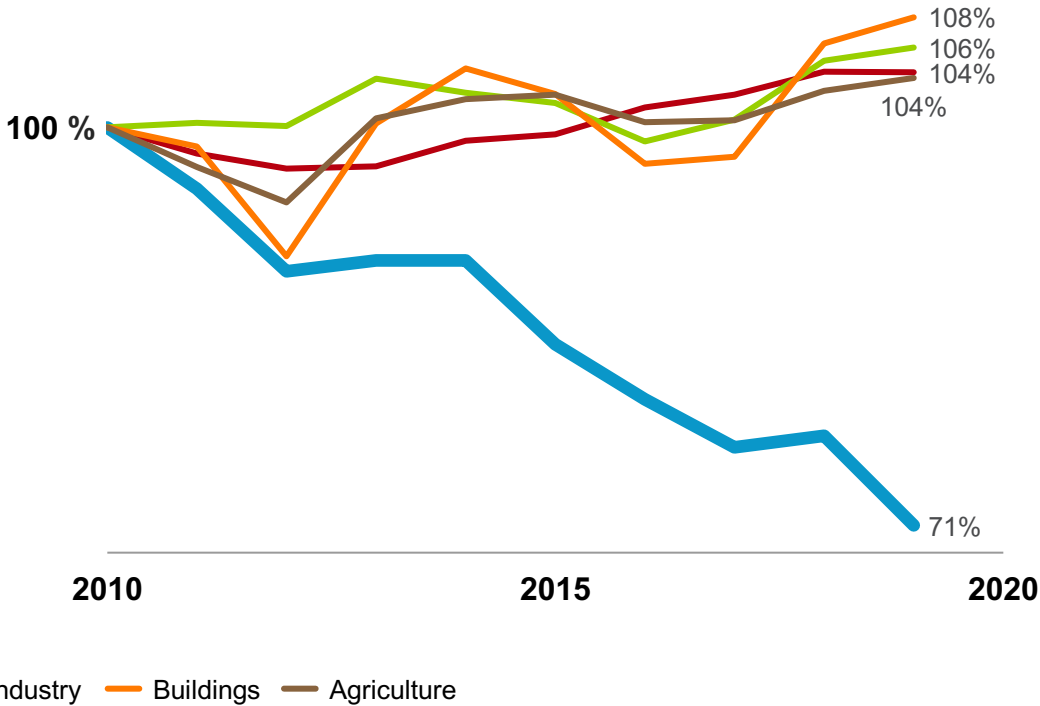


# Heightened attention is needed around industrial emissions; only Power Gen has reduced carbon footprint

Industrial emissions represent  
**24%** of total US emissions ...



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

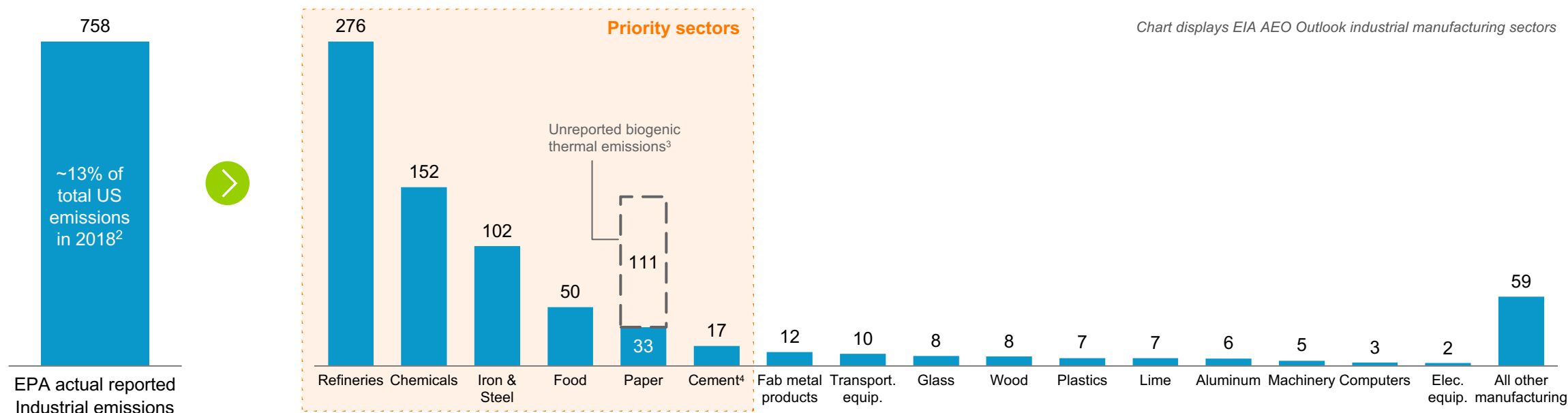




# US industrial thermal emissions totaled 758 million tonnes of CO<sub>2</sub>e in 2018<sup>1</sup>

## US industrial thermal emissions for all industrial manufacturing sectors (2018)<sup>1</sup>

Million tonnes of CO<sub>2</sub>e

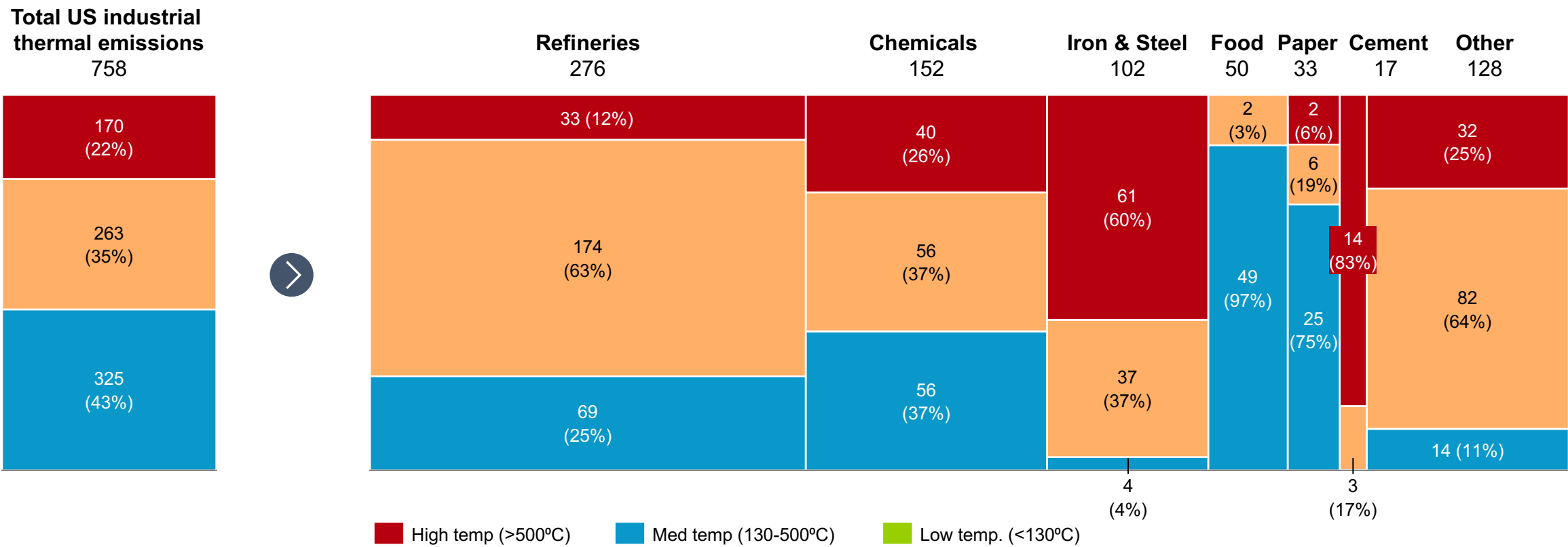


1. Based on AEO 2019 Outlook for 2018 energy consumption by combustible fuel (excludes purchased electricity) for each sector, and EPA emissions intensity of individual fuels except for biomass, which is estimated at 15 kg CO<sub>2</sub>e/mmBtu; excludes non-manufacturing sectors of Agriculture, Construction, 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 CO<sub>2</sub>e in 2018; gross emissions were 6,677 million tonnes of CO<sub>2</sub>e 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)



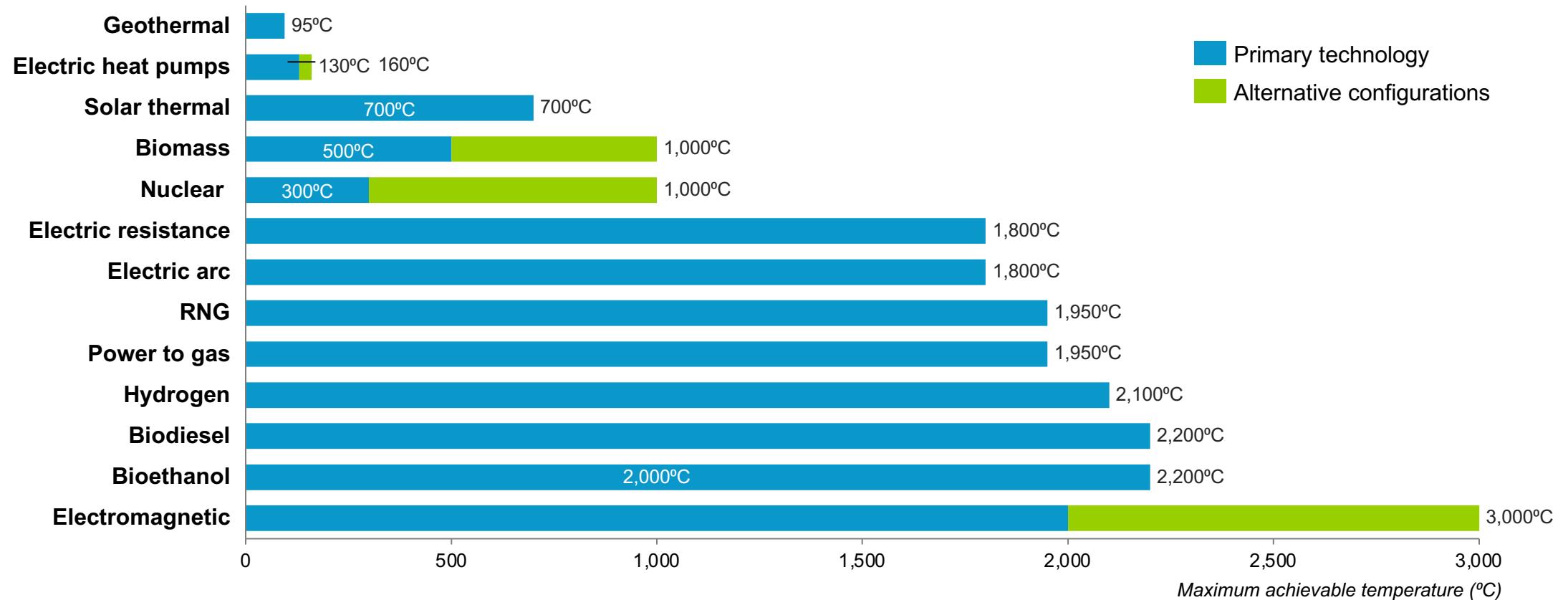
# Low & medium heat processes dominate industrial thermal emissions and account for ~78% of total

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



# Renewable thermal technologies are available across a range of temperatures

Available renewable thermal energy technologies and heat temperature range (°C)

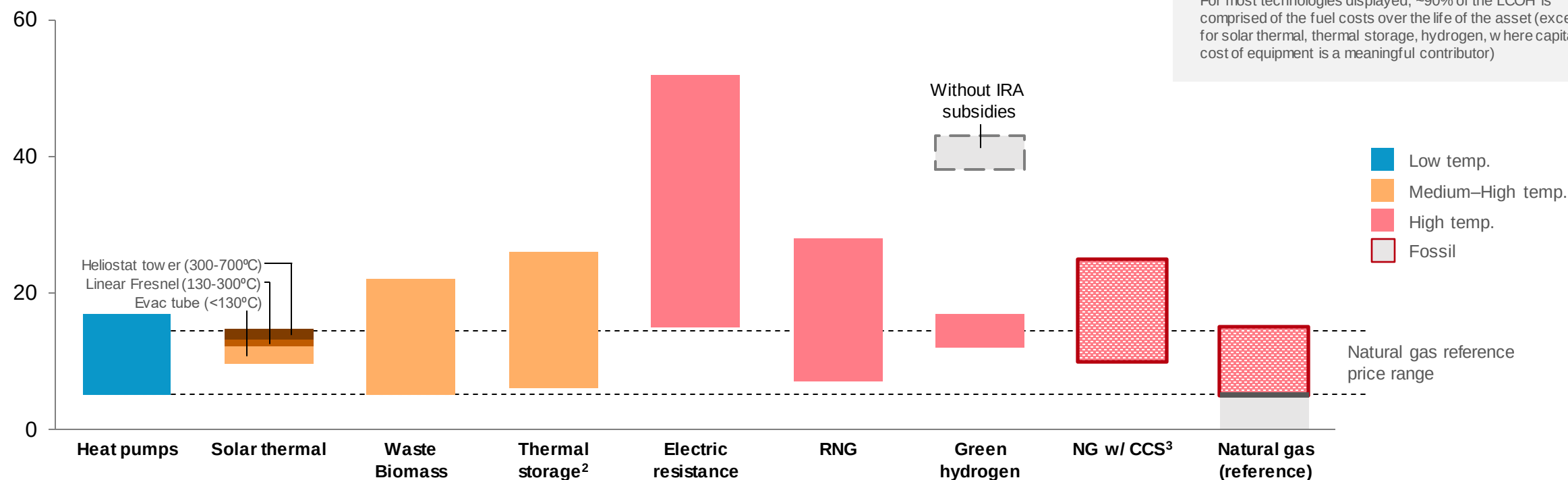




# Prioritized technologies offer competitive levelized cost of heat relative to natural gas

## Levelized cost of heat (LCOH) delivery across renewable thermal technologies<sup>1</sup>

Levelized cost of heat in 2022 (\$/MMBtu)



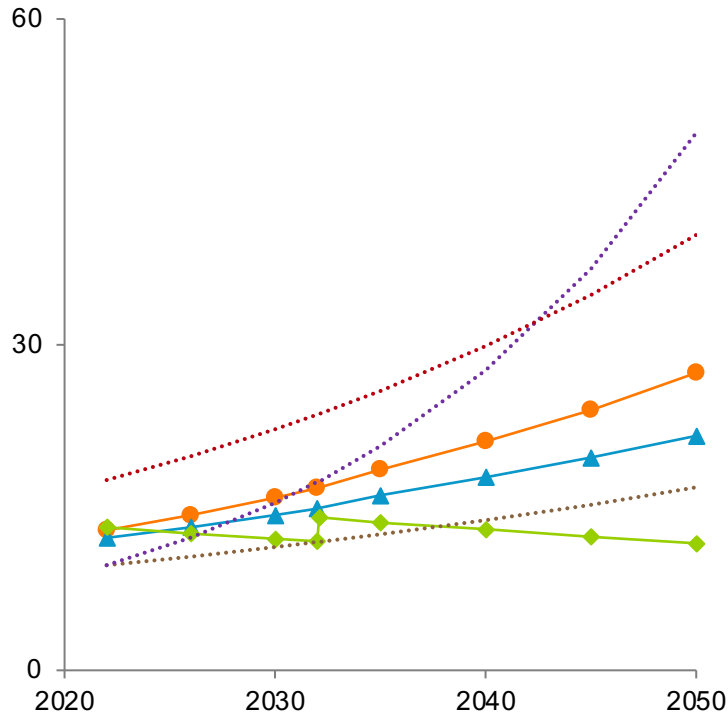
1. LCOH compares project lifetime costs against lifetime energy produced; costs include capital costs of equipment, fuel costs, and maintenance cost assumptions over the usable life of the energy asset. Electricity and natural gas pricing is based on state wholesale industrial end user electricity and 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

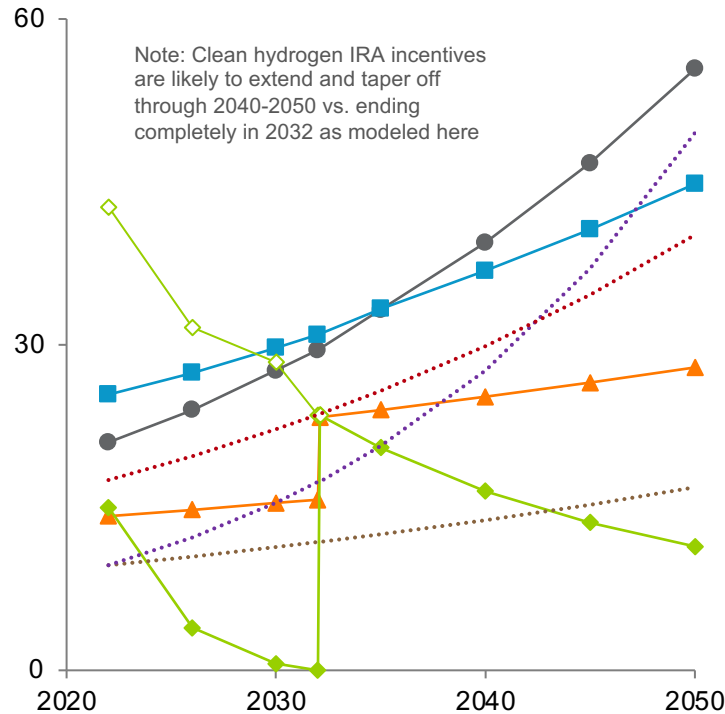
# Technologies are economic v. natural gas in several scenarios; heat pumps & solar thermal for low temp, hydrogen for high temp

LCOH: Low & medium heat (\$/MMBtu)<sup>1</sup>



- Biomass (<1,000°C)
- ▲ Heat pump (<160°C)
- ◆ Solar thermal (<700°C)
- ..... Natural gas - California (3% growth)
- ..... Natural gas - US avg. (2% growth)
- ..... Natural gas - US avg. (6% growth)

LCOH: High heat (\$/MMBtu)<sup>1</sup>



- Renewable natural gas (<1,950°C)
- Electric resistance (<1,800°C)
- ◆ Green hydrogen (<2,100°C)
- ▲ Thermal storage + resistance (<1,500°C)
- ◆ Unsubsidized hydrogen

## Key assumptions

- Assumes US average retail end user industrial price for electricity and NG in 2022<sup>1</sup> (including T&D costs)
- Electricity end user retail price is projected to grow at 2%<sup>2</sup> 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<sup>3</sup>
- 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 <sup>2</sup> | Other Electric <sup>3</sup> | RNG   | Green hydrogen | CCS <sup>4</sup>   | Natural gas (reference) |
|-------------------------------------|-------------------|------------|---------------|---------|------------------------------|-----------------------------|-------|----------------|--------------------|-------------------------|
|                                     | Primary temp (°C) | 160        | 700           | 1,000   | 1,500                        | 1,800                       | 1,950 | 2,100          | N/A                | 1,950                   |
| Food                                | <130°C            | ✓          | ✓             | ✓       | ✓                            | ✓                           | ✓     | ✓              | ✓                  | ✓                       |
| Refineries                          | <480°C            | ✓          |               | ✓       | ✓                            | ✓                           | ✓     | ✓              | ✓                  | ✓                       |
| Chemicals                           | <815°C            | ✓          |               | ✓       | ✓                            | ✓                           | ✓     | ✓              | ✓                  | ✓                       |
| Paper                               | <200°C            | ✓          | ✓             | ✓       | ✓                            | ✓                           | ✓     | ✓              | ✓                  | ✓                       |
| Cement                              | 600-1,500°C       |            |               | ✓       | ✓                            | ✓                           | ✓     | ✓              | ✓                  | ✓                       |
| Iron & Steel                        | 1,600-2,000°C     |            |               | ✓       | ✓                            | ✓                           | ✓     | ✓              | ✓                  | ✓                       |
| Avg US LCOH <sup>1</sup> (\$/MMBtu) |                   | 12         | 13            | 13      | 14                           | 25                          | 21    | 15             | 15-20 <sup>2</sup> | 10                      |

✓ Technology is applicable in the sector

✓ Technology identified as priority for the sector

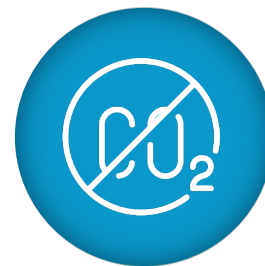
1. Levelized cost of heat in 2022 using national weighted averages for end user industrial electricity and natural gas pricing for the past 12 months as of June 2022 2. Combined with electric resistance 3. Includes electric resistive technologies, electric arc heating, and other developed electric heating 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



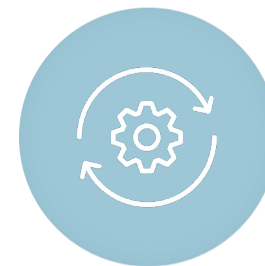
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# Our analysis uncovered four important findings, which guided the decarbonization roadmap



**Low & medium heat processes (<500°C) 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 ~130°C**, representing up to ~42% of industrial thermal emissions; heat pumps are expected to reach 200°C by 2030, representing up to ~60% of industrial thermal emissions



Clean<sup>1</sup> 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 CO<sub>2</sub>e emissions<sup>2</sup> annually, **if captured, could offset ~15% of US industrial thermal emissions**; IRA carbon capture credits of \$85/metric ton provide a cost competitive<sup>3</sup> pathway to capture these emissions

1. Clean hydrogen includes green and blue hydrogen 2. Total paper sector biogenic CO<sub>2</sub>e emissions totaled 111 million tonnes in 2018 with the top 50 facilities generating ~75 million tonnes of biogenic CO<sub>2</sub>e; 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



# Four parallel pathways to decarbonize industrial heat<sup>1</sup>



## Electrify industrial heat processes in short, med, long-term

- Electrify low temperature processes with cost competitive heat pumps
- Electrify remaining ~14 steel blast furnaces with DRI-EAF<sup>2</sup>
- Electrify steam boilers & deploy other electric resistance technologies in medium-high temp. processes



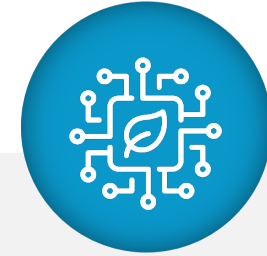
## Procure, consume, and advocate for green electricity

- 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



## Displace fossil combustion with sustainable NZ fuels

- Avoid natural gas, oil, coal
- Deploy low carbon biofuels from waste feedstock as a bridge to sustainable NZ fuels
- Develop, procure, and deploy clean hydrogen as a sustainable net zero fuel



## Pair renewables with clean technologies to bridge gaps

- Strategically deploy CCS, DAC, BECCS, or offsets using scale efficiencies as a short- and medium-term lever in specific use cases<sup>1</sup>
- Deploy thermal storage to resolve intermittency and maximize renewables

*Energy efficiency spans across pillars<sup>1</sup>*

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



# Parallel pathways to decarbonize industrial heat<sup>1</sup>



## 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



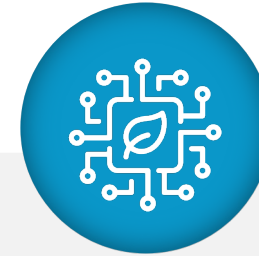
## Green the grid

- 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



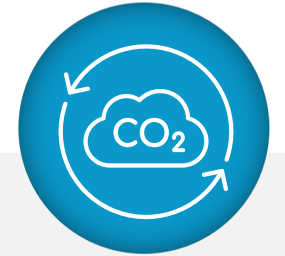
## Electrify industry processes

- Avoid natural gas, oil, coal
- Deploy biomass from waste feedstock as a bridge to sufficient supply of net zero fuels
- Develop, procure, and deploy clean hydrogen as a sustainable net zero fuel



## 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 out CCS as industry transitions to clean processes
- Deploy BECCS (Bio-energy w/ CCS) on existing and new biomass combustion to 'inset' emissions

*Energy efficiency spans across pillars<sup>1</sup>*

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



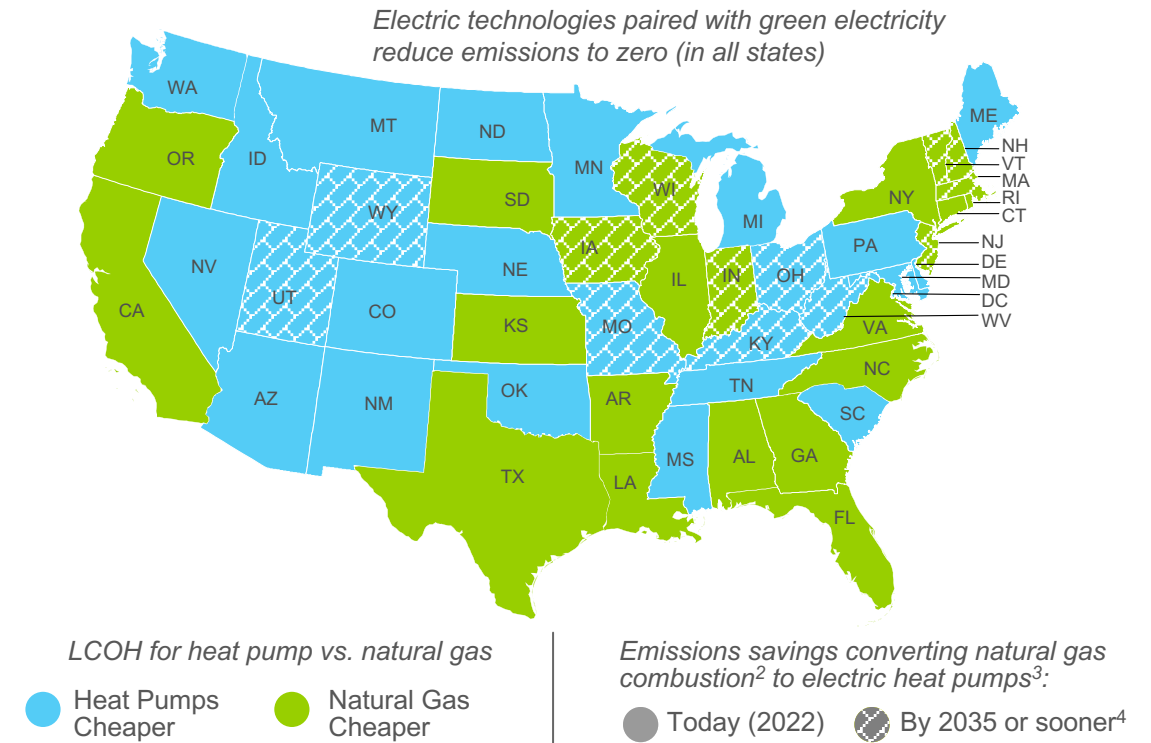


# Electrification is a primary decarbonization pathway in the short, medium, and long-term

## Electricity offers immediate decarbonization opportunities and a sustainable net zero fuel

- Electric heat pumps can be deployed effectively today at temperatures under  $\sim 130^{\circ}\text{C}$ , representing  $\sim 42\%$ <sup>1</sup> 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  $\sim$ 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  $\sim 200^{\circ}\text{C}$  by 2030+ and may become applicable for up to  $\sim 60\%$ <sup>1</sup> of industrial thermal energy consumption occurring under  $\sim 200^{\circ}\text{C}$

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



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



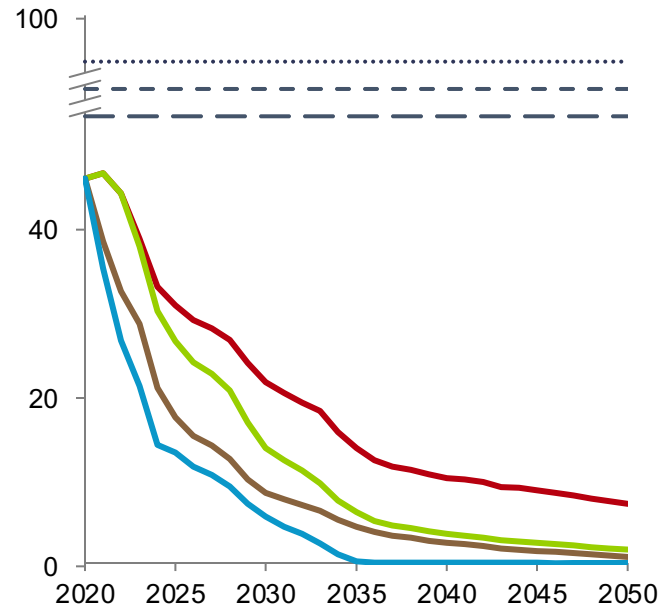




# Grid decarbonization will unlock even more abatement opportunities and enable a NZ 2050

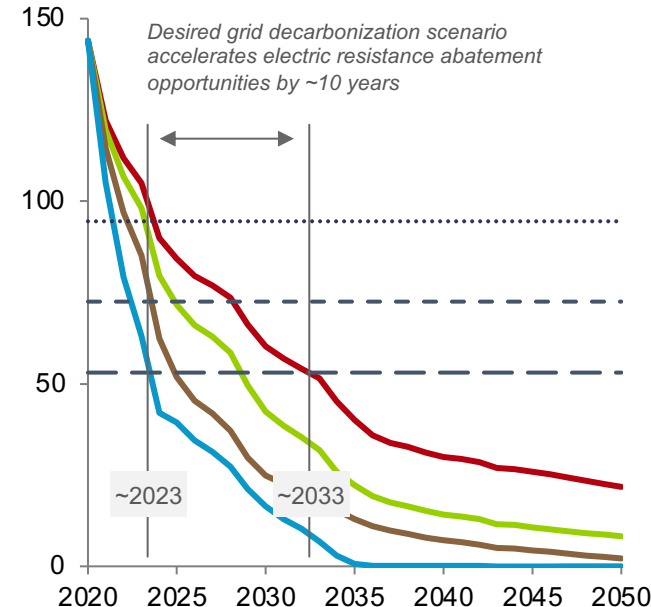
## Heat pumps with grid electricity reduce emissions immediately

Electric heat pump emissions intensity v. fossil fuels (Kg CO<sub>2</sub>e/mmBtu)



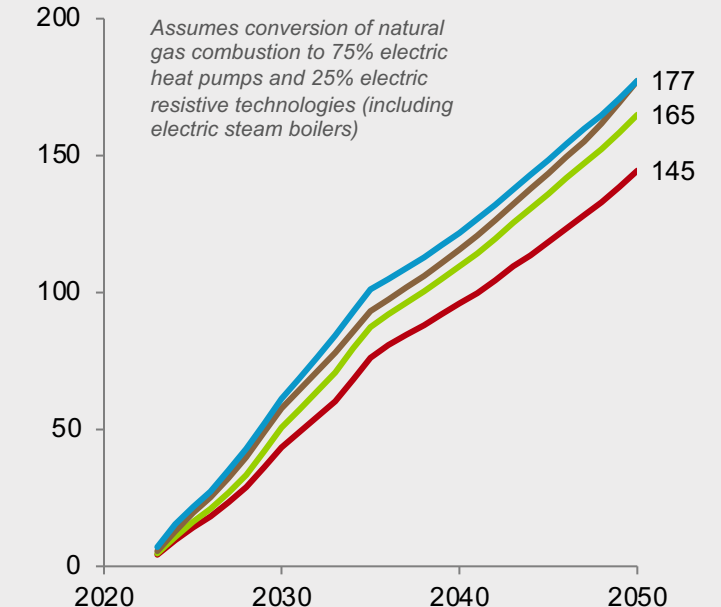
## Elec. resistance with grid electricity offers abatement in a few years

Electric resistance emissions intensity v. fossil fuels (Kg CO<sub>2</sub>e/mmBtu)



## "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 CO<sub>2</sub>e/year)



— 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

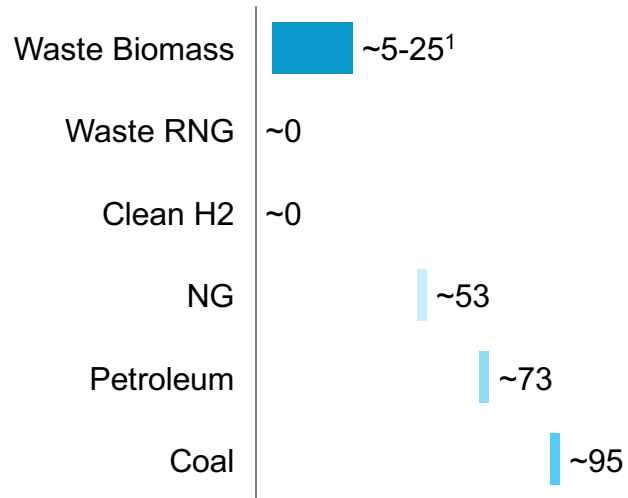




# Hydrogen & RNG are supply constrained, allowing biomass to also play a role as a combustible fuel

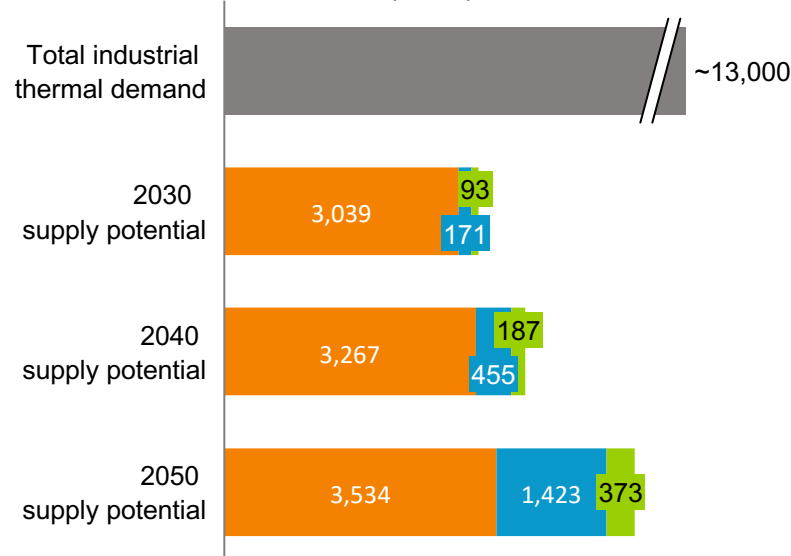
**RNG & clean H2 are preferred over biomass but ...**

Emissions intensity (kg CO<sub>2</sub>e / 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 preferable 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

● Waste Biomass<sup>2</sup> ● Clean H2<sup>3</sup> ● Waste RNG<sup>4</sup> ● Total Ind. thermal<sup>5</sup>

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 (~1/3<sup>rd</sup> share) and refinery byproducts (~2/3<sup>rd</sup> 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<sup>2</sup>) is expected to be lower than the cost of CCS paired with natural gas combustion (~\$15-20/mmBtu<sup>2</sup>); as supply constraints ease, clean hydrogen is likely preferable 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%<sup>1</sup> and reduce LCOH by ~\$5/mmBtu<sup>2</sup>
- 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+ CO<sub>2</sub>e in 2018 from biogenic emissions<sup>3</sup> (~3x the reported paper sector thermal emissions) - offering significant opportunity for negative emissions



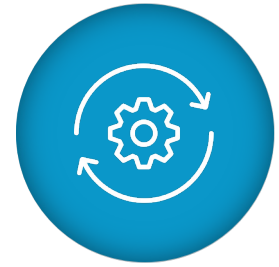
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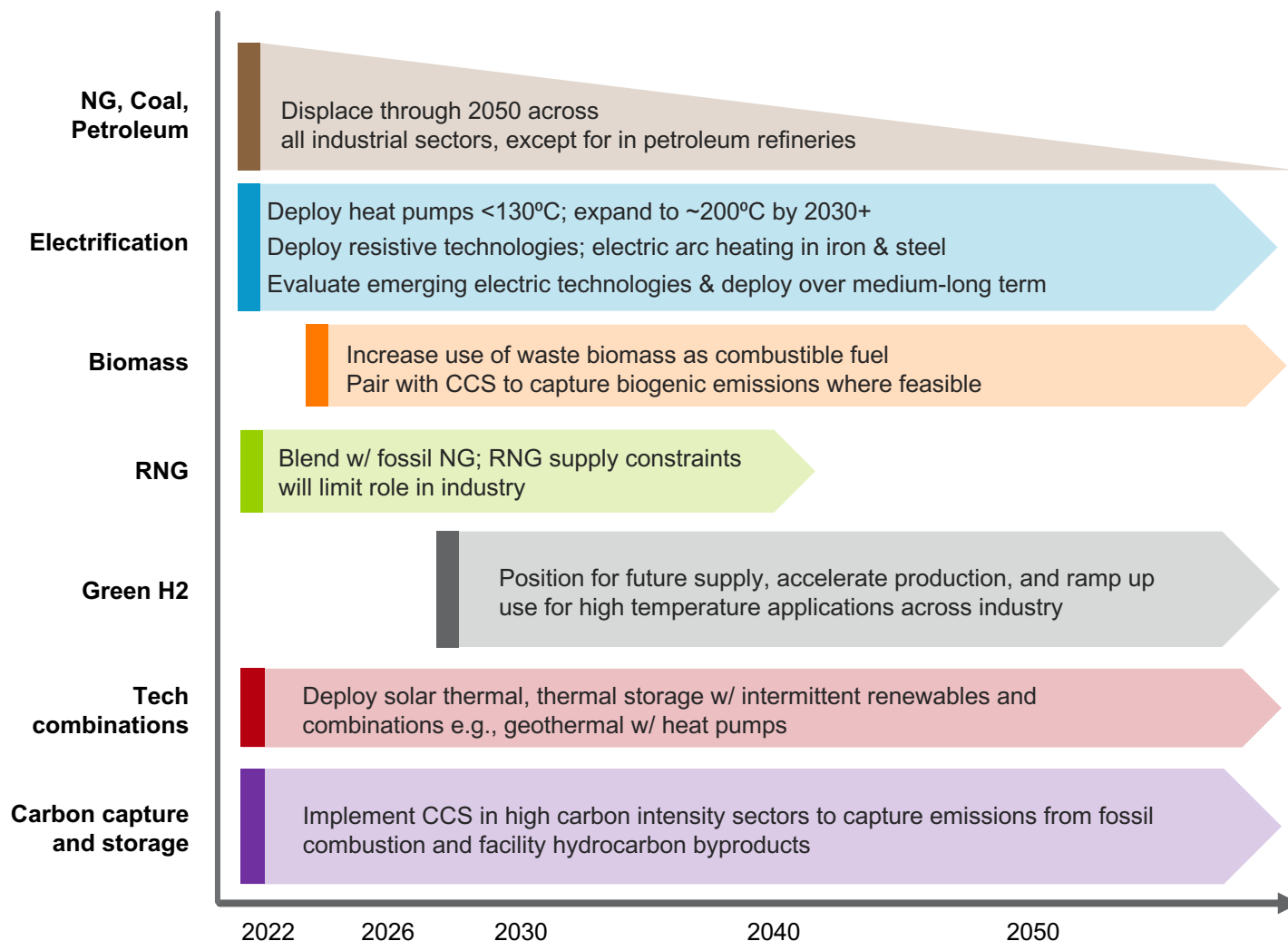
## Priority actions will need attention across multiple fronts

- ✓ Displace virtually all fossil combustion across industrial sectors except refiners
- ✓ 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



# Decarbonization Roadmap

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

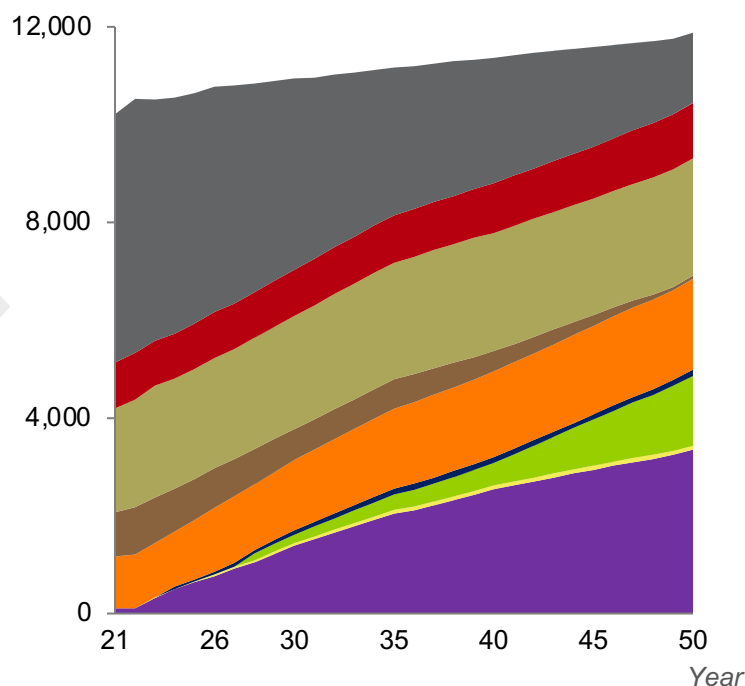
\*For consistency across sectors, EIA energy consumption forecast for refineries is used below; however, refinery energy consumption is likely to decline in the 2030-2050 period as fossil fuel usage is reduced globally. Accordingly, overall thermal energy consumption, thermal emissions, and related carbon 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 goals<sup>6</sup>
- 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<sup>1</sup>

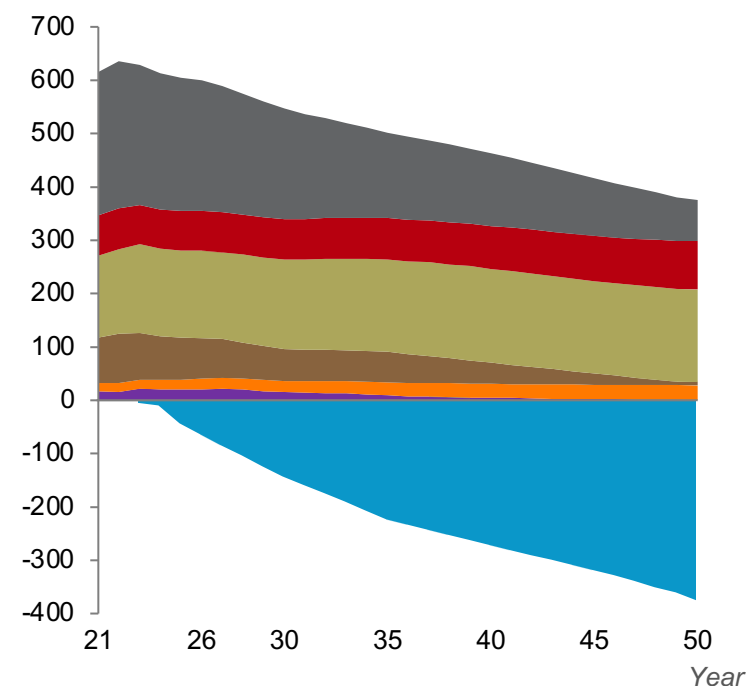
Tbtu of thermal energy



■ Natural gas ■ Petroleum & other ■ Coal ■ Clean Hydrogen ■ Electrification  
■ Biofuels & coproducts ■ Waste Biomass ■ RNG ■ Solar thermal ■ CCS

### Thermal emissions<sup>2</sup>

Millions tonnes of CO<sub>2</sub>e 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 CO<sub>2</sub>e 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

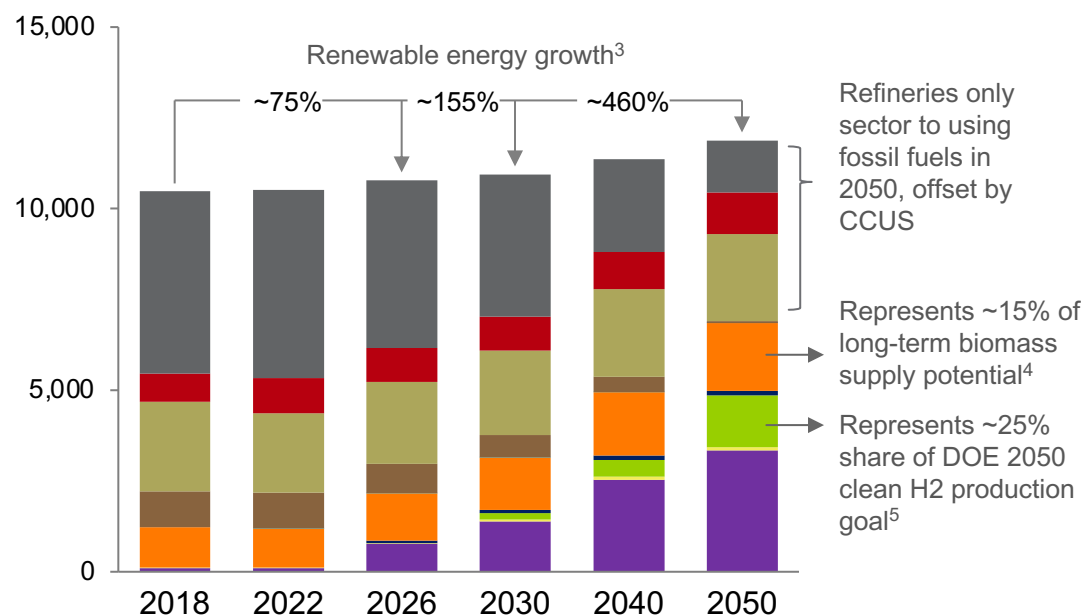




# Strategic deployment of clean fuels & abatement technologies will enable emission reduction goals for 2026 and 2030

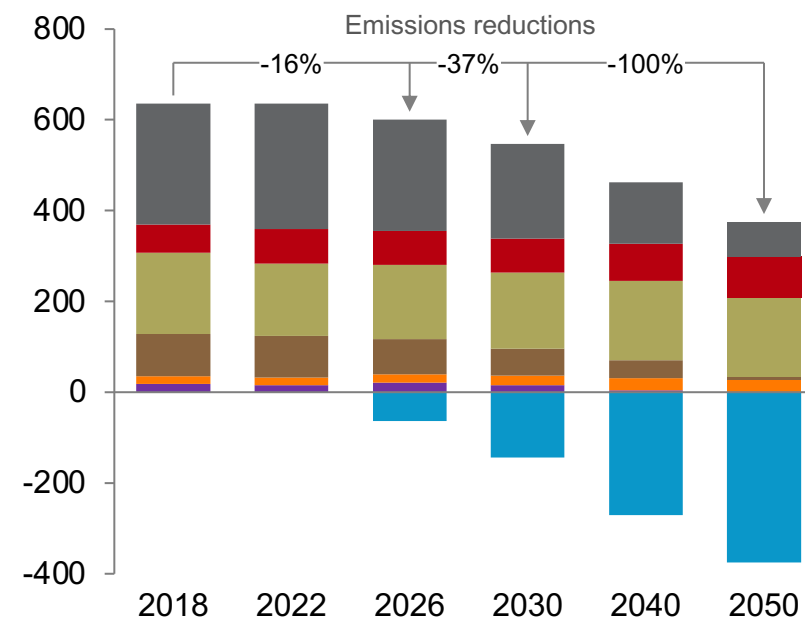
## Thermal energy consumption<sup>1</sup>

TBtu of thermal energy



## Thermal emissions<sup>2</sup>

Million tonnes of CO<sub>2</sub>e thermal emissions



Natural gas
  Biofuels & coproducts
  Petroleum & other
  Coal
  Waste Biomass
  RNG
  Clean Hydrogen
  Solar thermal
  Electrification
  CCS

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 CO<sub>2</sub>e 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





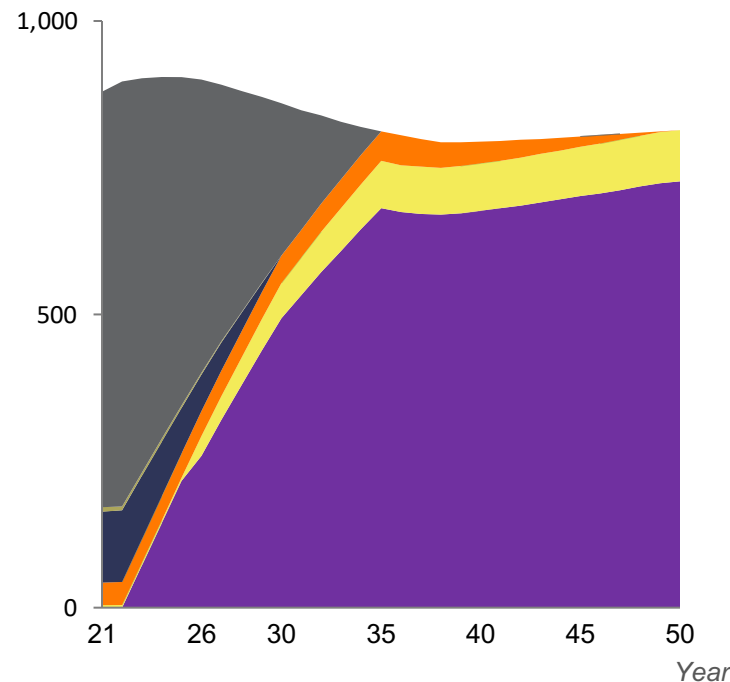
# Thermal Energy Decarbonization

## Decarbonization pathways

- 97% of industrial heat needs are for applications in the low temperature range (<130°C), which can be decarbonized on an accelerated timeline with electrification and heat pumps. Natural gas, which combusts at ~1,850°C 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)

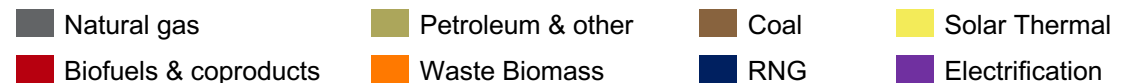
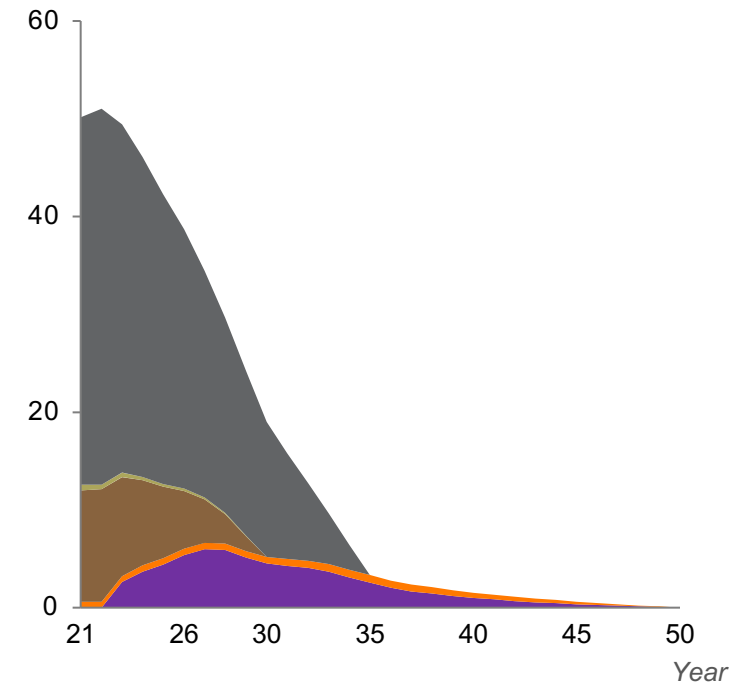
## Thermal energy consumption<sup>1</sup>

Tbtu of thermal energy



## Thermal emissions<sup>2</sup>

Millions tonnes of CO<sub>2</sub>e 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 CO<sub>2</sub>e 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



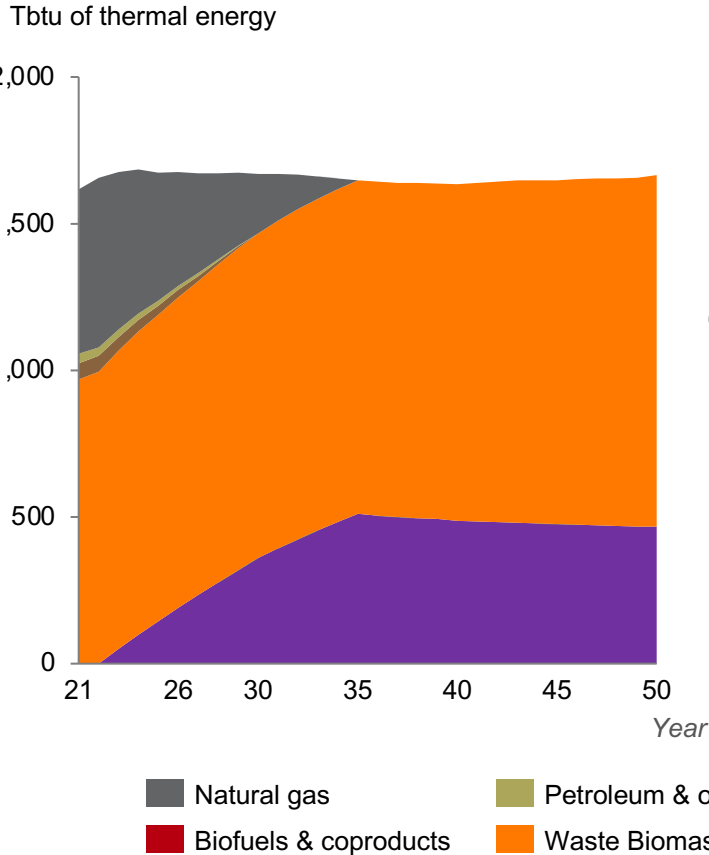
# Paper

## Thermal Energy Decarbonization

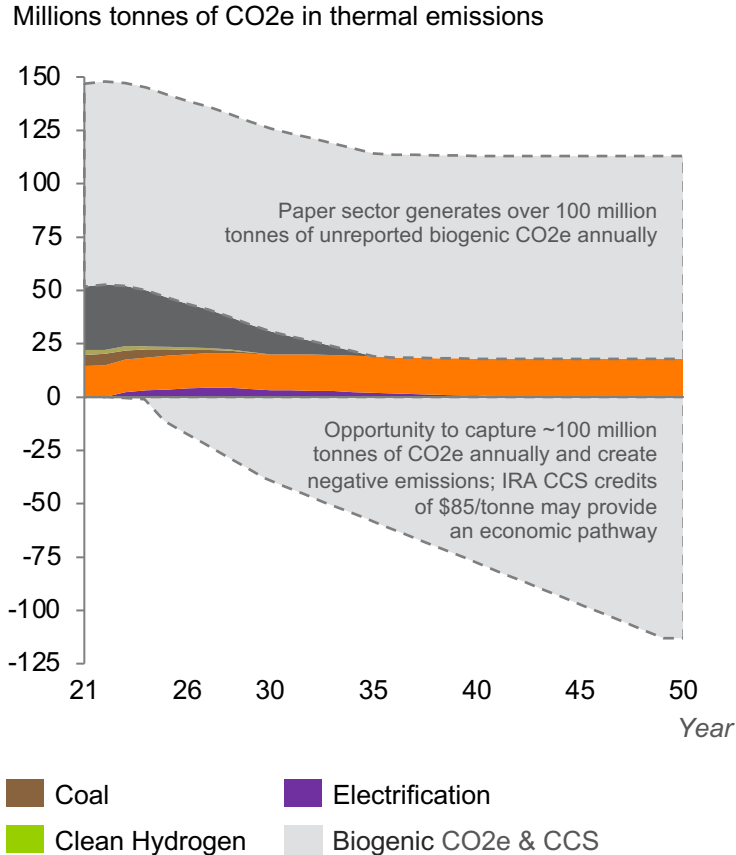
### Decarbonization pathways

- 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 CO<sub>2</sub>e<sup>3,4</sup> 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<sup>1</sup>



### Thermal emissions<sup>2</sup>



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 CO<sub>2</sub>e 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 CO<sub>2</sub>e. Source: EIA outlook; EIA emissions intensity; Global Forest Watch; USDA; industry reports; BCG analysis



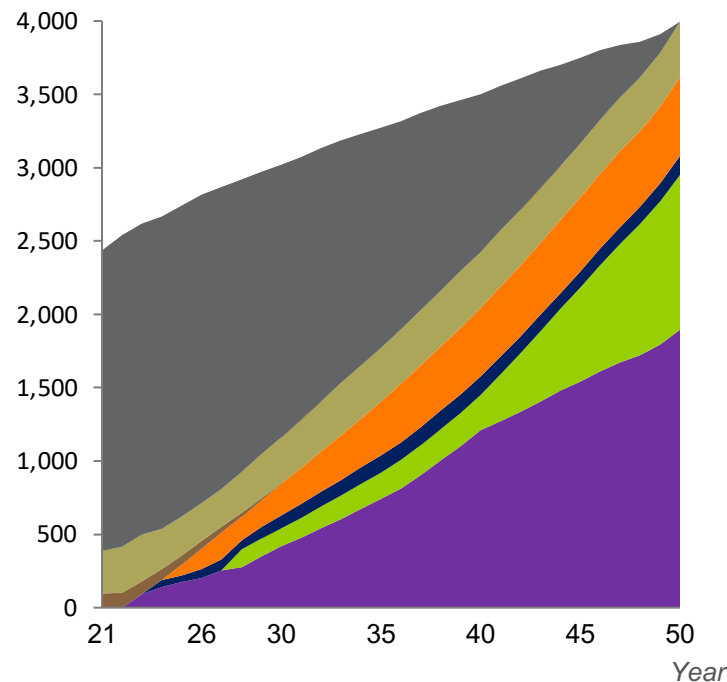
# Thermal Energy Decarbonization

## 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 <130°C processes representing ~37% of total thermal emissions in the sector. As heat pumps improve to ~200°C, higher heat applications can be electrified (~X% of total thermal emissions were generated <200°C 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

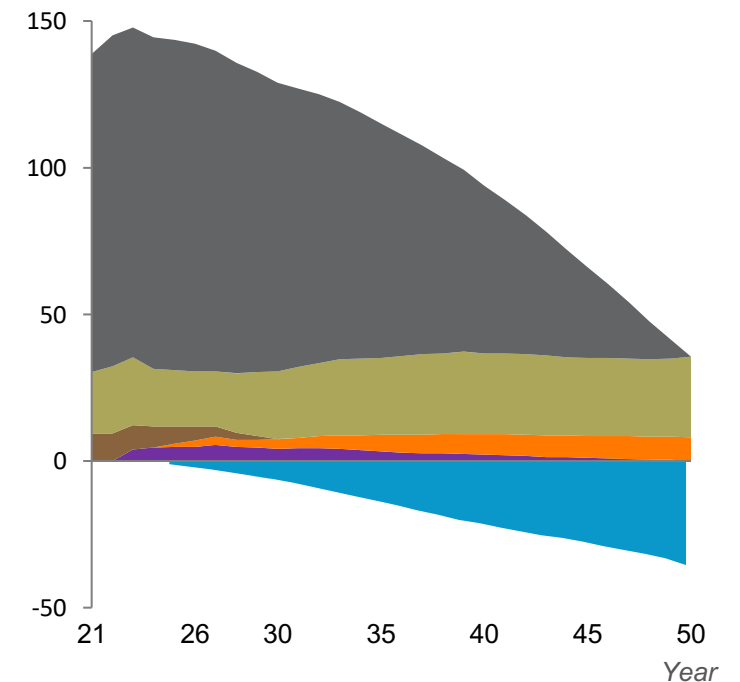
## Thermal energy consumption<sup>1</sup>

Tbtu of thermal energy



## Thermal emissions<sup>2</sup>

Millions tonnes of CO<sub>2</sub>e in thermal emissions



Natural gas    Petroleum & other    Coal    Clean Hydrogen    CCS  
 Biofuels & coproducts    Waste Biomass    RNG    Electrification

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 CO<sub>2</sub>e 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

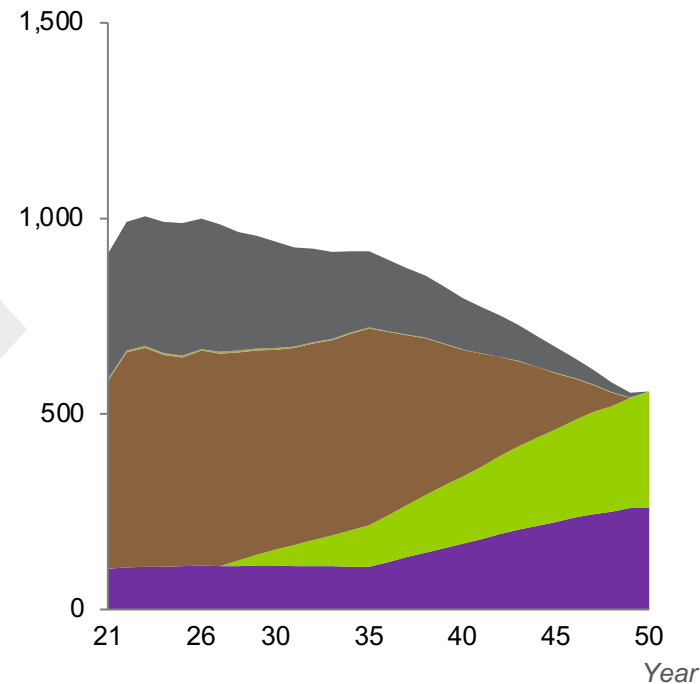
# Thermal Energy Decarbonization

### 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

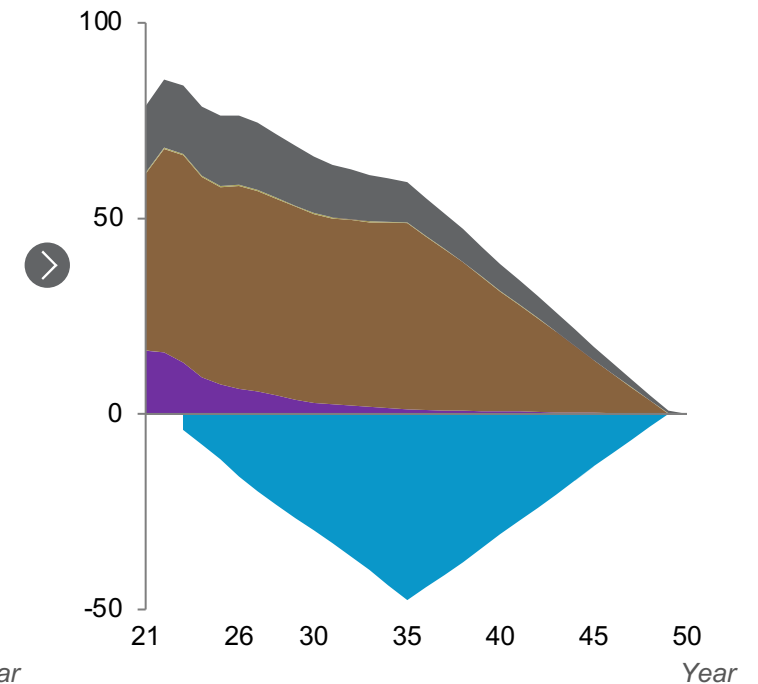
### Thermal energy consumption<sup>1</sup>

Tbtu of thermal energy



### Thermal emissions<sup>2</sup>

Millions tonnes of CO<sub>2</sub>e in thermal emissions



■ Natural gas      ■ Petroleum & other      ■ Electrification (EAF)      ■ CCS  
■ Biofuels & coproducts      ■ Coal      ■ Clean Hydrogen

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 CO<sub>2</sub>e 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





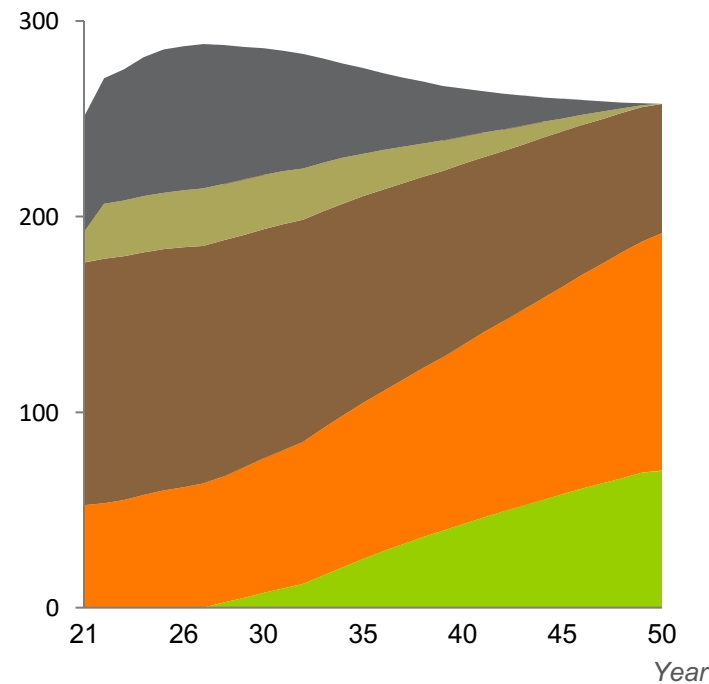
## Thermal Energy Decarbonization

### 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%)<sup>3</sup>
- 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)<sup>4</sup>
- 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

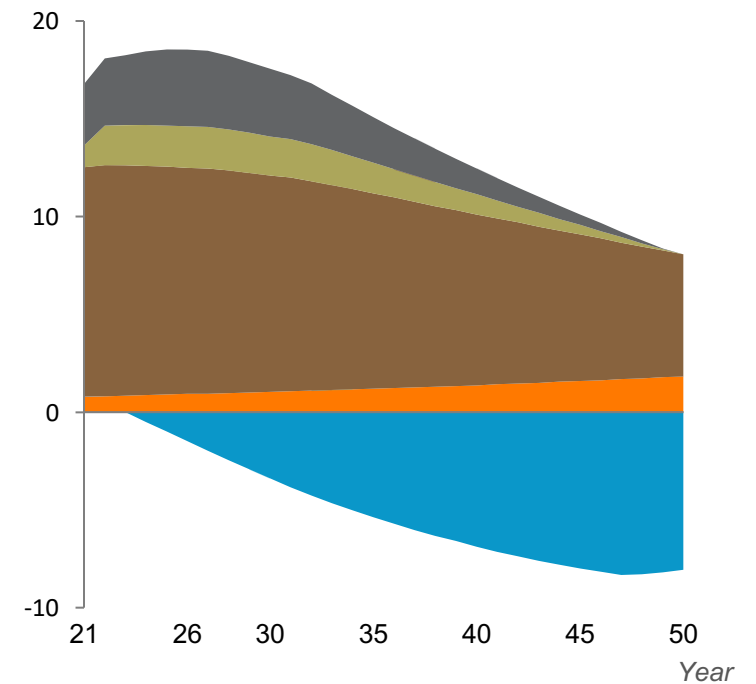
### Thermal energy consumption<sup>1</sup>

Tbtu of thermal energy



### Thermal emissions<sup>2</sup>

Millions tonnes of CO<sub>2</sub>e in thermal emissions



Natural gas
  Petroleum & other
  Coal
  CCS
  Biofuels & coproducts
  Waste Biomass
  Clean Hydrogen

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 CO<sub>2</sub>e 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

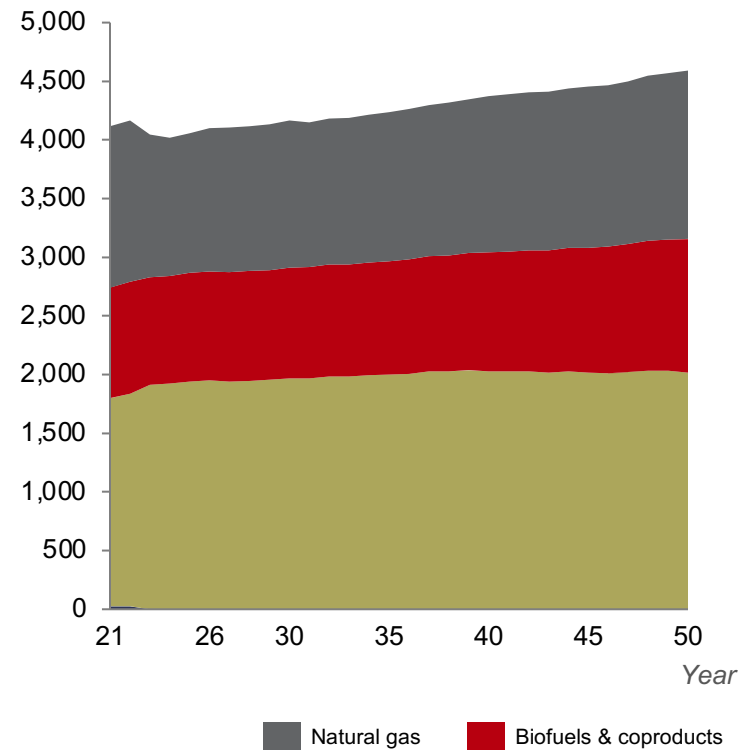
*\*For consistency across sectors, EIA energy consumption forecast for refineries is used below; however, refinery energy consumption is likely to decline in the 2030-2050 period as fossil fuel usage is reduced globally. Accordingly, overall thermal energy consumption, thermal emissions, and related 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 ~2/3<sup>rd</sup>s of total fuel combustion; natural gas combustion represents ~1/3<sup>rd</sup>
- 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

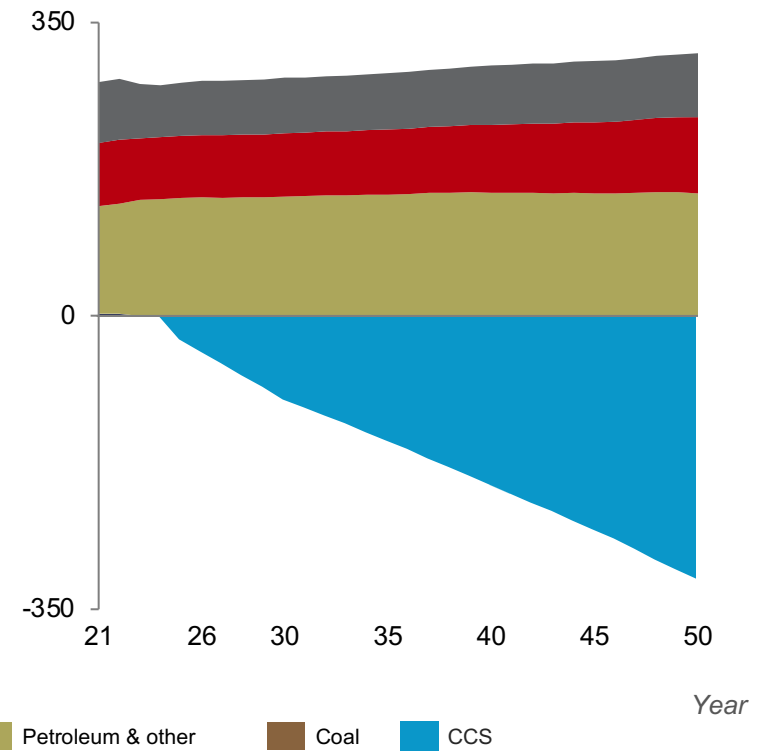
### Thermal energy consumption<sup>1</sup>

Tbtu of thermal energy



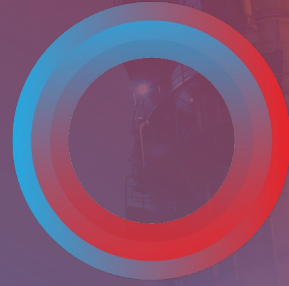
### Thermal emissions<sup>2</sup>

Millions tonnes of CO<sub>2</sub>e 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 CO<sub>2</sub>e 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

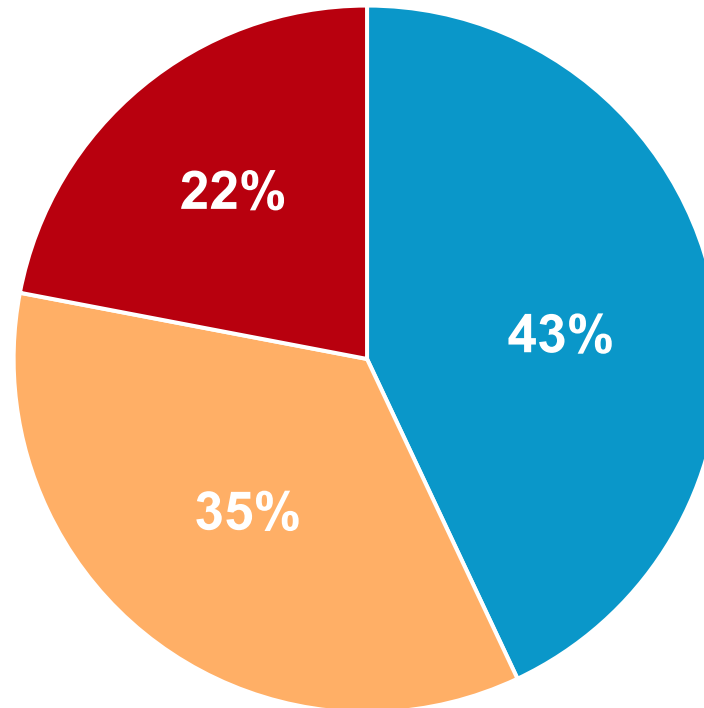
US industrial thermal energy use

**78% of industrial heat is needed for low & medium heat applications (<500°C); only 22% is needed for high heat (>500°C)**

Industrial thermal energy consumption by heat temperature range

**High heat processes (22% 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 ~130°C** and can target ~43% of industrial thermal energy use

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

● Low-temperature range (<130°C)

● Mid-temperature range (130-500°C)

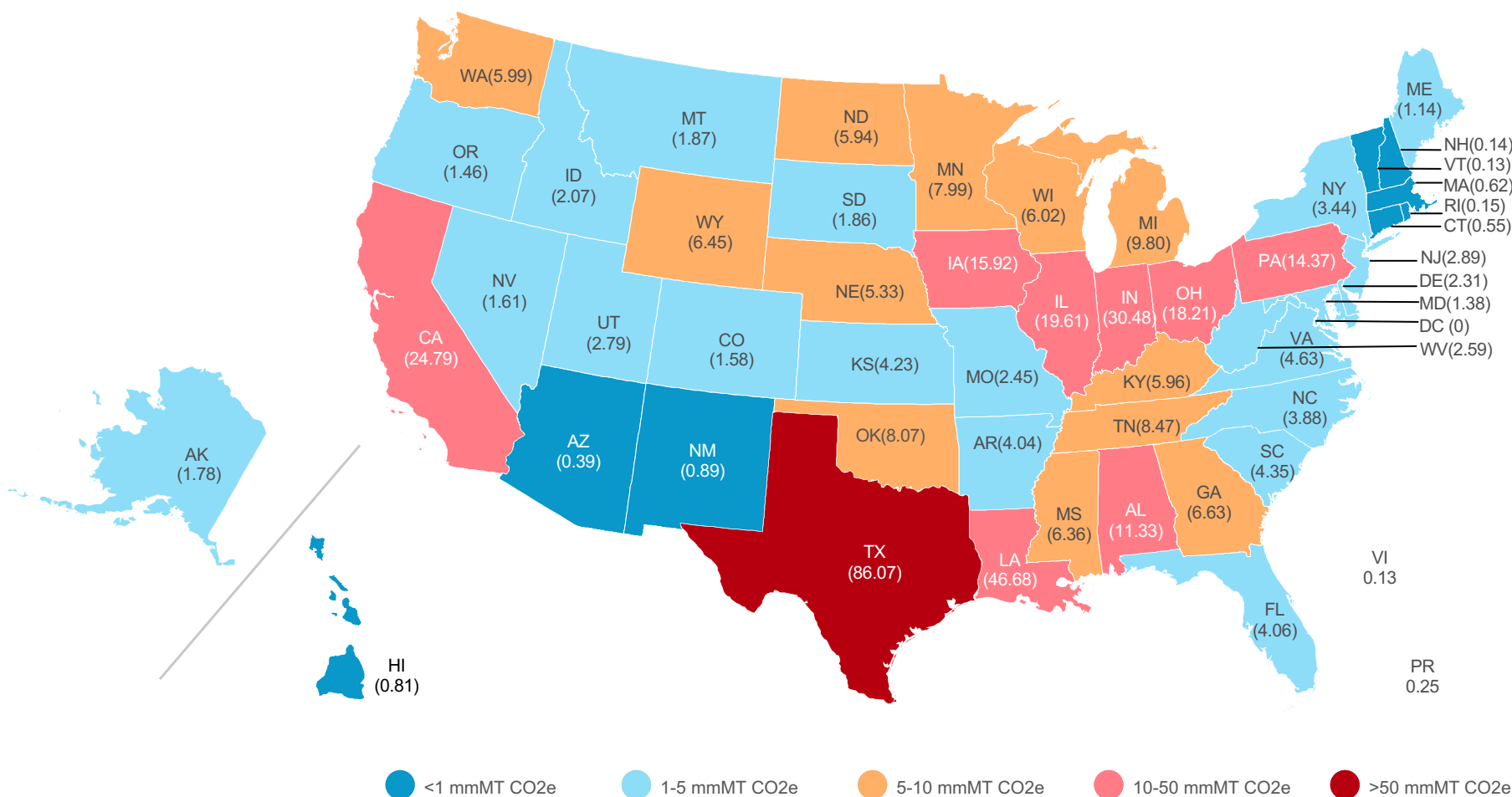
● High-temperature range (>500°C)





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

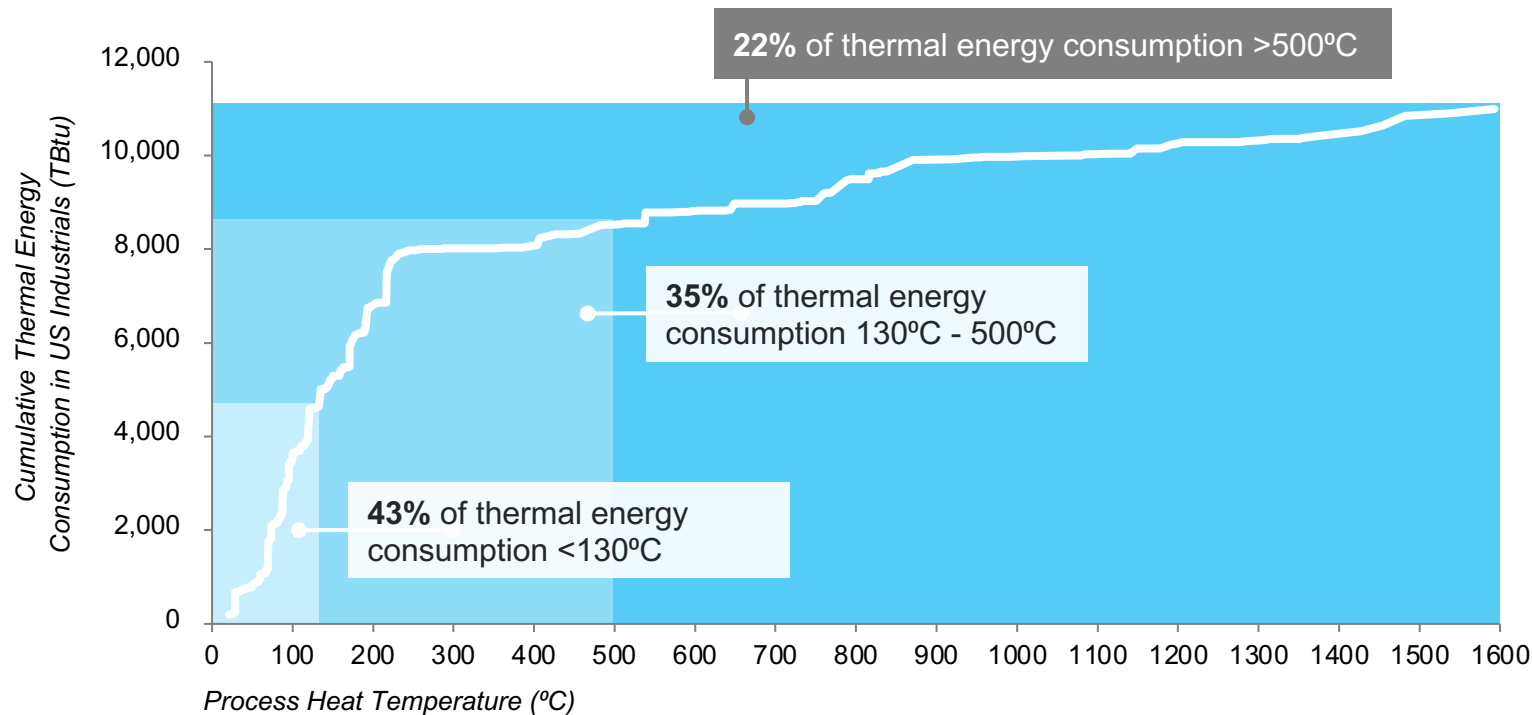




## US industrial thermal energy use

**78% of industrial heat is needed for low & medium heat applications (<500°C); only 22% is needed for high heat (>500°C)**

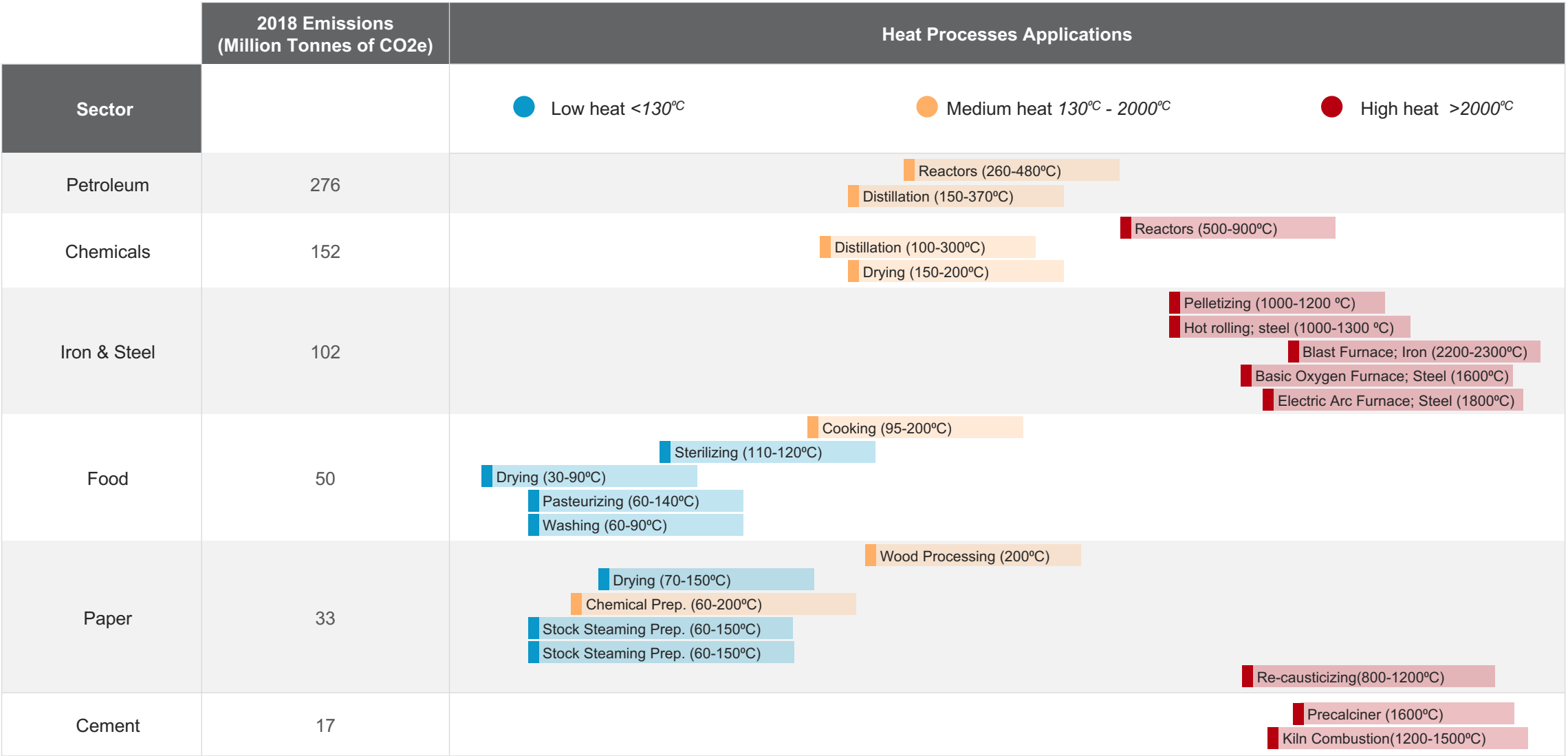
Industrial thermal energy consumption by heat temperature



- Low and medium heat applications are easier to convert to renewable thermal energy and abate emissions
- Electric heat pumps are effective under ~130°C and can target ~43% of industrial thermal energy use
- High heat processes (22% 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



# Most industrial sector applications occur at low & medium heat temperatures



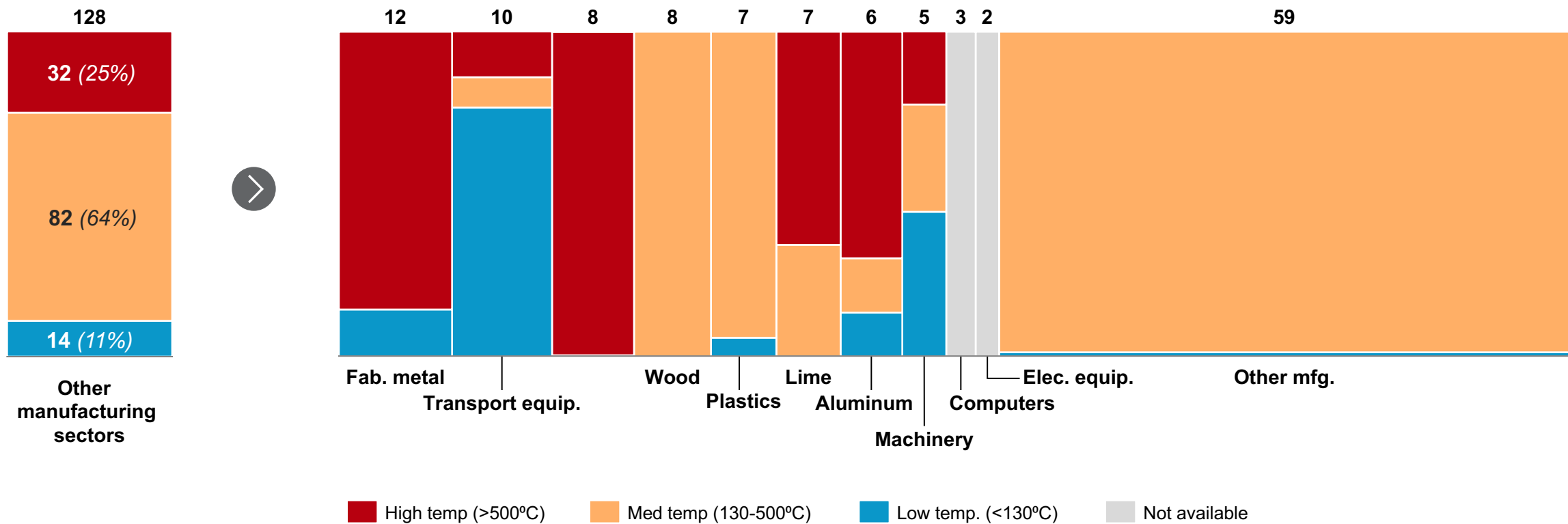
Source: DOE; research reports, papers, and studies; BCG analysis



# 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         | °C        | Low temp (42%)                  | Med temp (36%) | High temp (22%) |                     |
| Geothermal                           | 95        | ✓                               |                |                 | Low                 |
| Electric heat pump                   | 160       | ✓                               | ✓              | ✓               | Medium              |
| Nuclear <sup>1</sup>                 | 300+      |                                 | ✓              |                 | Low                 |
| Waste Biomass                        | 500       | ✓                               | ✓              | ✓               | Medium-High         |
| Solar thermal                        | 700       | ✓                               | ✓              | ✓               | Medium-High         |
| Electric resistance                  | 1,800     | ✓                               | ✓              | ✓               | Medium-High         |
| Electric arc heating <sup>2</sup>    | 1,800     |                                 |                | ✓               | Low                 |
| Power to gas <sup>3</sup>            | 1,950     | ✓                               | ✓              | ✓               | High                |
| Renewable natural gas                | 1,950     | ✓                               | ✓              | ✓               | High                |
| Electromagnetic heating <sup>2</sup> | 2,000     |                                 |                | ✓               | Low                 |
| Clean hydrogen                       | 2,100     | ✓                               | ✓              | ✓               | High                |
| Biodiesel                            | 2,200     | ✓                               | ✓              | ✓               | Low                 |
| Bioethanol                           | 2,200     | ✓                               | ✓              | ✓               | Low                 |
| Thermal energy storage <sup>4</sup>  | 1,500     | ✓                               | ✓              | ✓               | Medium-High         |
| CCS                                  | -         | ✓                               | ✓              | ✓               | Medium-High         |



High applicability



Moderate applicability

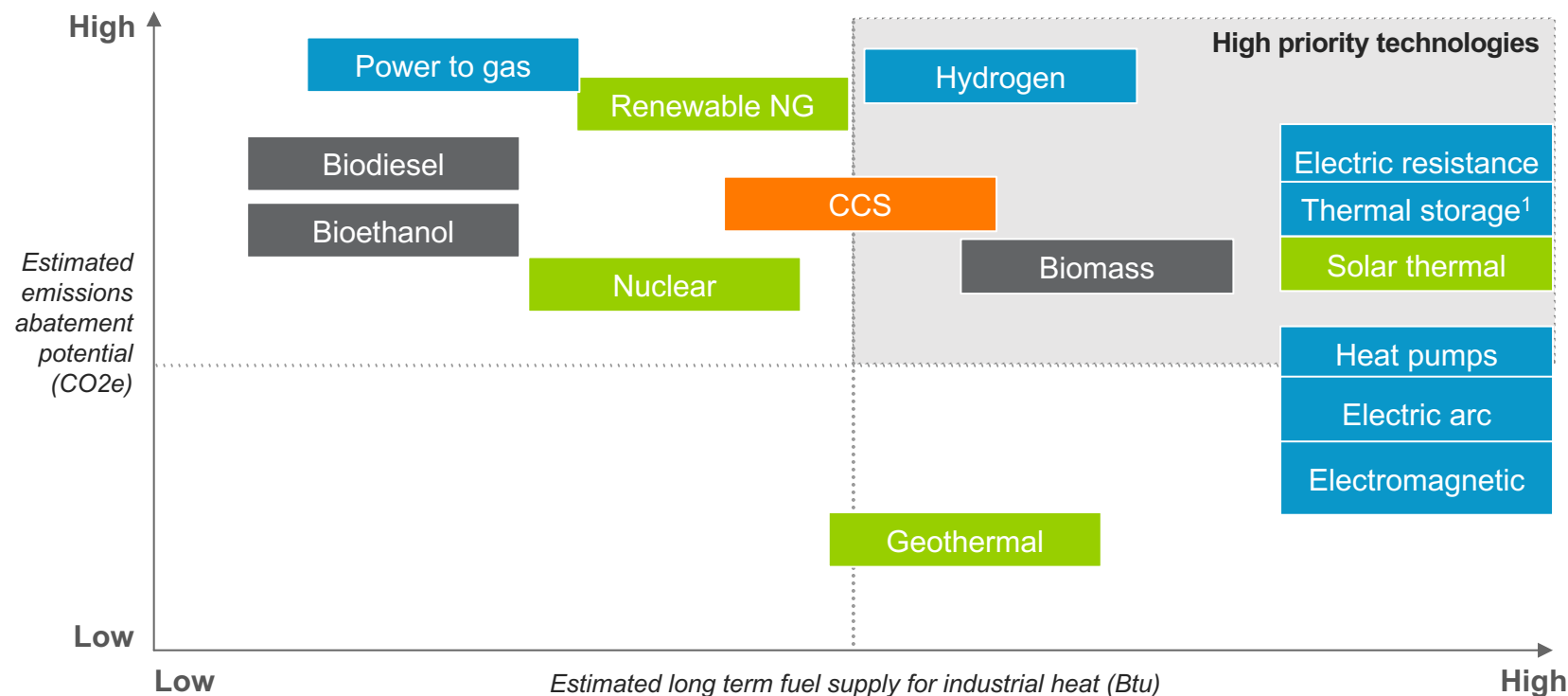
- RNG and hydrogen can serve nearly all industrial heat applications, and can largely be deployed within current natural gas infrastructure
- Electric heat pumps can serve low temperature applications representing 42% of thermal energy use
- Waste biomass and solar thermal technologies can serve low 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 CO<sub>2</sub>e concentration in the emissions stream

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

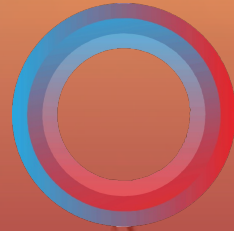


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# Cement

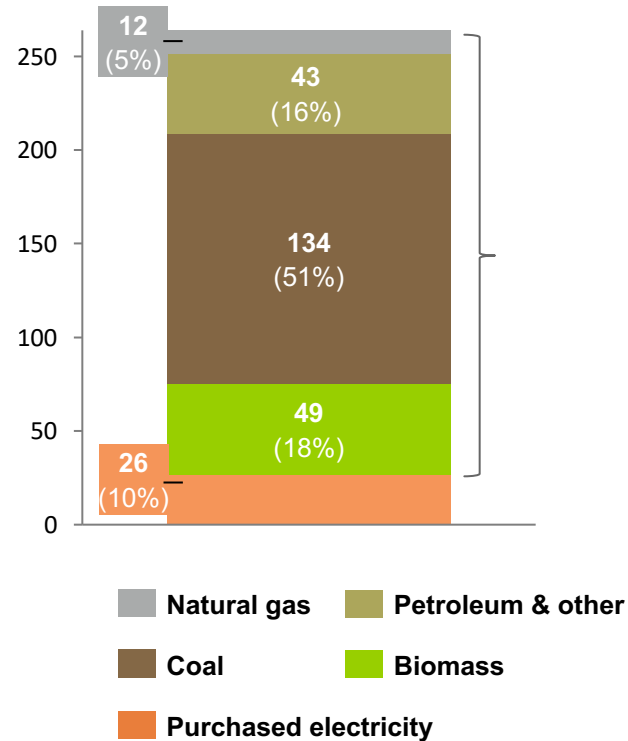
Sector Perspectives



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

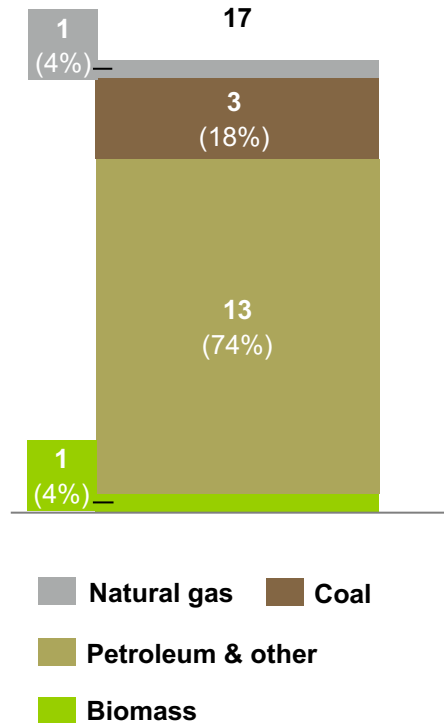
Total energy consumption (2018)<sup>1</sup>

Trillion Btu



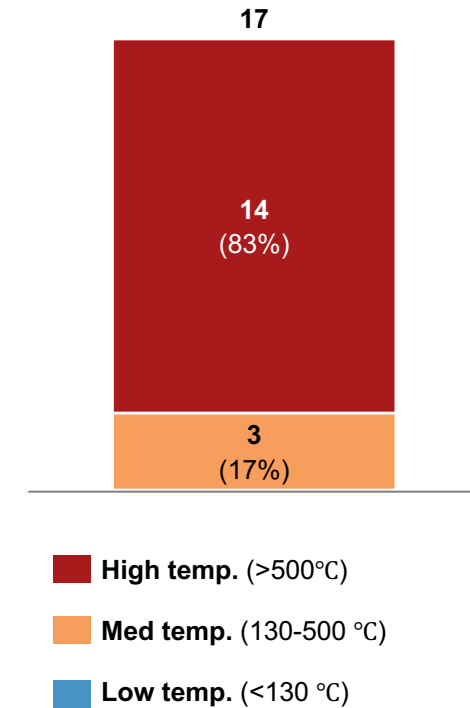
Thermal emissions (2018)<sup>2</sup>

Million Tonnes of CO<sub>2</sub>e



Estimated thermal emissions by process temperature (2018)<sup>3</sup>

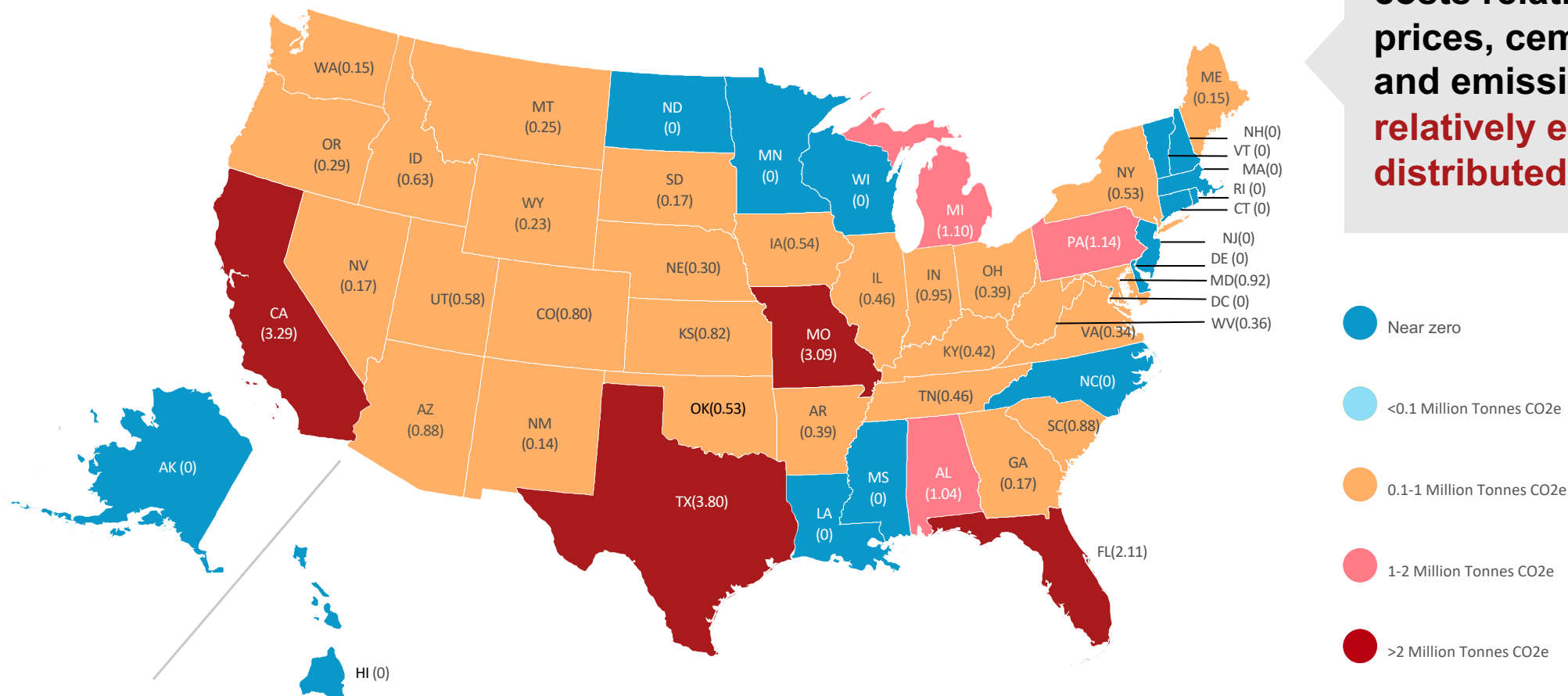
Million Tonnes of CO<sub>2</sub>e



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 CO<sub>2</sub>e/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

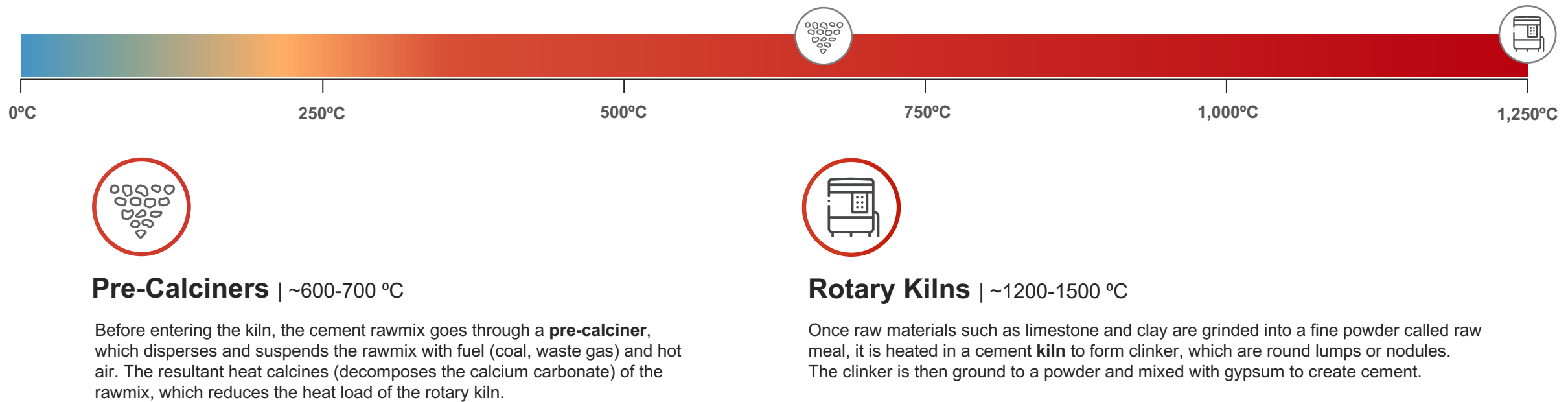
## Cement thermal emissions by state (Million Tonnes of CO<sub>2</sub>e)<sup>1</sup>



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

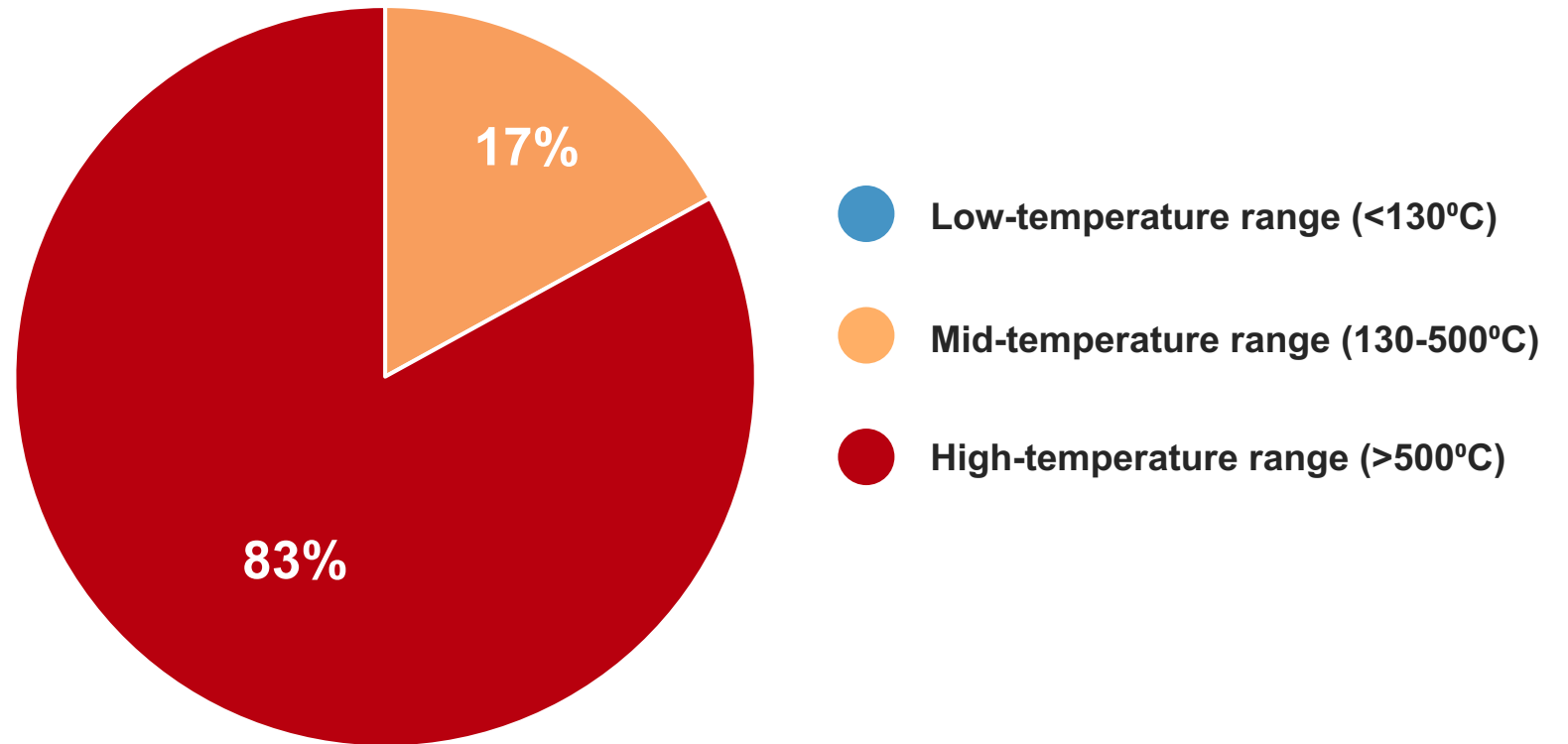
1. EPA GHGRP Inventory FLIGHT Database (2018); captures actual onsite reported emissions for large emitters emitting >25K tonnes of CO<sub>2</sub>e/year

# Key thermal applications in cement manufacturing occur at high temperatures



**83% of thermal emissions are produced at high temperatures**

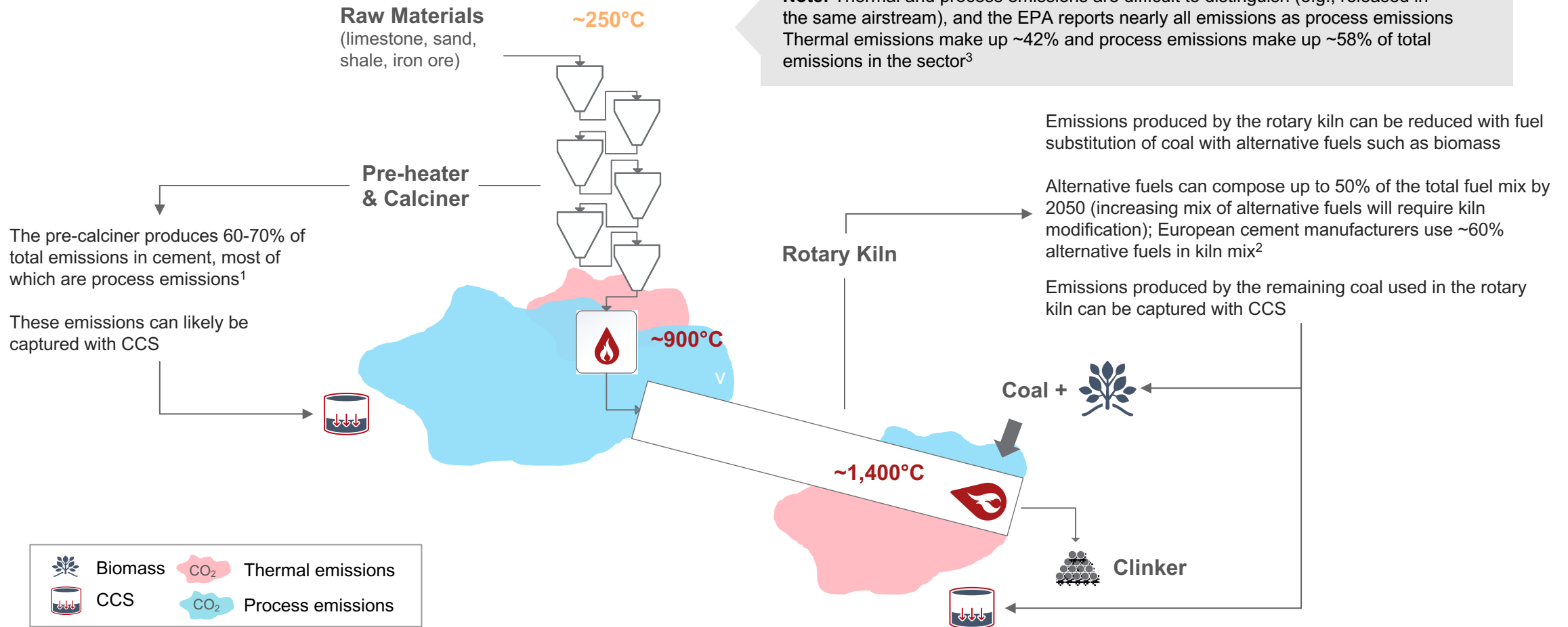
**Thermal energy consumption (TBtu) by heat temperature range (°C)<sup>1</sup>**



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<sup>3</sup>

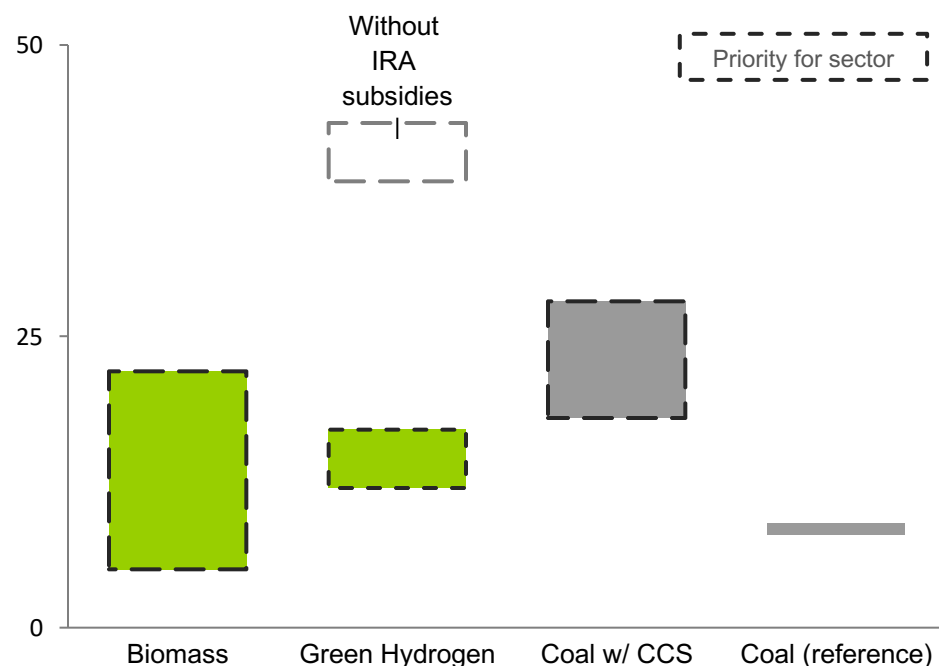




# Biomass & green H2 appear most economic renewable-fuel alternatives

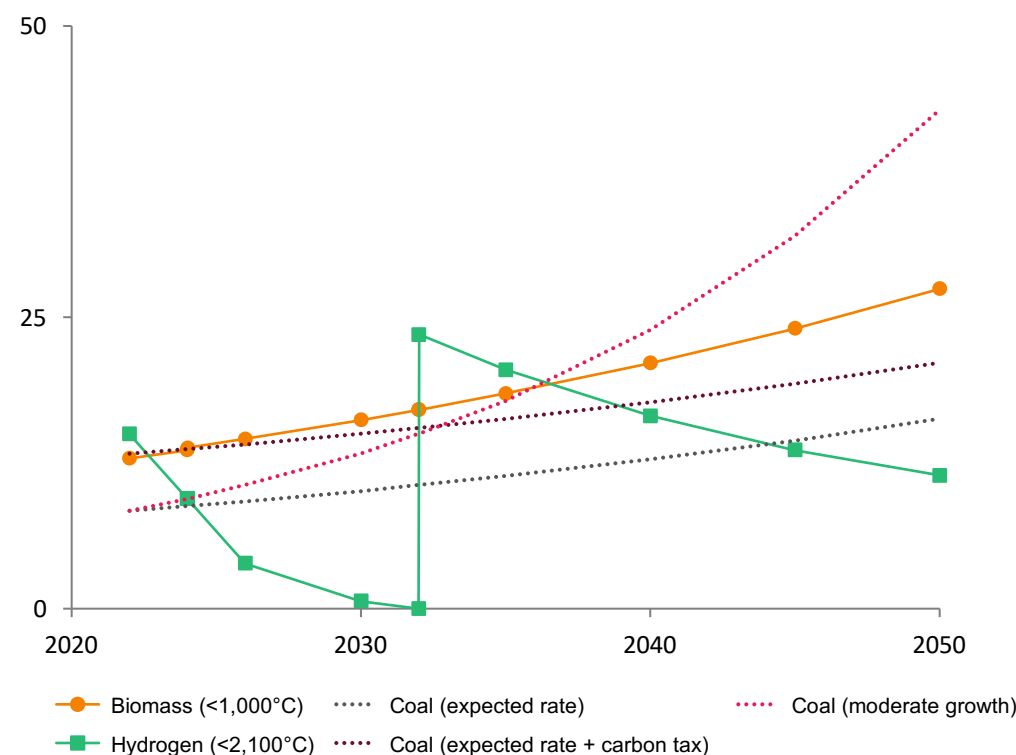
## 2022 LCOH for relevant technologies<sup>1</sup>

(\$/MMBtu)



## Projected LCOH for relevant technologies<sup>1</sup>

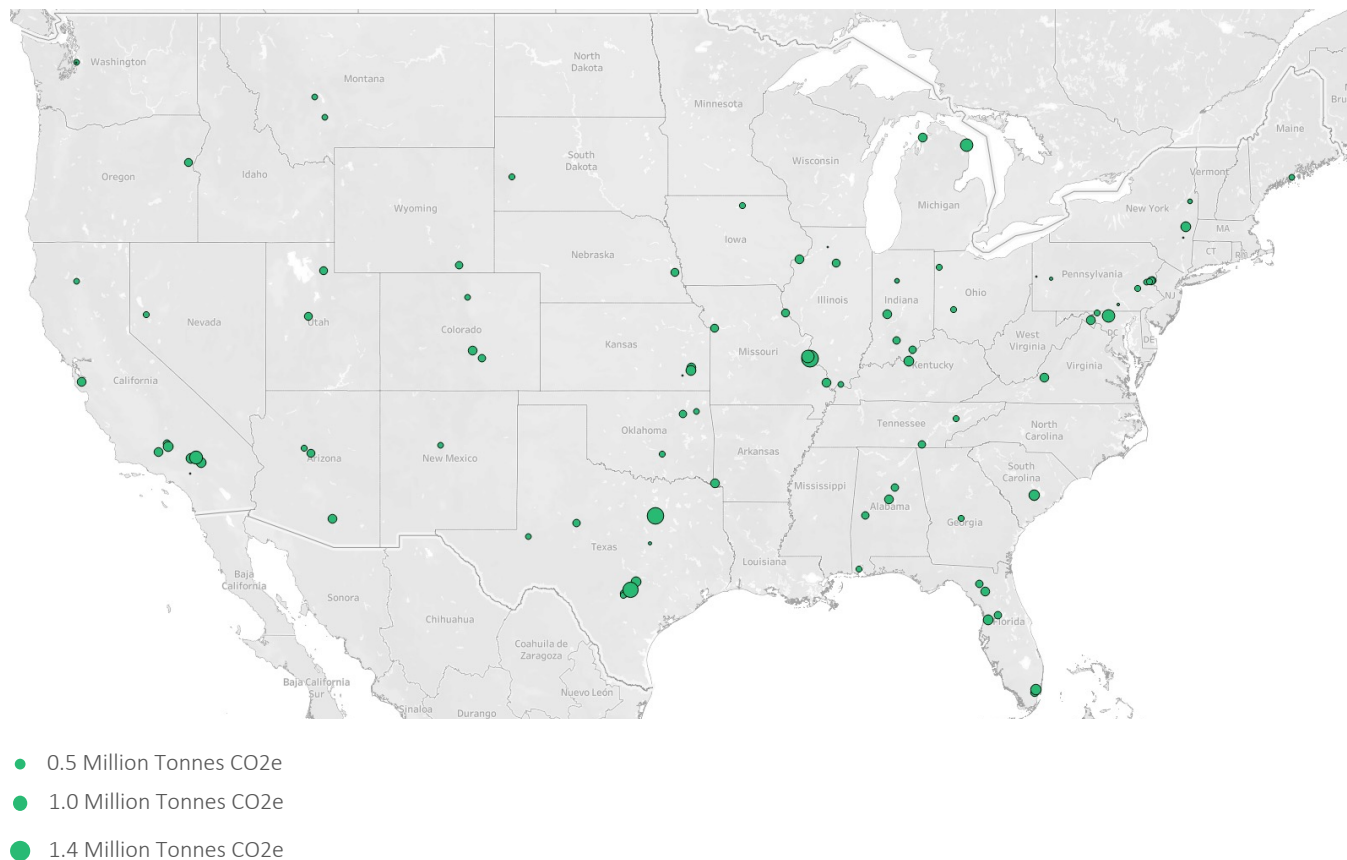
Average US LCOH (\$/MMBtu)



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

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

## US Cement thermal emissions by zip code<sup>1</sup>

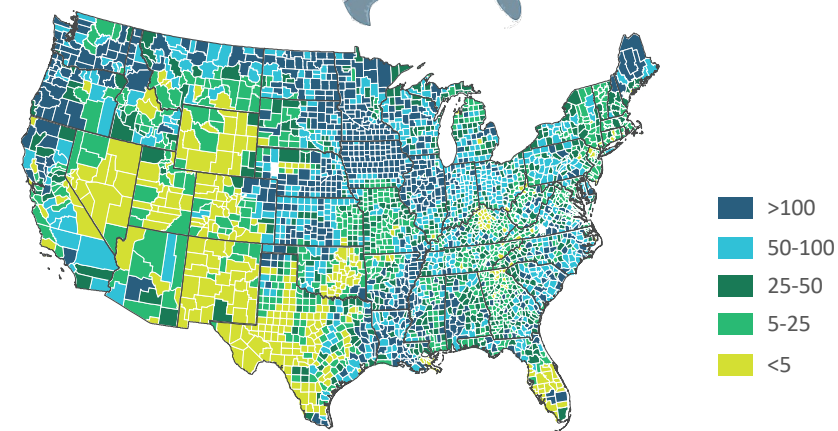


1. EPA GHGRP Inventory FLIGHT Database (2018); captures actual onsite reported emissions for large emitters emitting >25K tonnes of CO<sub>2</sub>e per year 2. USGS, NETL NATCAB 3. NREL Biofuels Atlas 4. CSIS (2022)

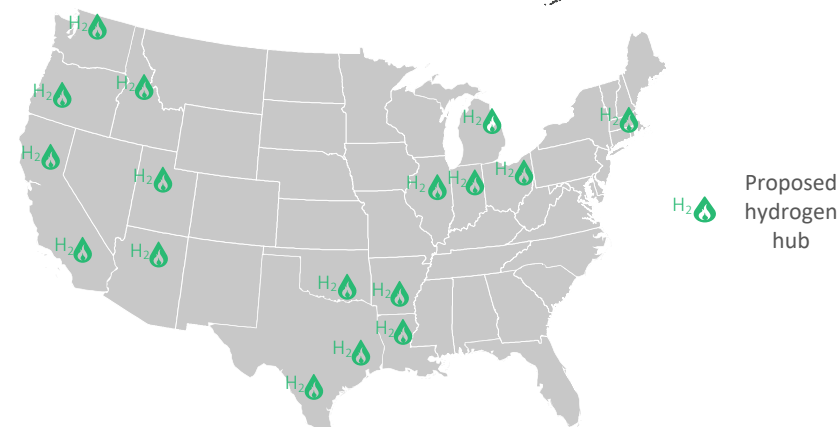
Carbon sequestration  
availability<sup>2</sup>



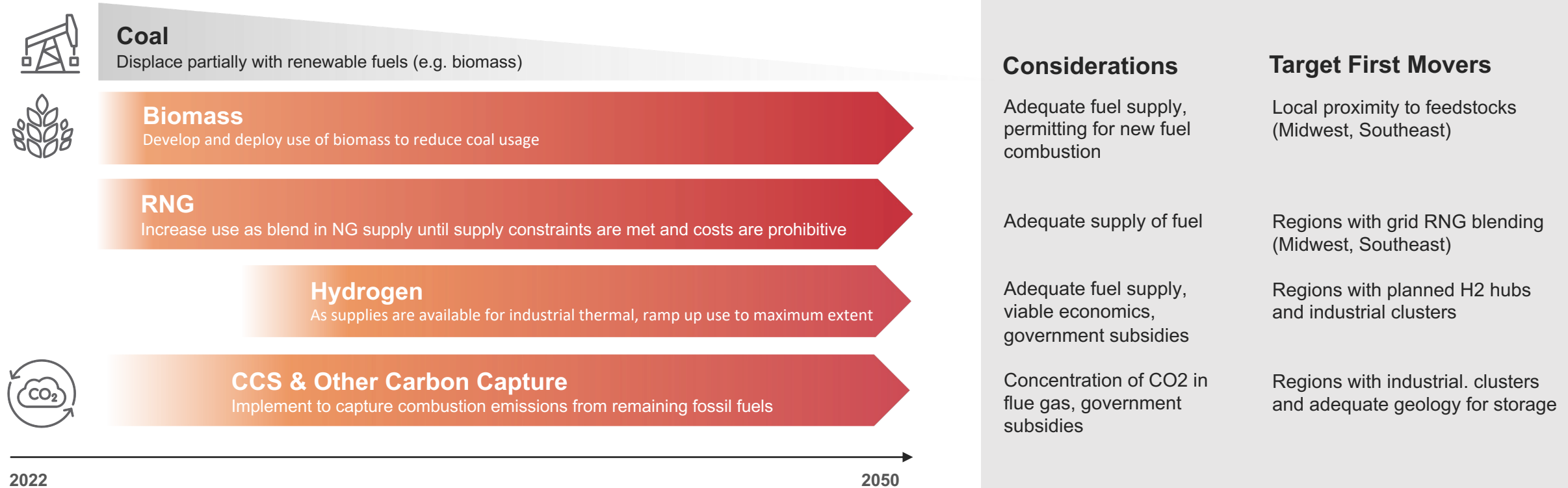
Biomass supply<sup>3</sup>



Proposed  
hydrogen hubs<sup>4</sup>



# Decarbonization pathways



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

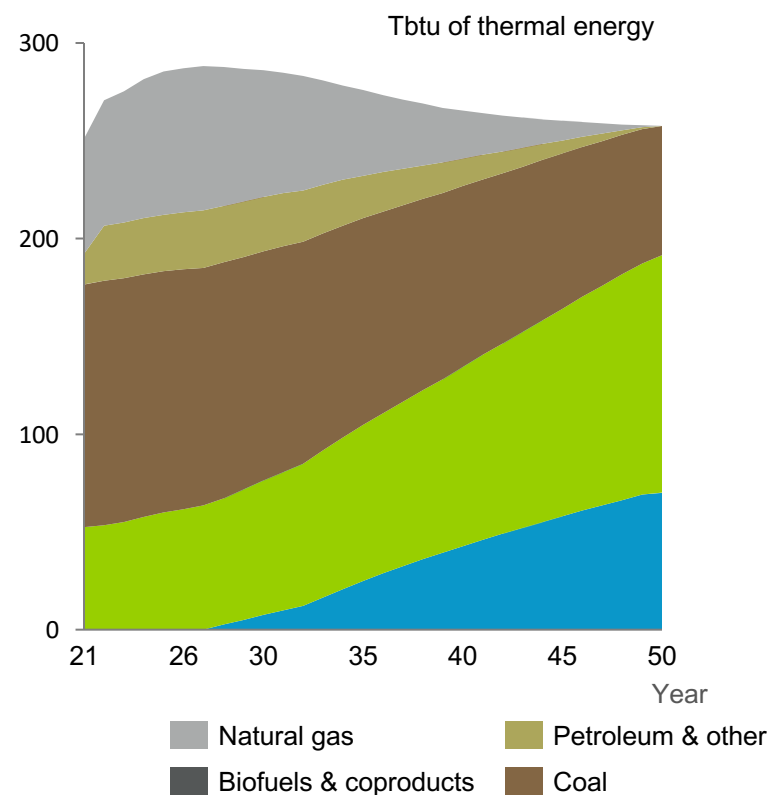
The Cement sector creates more process emissions than thermal emissions, and both emissions are typically emitted in the same air stream. As a result, **it is difficult to distinguish between process and thermal emissions** and the EPA GHGRP flight database does not identify meaningful thermal emissions.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

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

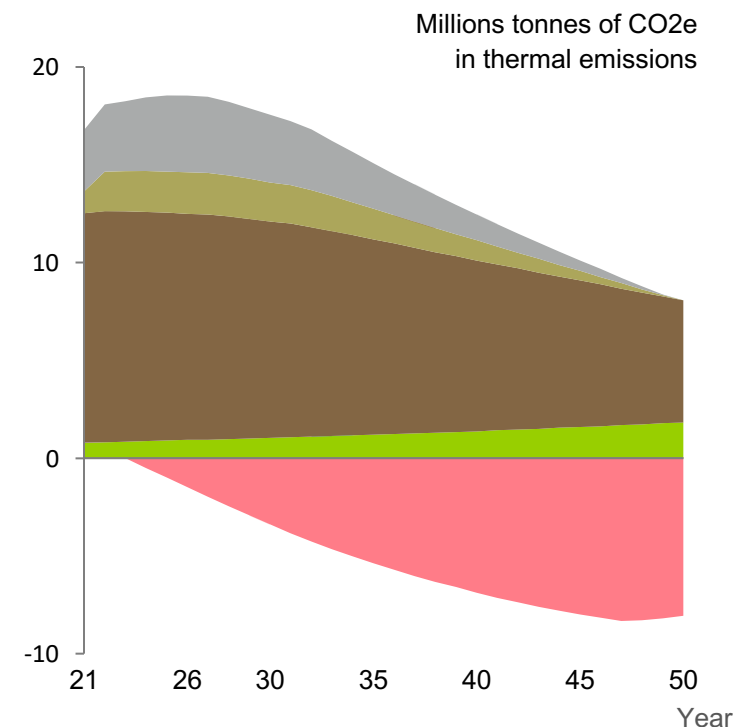
Heavy emitting coal, which is used for heat and as feedstock in the rotary kiln, can be **partially displaced with biomass**, which can compose up to 50% of the total rotary kiln mix by 2050; some European cement manufacturers are using ~60% alternative fuels in their rotary kiln mix (displacing ~40%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

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<sup>1</sup>



## Thermal emissions<sup>2</sup>



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 CO<sub>2</sub>e 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

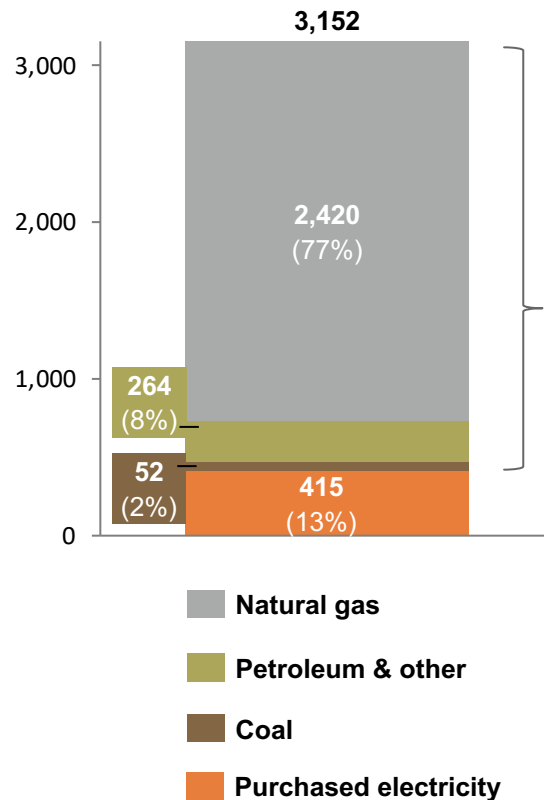
Sector Perspectives



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

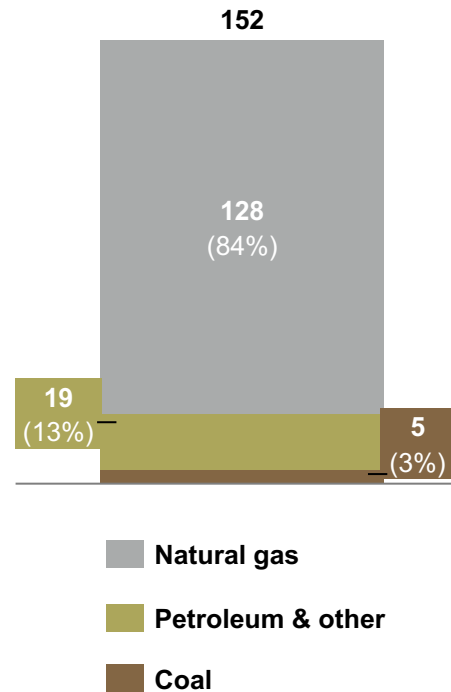
## Total energy consumption (2018)<sup>1</sup>

Trillion Btu



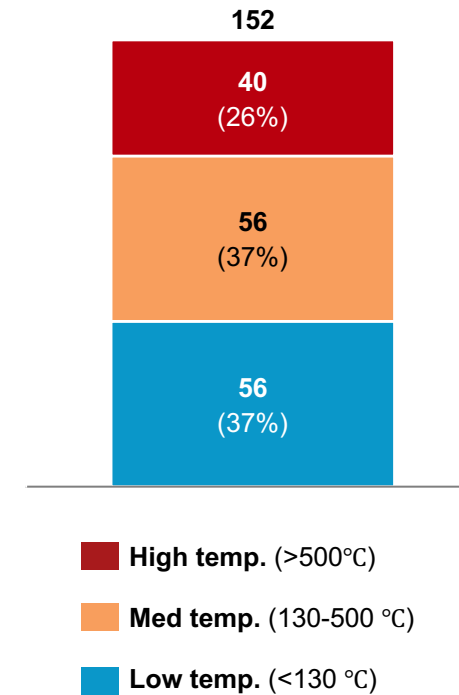
## Thermal emissions (2018)<sup>2</sup>

Million Tonnes of CO<sub>2</sub>e



## Estimated thermal emissions by process temperature (2018)<sup>3</sup>

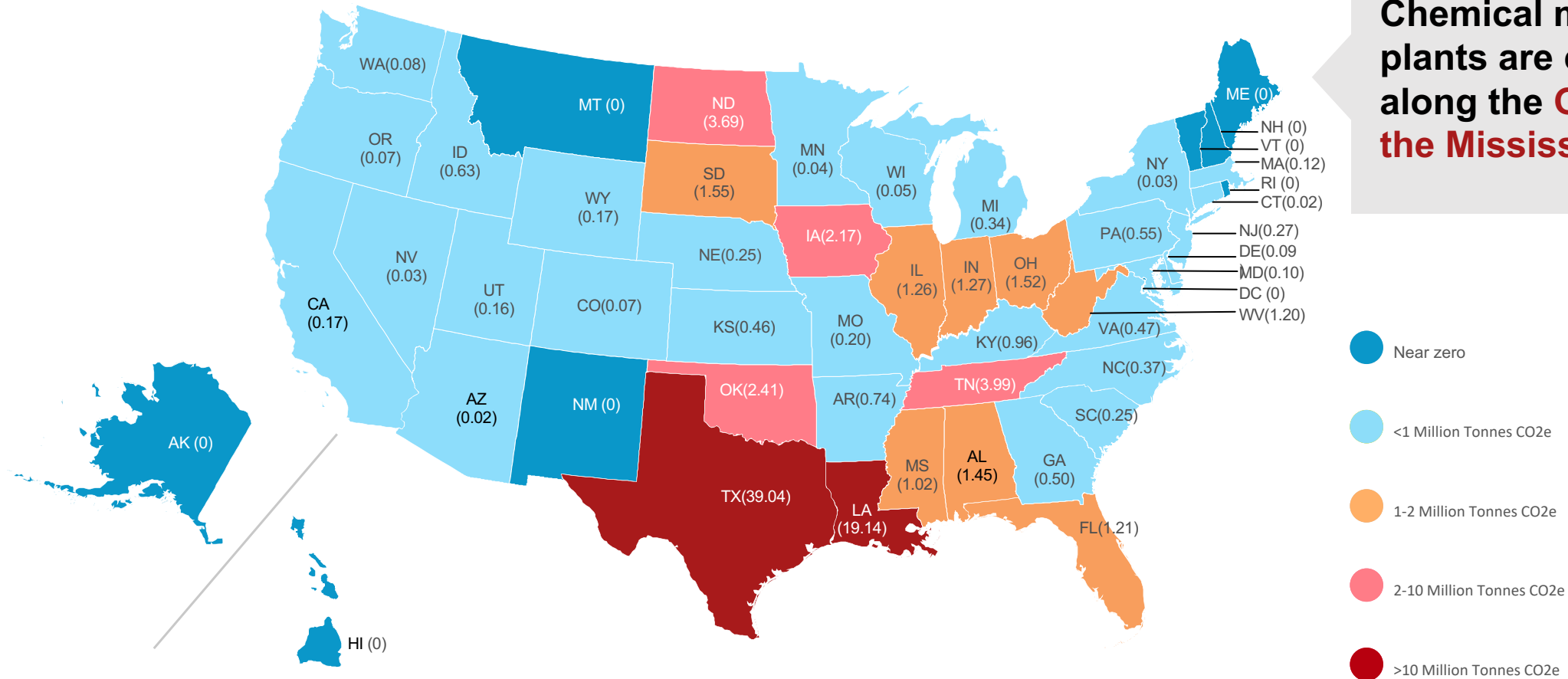
Million Tonnes of CO<sub>2</sub>e



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 CO<sub>2</sub>e/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 CO<sub>2</sub>e)<sup>1</sup>



1. EPA GHGRP Inventory FLIGHT Database (2018); captures actual onsite reported emissions for large emitters emitting >25K tonnes of CO<sub>2</sub>e/year

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



### **Drying** | ~150-200 °C

**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 °C

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.

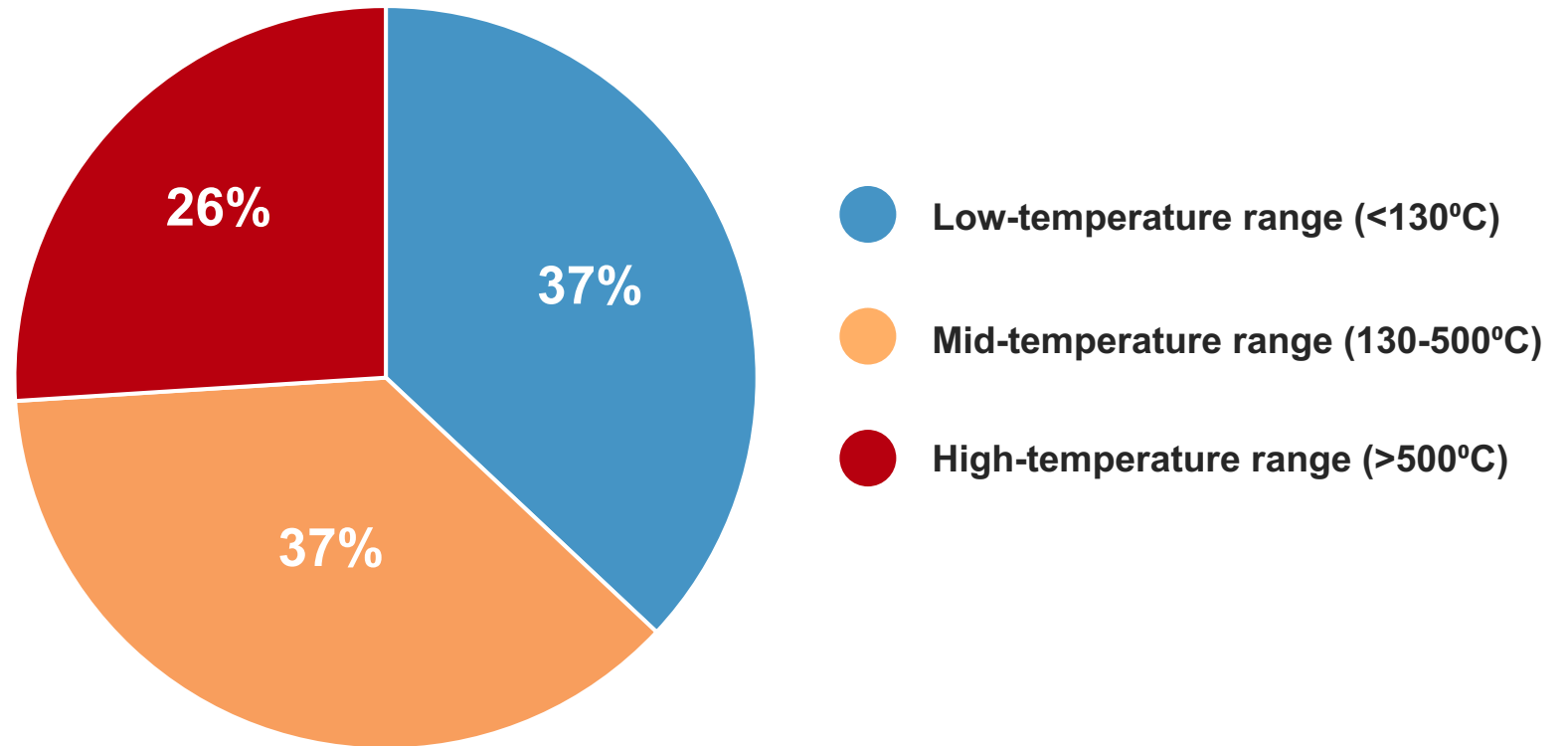


### **Reactors** | ~500-900 °C

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.

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

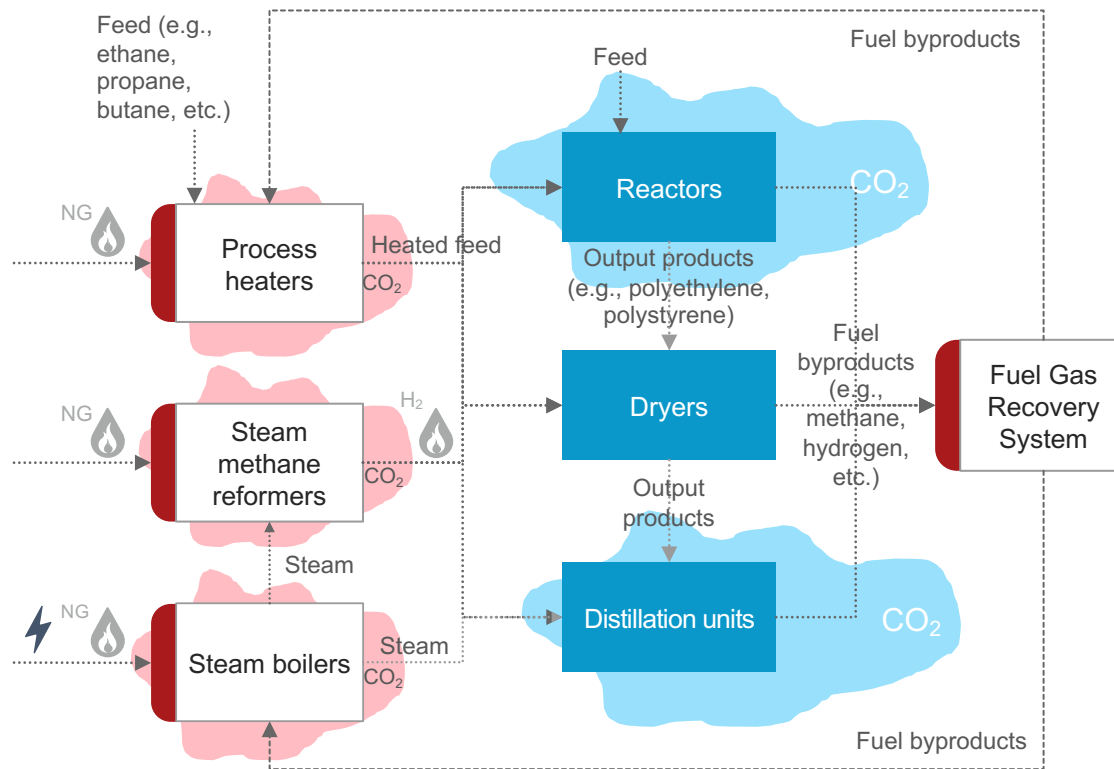
**Thermal energy consumption (TBtu) by heat temperature range (°C)<sup>1</sup>**



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



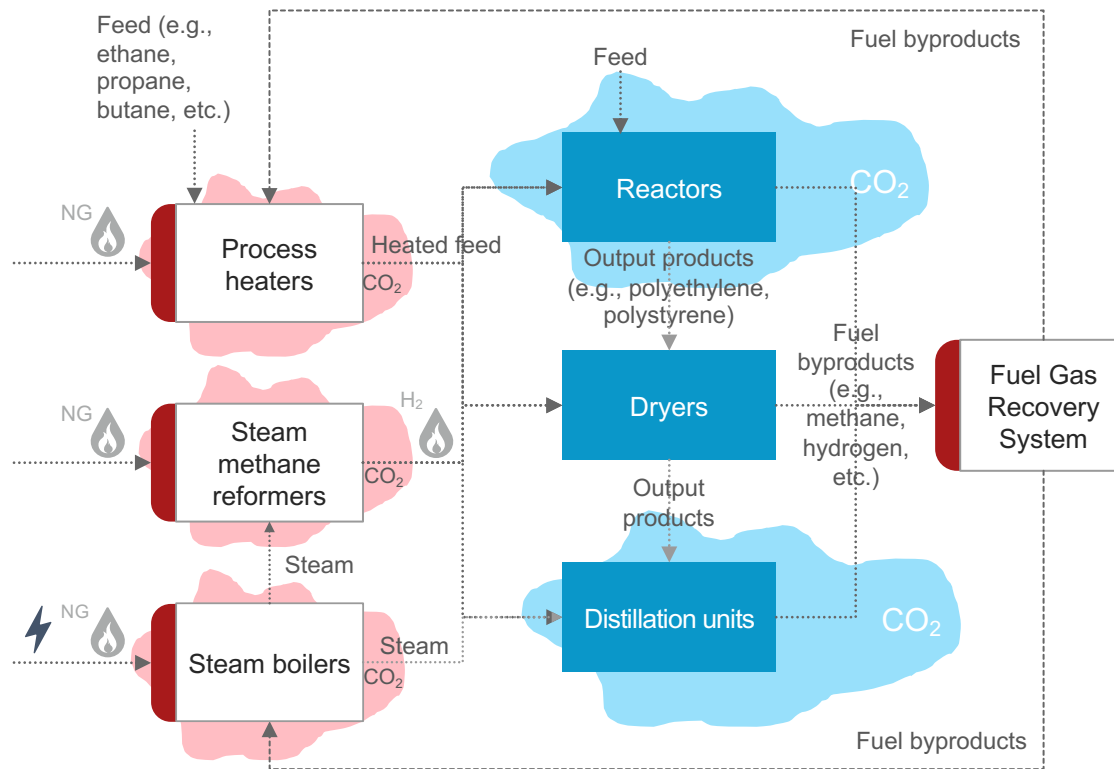
- Chemical facilities typically use process heaters and steam boilers that burn natural gas to create steam heat, which is moved around the facility through a steam network system distributing heated steam to thermal applications
- Natural gas is also used in steam methane reformers to produce hydrogen, which is used as a feedstock in thermal applications
- Process heaters, steam boilers, and steam methane reformers (SMR) release CO<sub>2</sub>e thermal emissions representing ~45% of total onsite emissions
- The heat applications (e.g. reactors, distillation units) release CO<sub>2</sub>e 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<sub>2</sub> Fuel source CO<sub>2</sub> Thermal emissions CO<sub>2</sub> Process emissions

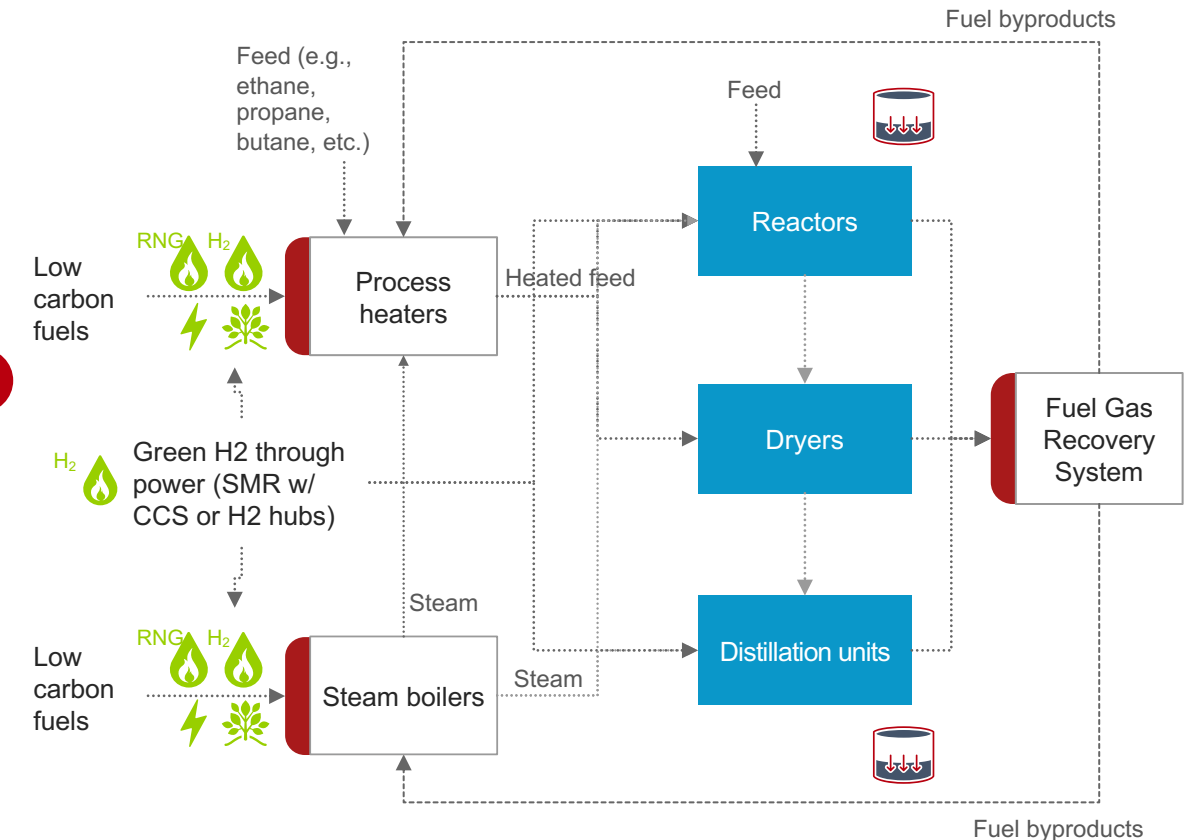


# Electrification and low carbon fuels can reduce thermal emissions; CCS is likely needed to capture the larger process emissions

Typical chemical plant processes today

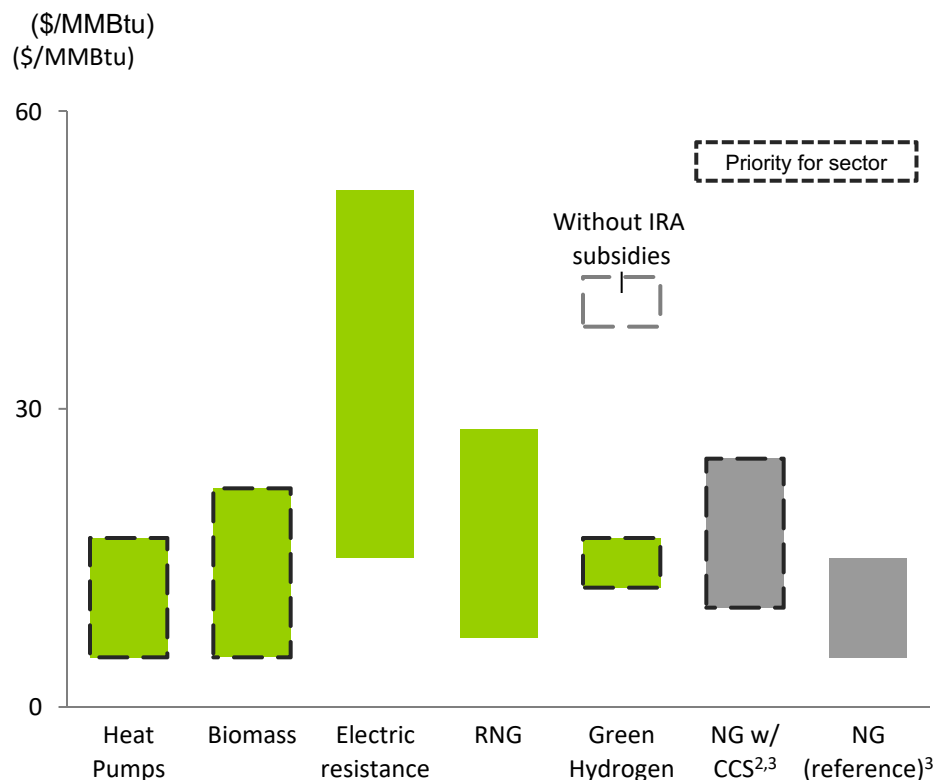


Chemical plant with renewable thermal + CCS



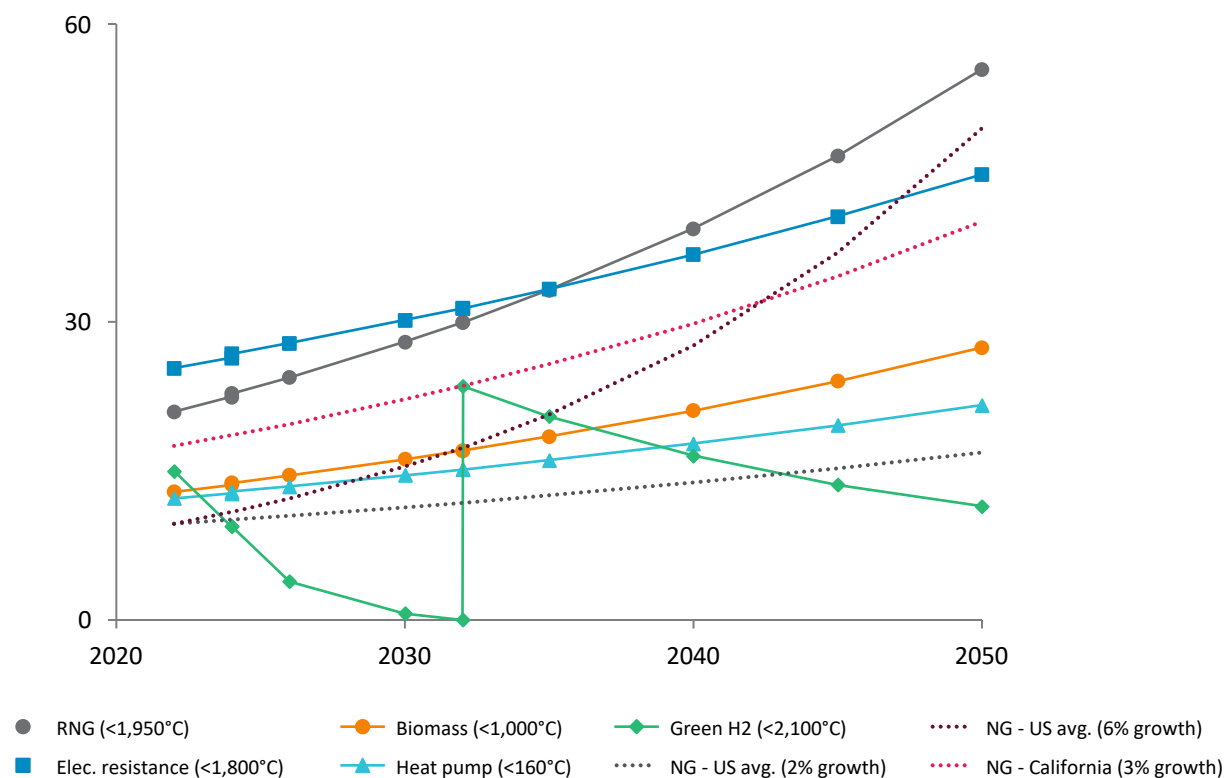
# Heat pumps, biomass and green H2 are most economic renewable fuel alternatives to natural gas, and have lower cost of heat than NG w/ CCS

## 2022 LCOH for relevant technologies<sup>1</sup>



## Projected LCOH for relevant technologies<sup>1</sup>

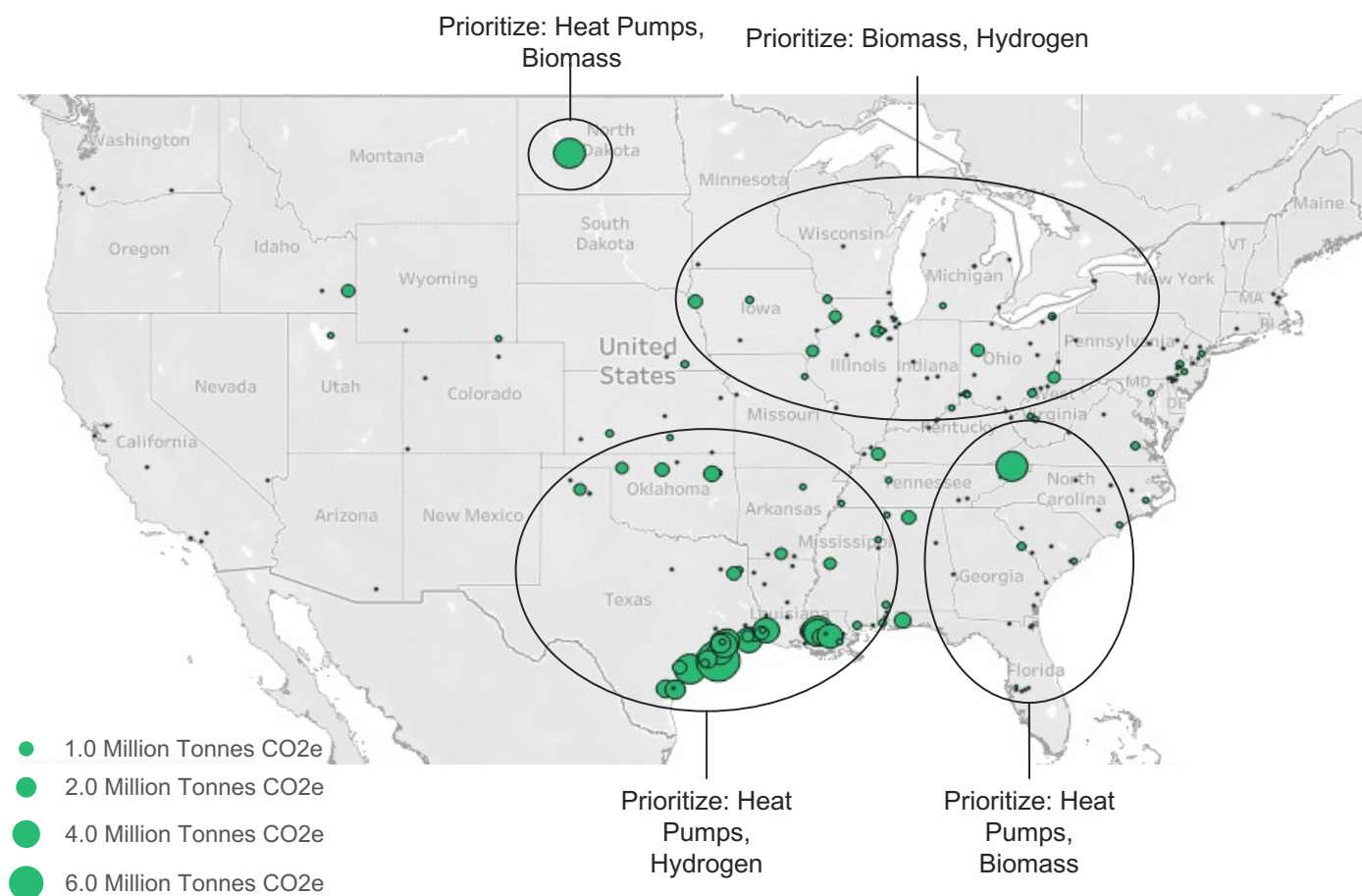
Average US LCOH (\$/MMBtu)



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

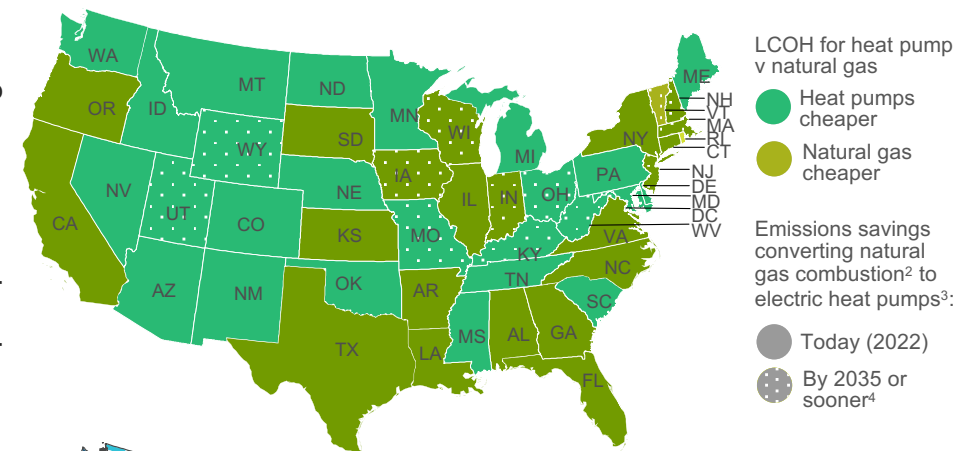
# Hydrogen, biomass, and heat pumps are available in heavy-emissions areas

## US Chemicals sector thermal emissions by zip code<sup>1</sup>

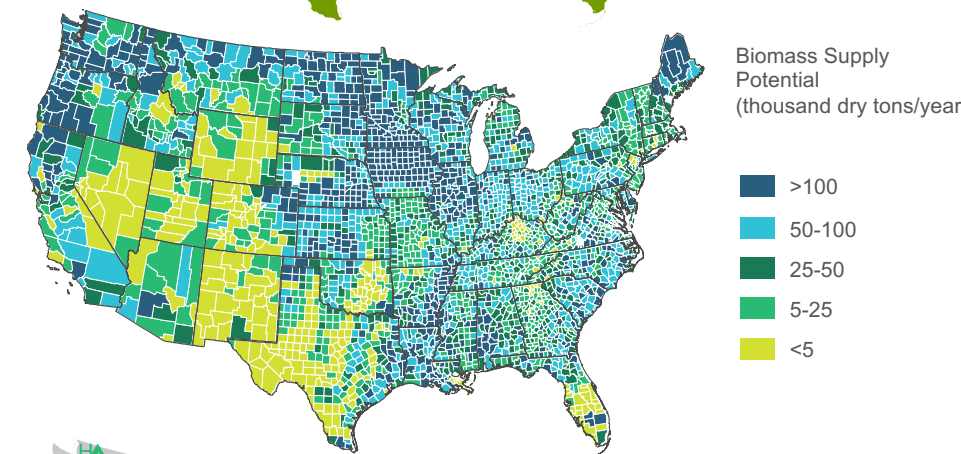


1. EPA GHGRP Inventory FLIGHT Database (2018); captures actual onsite reported emissions for large emitters emitting >25k tonnes of CO<sub>2</sub>e per year 2. USGS, NETL NATCAB 3. CSIS (2022)

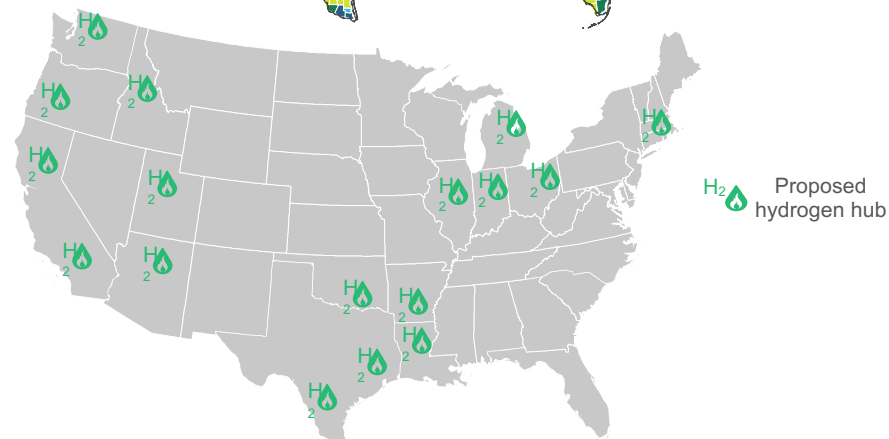
## Heat pumps v. Natural gas<sup>2,4</sup>



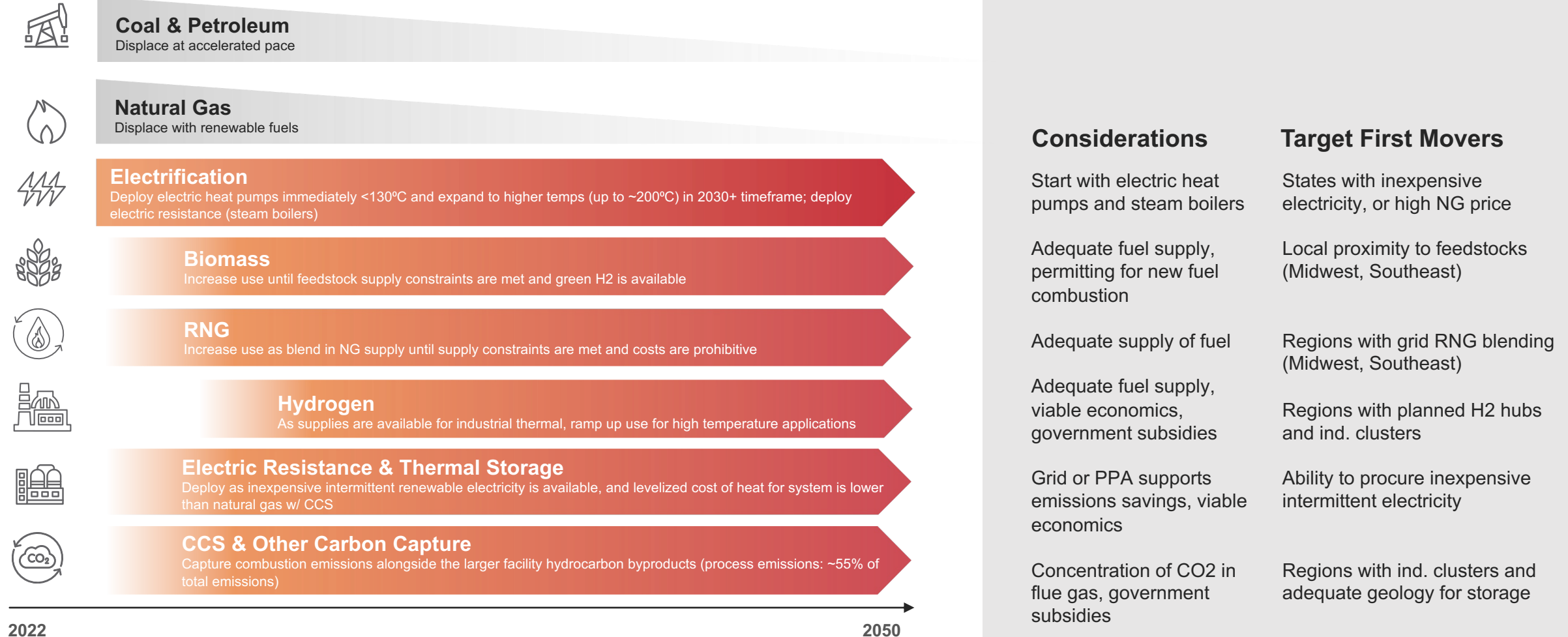
## Biomass supply<sup>3</sup>



## Proposed hydrogen hubs<sup>4</sup>



# Decarbonization pathways



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

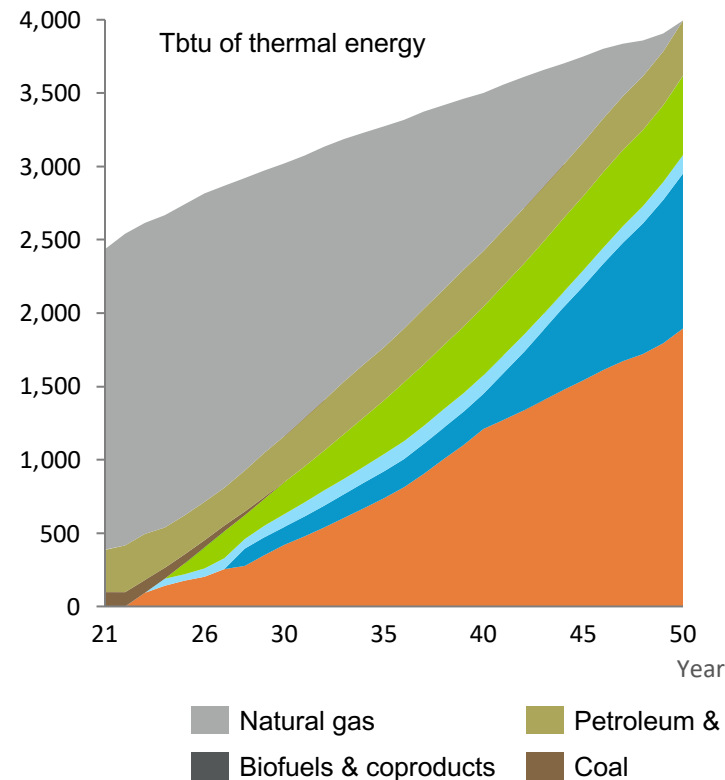
## Use of fossil natural gas is eliminated through 2050

**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)

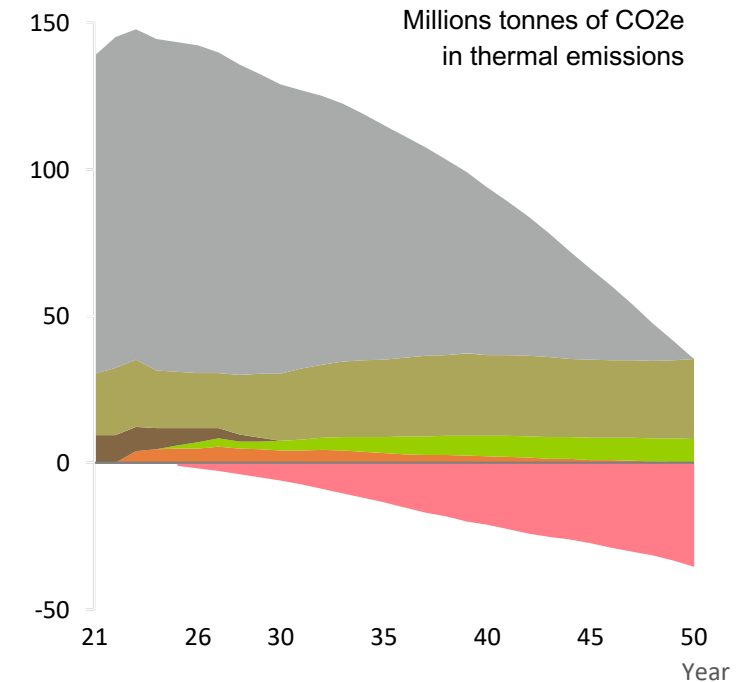
**Electrification** of low and medium temperature applications is deployed beginning immediately; electric grid emissions intensity is lower than fossil NG for heat pumps in nearly all states today; can be deployed against <130°C processes representing ~37% of total thermal emissions in the sector. As heat pumps improve to ~200°C, 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<sup>1</sup>



## Thermal emissions<sup>2</sup>



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 CO<sub>2</sub>e 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





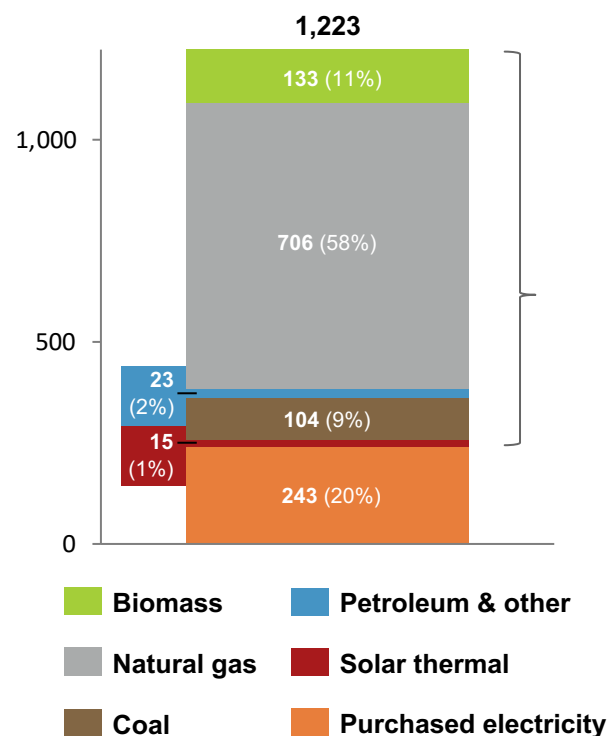
# Food

Sector Perspectives

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

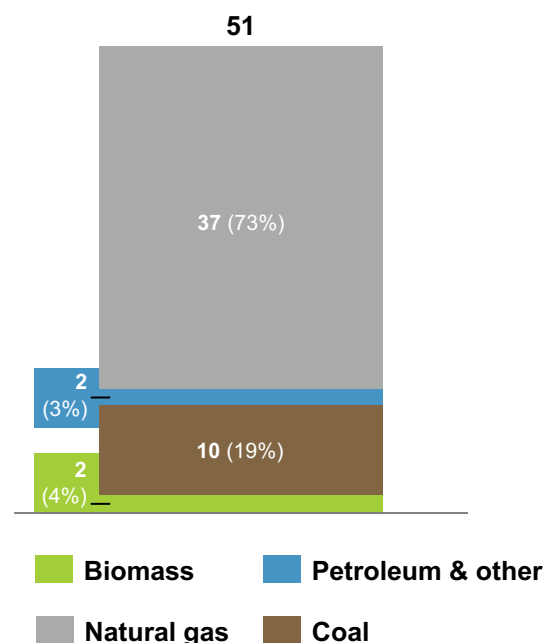
**Total energy consumption (2018)<sup>1</sup>**

Trillion Btu



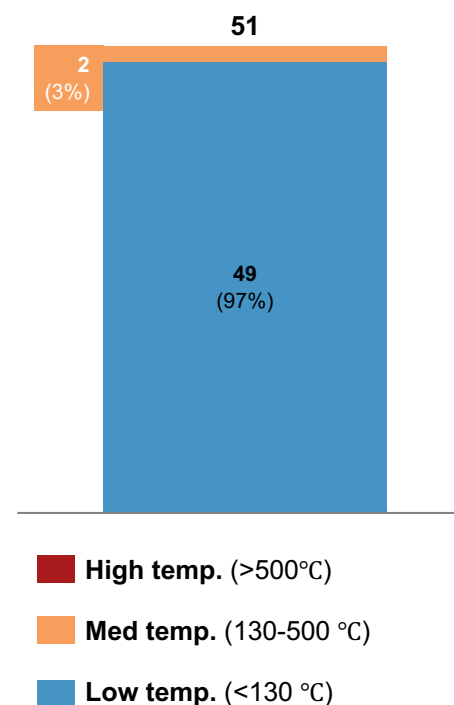
**Thermal emissions (2018)<sup>2</sup>**

Million Tonnes of CO<sub>2</sub>e



**Estimated thermal emissions by process temperature (2018)<sup>3</sup>**

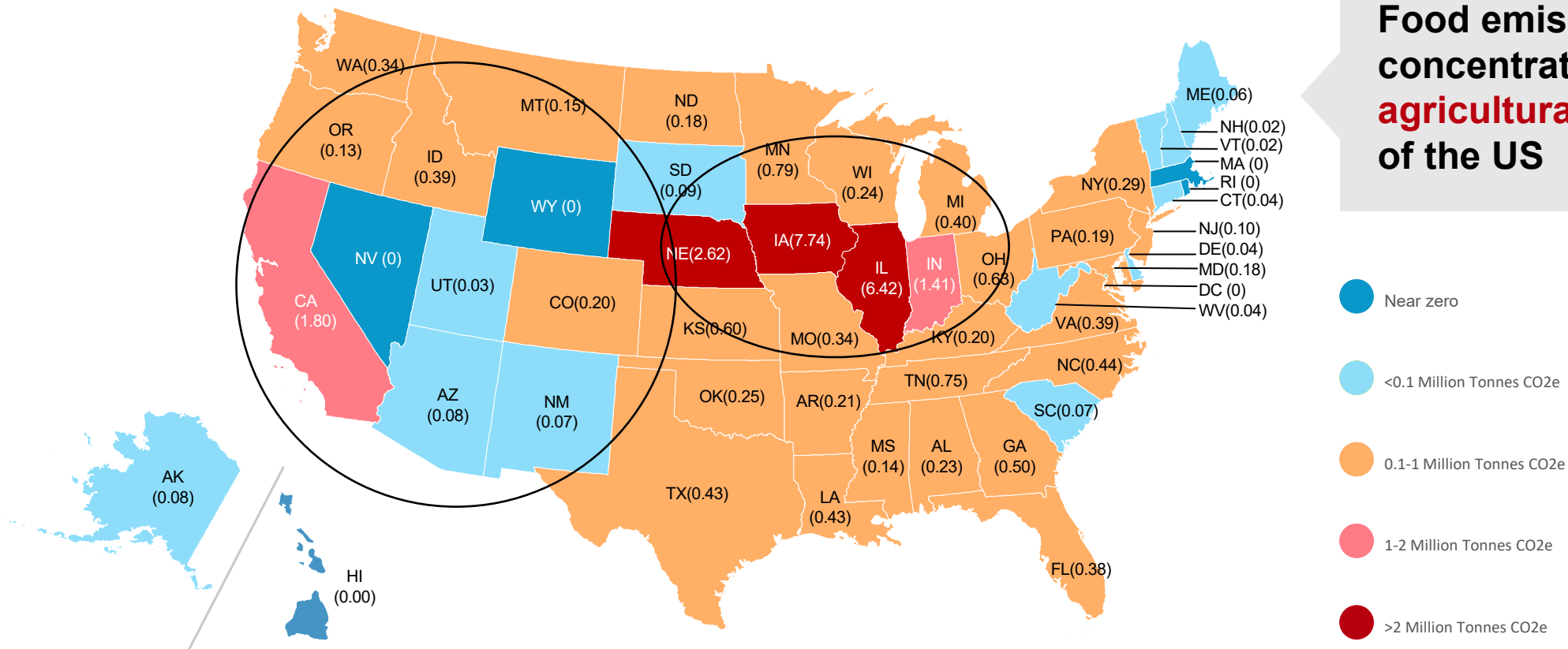
Million Tonnes of CO<sub>2</sub>e



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 CO<sub>2</sub>e/mmBtu 3. Calculated using the NREL MECS survey data for thermal energy use (2014) Source: EIA; EPA; NREL; BCG analysis

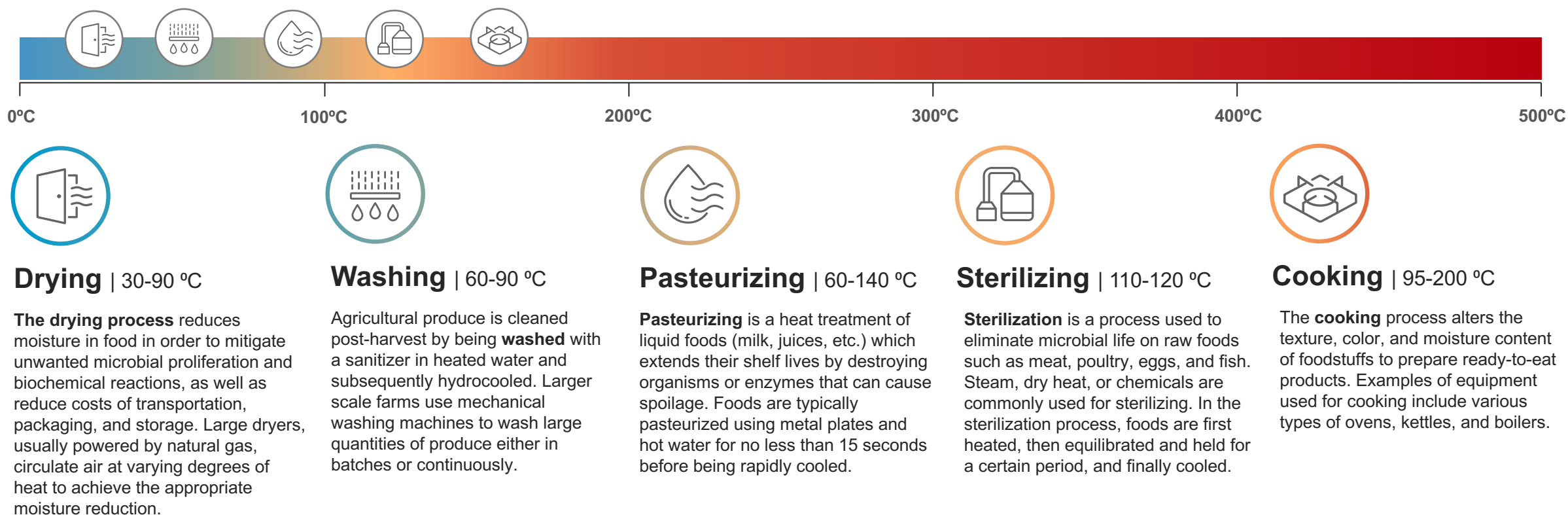
# Thermal emissions are concentrated in the Midwest and California

Food thermal emissions by state (Million Tonnes of CO<sub>2</sub>e)<sup>1</sup>



1. EPA GHGRP Inventory FLIGHT Database (2018); captures actual onsite reported emissions for large emitters emitting >25K tonnes of CO<sub>2</sub>e/year

# Key heat applications occur in the low and medium temperature ranges

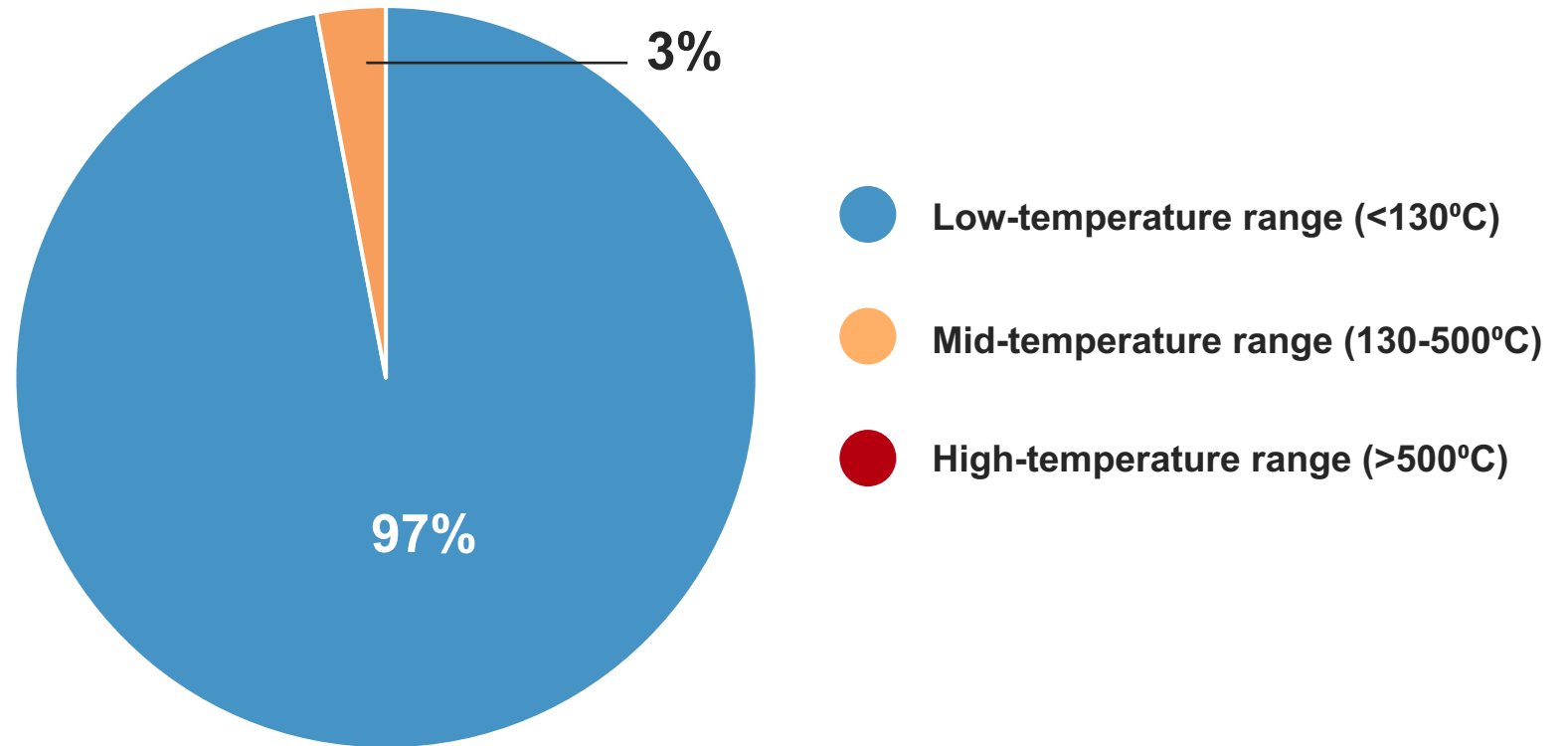


**Low temperature heat processes are well suited for electrification in the immediate, mid, and long term**



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

**Thermal energy consumption (TBtu) by heat temperature range (°C)<sup>1</sup>**



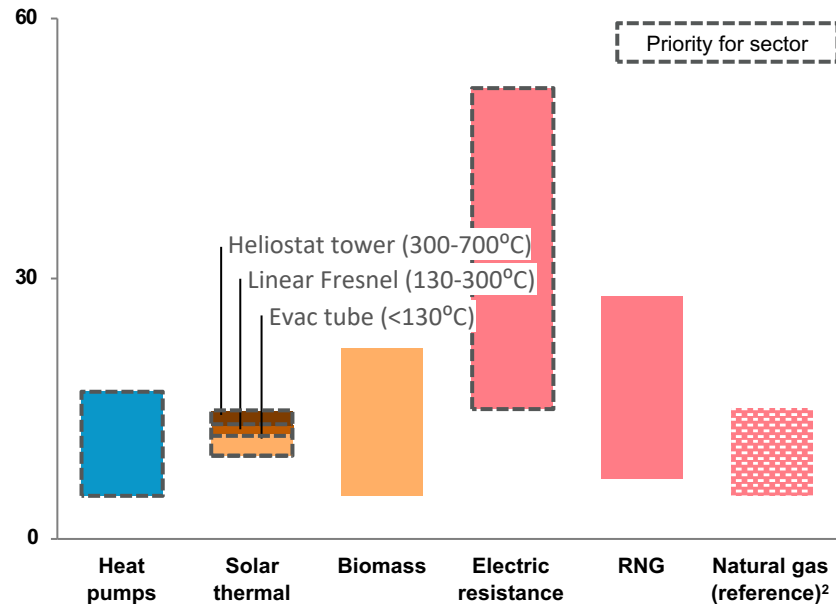
1. NREL Manufacturing Thermal Energy Use in 2014



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

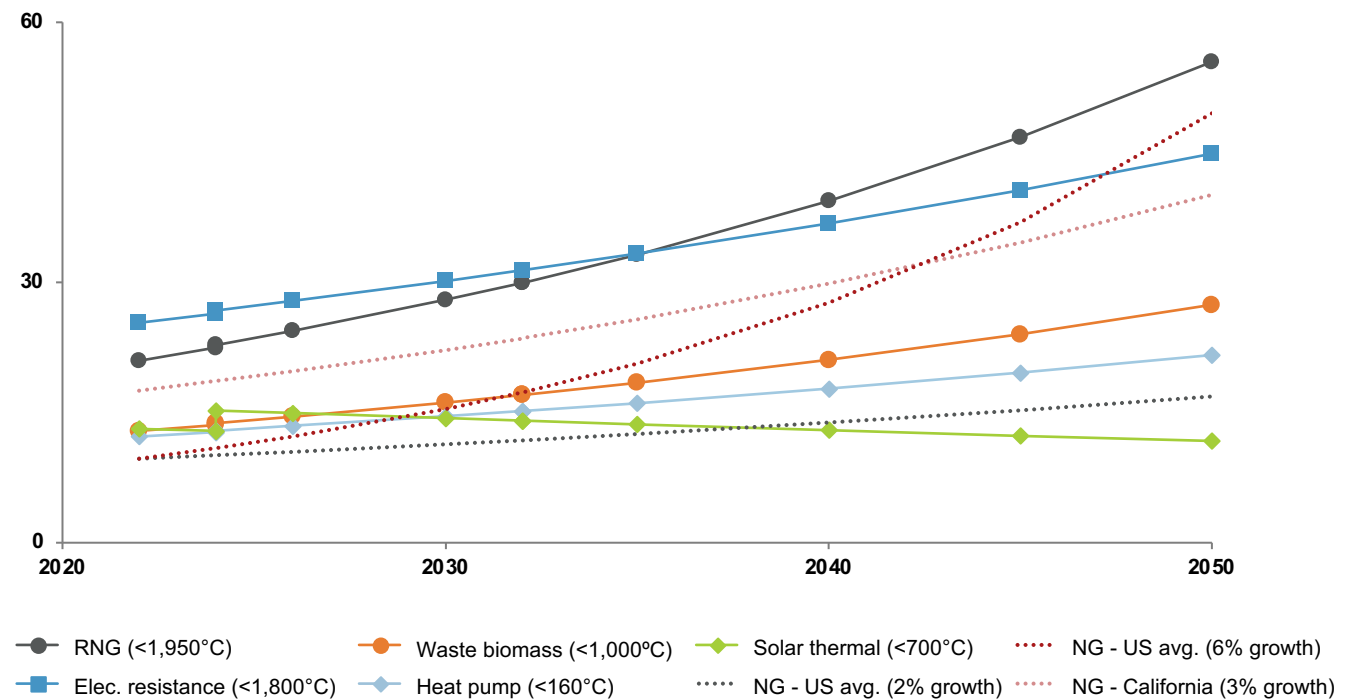
## 2022 LCOH for relevant technologies<sup>1</sup>

(\$/MMBtu)



## Projected LCOH for relevant technologies<sup>1</sup>

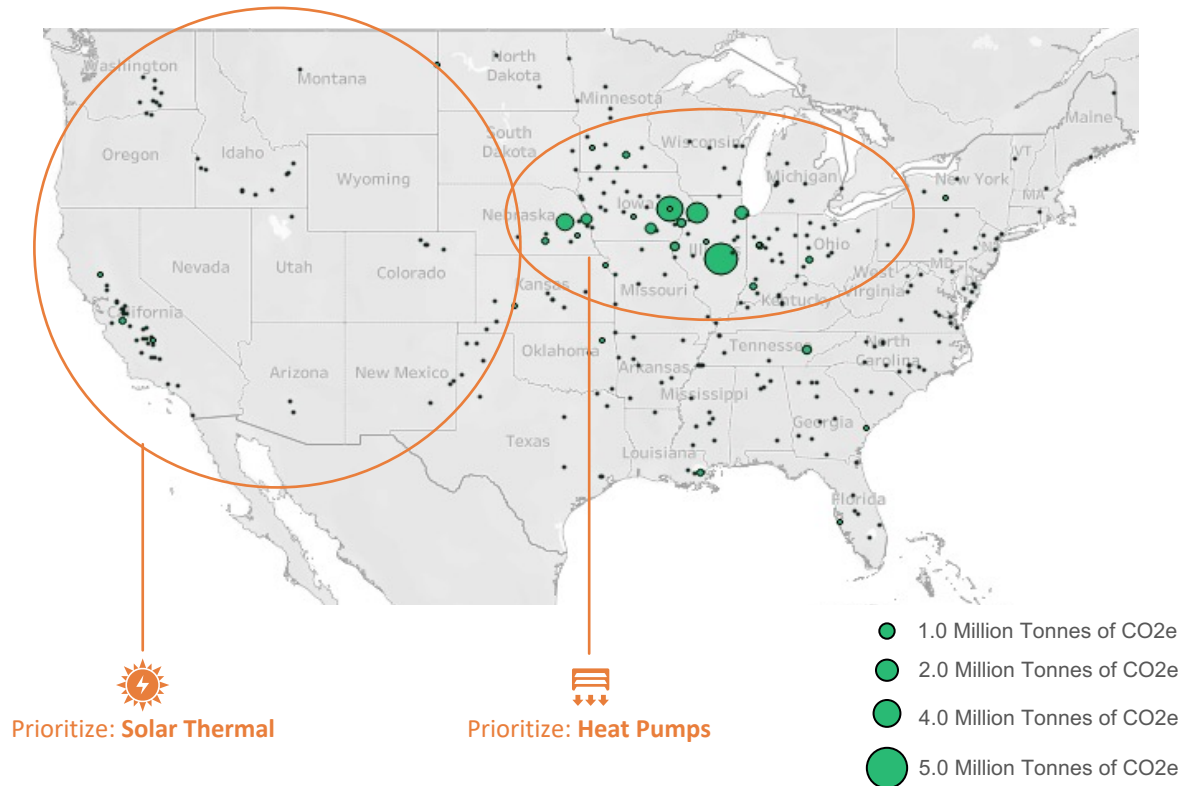
Average US LCOH (\$/MMBtu)



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. 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

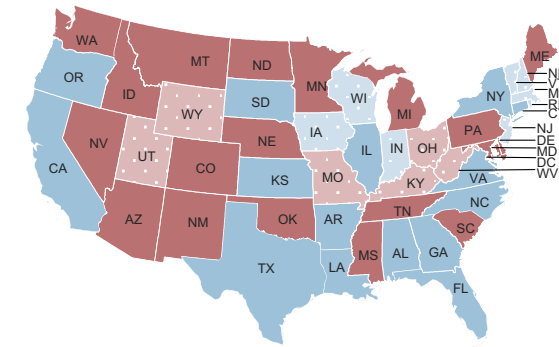
# Heat pumps and solar thermal can be deployed in most heavy-emissions areas

## US Food thermal emissions by zip code<sup>1</sup>



1. EPA GHGRP Inventory FLIGHT Database (2018); captures actual onsite reported emissions for large emitters emitting >25k tons of CO<sub>2</sub>e 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

## Heat pumps v. Natural gas<sup>2,4</sup>



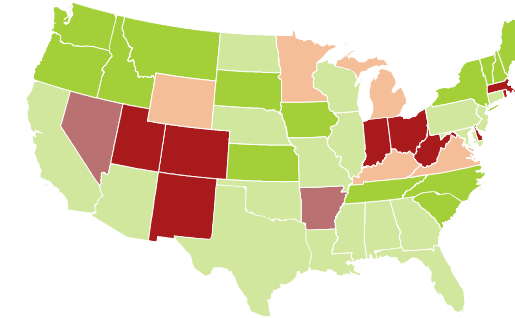
### LCOH for heat pump v natural gas

- Heat pumps cheaper
- Natural gas cheaper

### Emissions savings converting natural gas combustion<sup>2</sup> to electric heat pumps<sup>3</sup>:

- Today (2022)
- By 2035 or sooner<sup>4</sup>

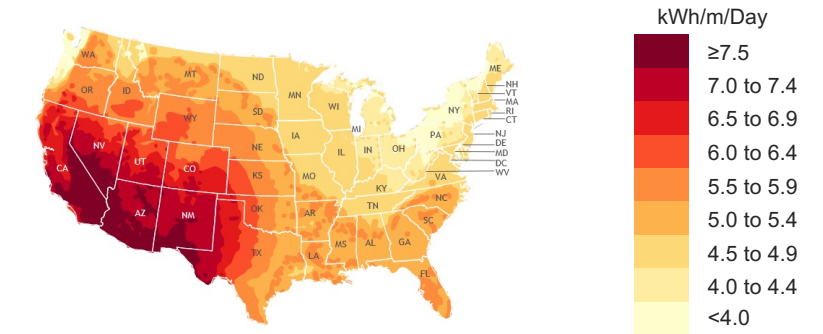
## Elec. resistance v. NG<sup>3</sup>



### Likely reduction in emissions by switching from NG combustion<sup>5</sup> to electric resistance heating:

- Today
- By 2026
- By 2030
- By 2035
- Beyond 2035

## Solar thermal availability<sup>4</sup>



# Decarbonization pathways



## Natural Gas

Displace with renewable fuels



## Electrification

Deploy **heat pumps** <130°C; expand to ~200°C 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

2022

2050

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

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)

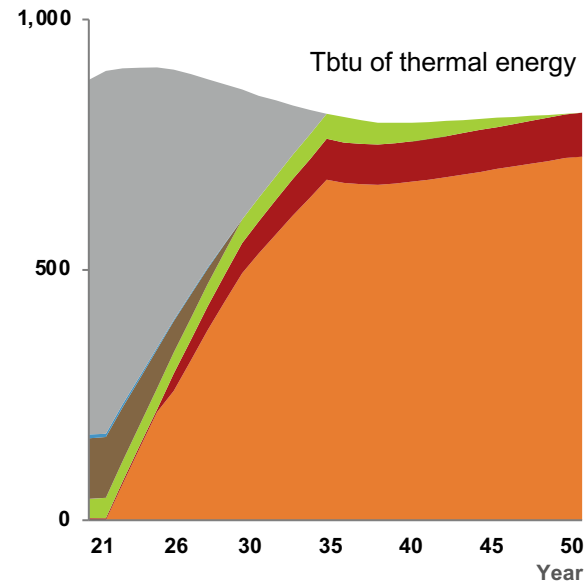
# Thermal decarbonization pathways

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

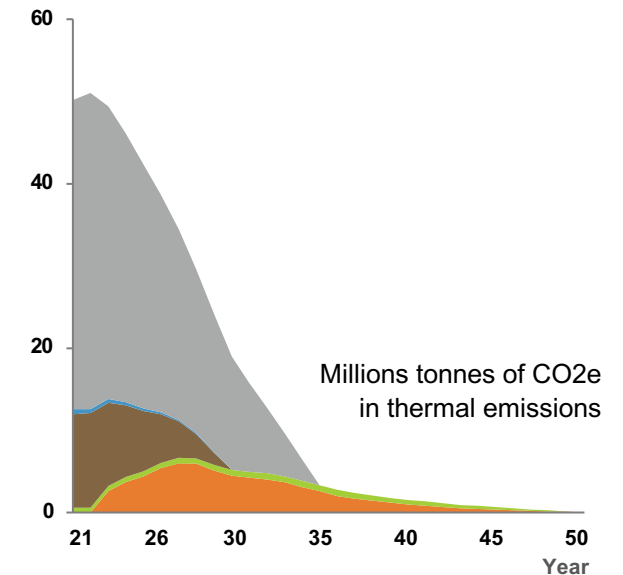
Use of fossil coal and petroleum is **phased out by 2030**, and natural gas **phased out by 2035** – replaced with electrification.

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<sup>1</sup>



## Thermal emissions<sup>2</sup>



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 CO<sub>2</sub>e 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

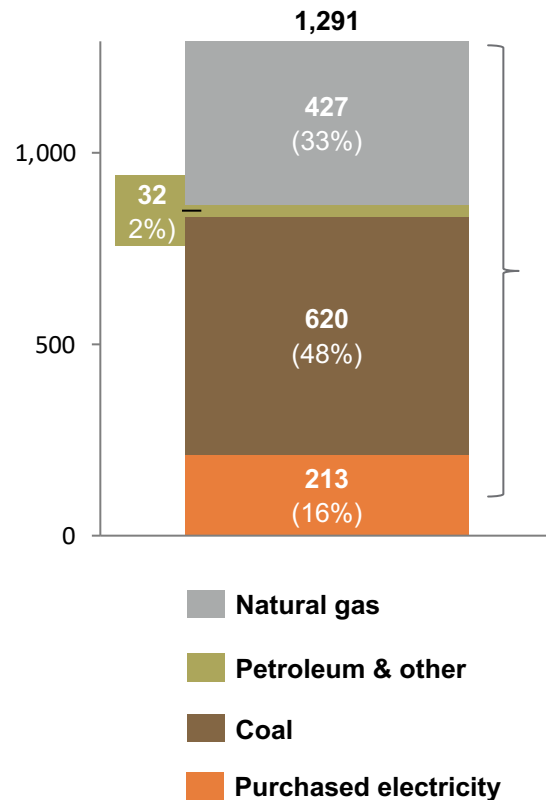
Sector Perspectives



# Thermal applications are fueled by coal, natural gas and electricity (electric arc furnaces<sup>4</sup>)

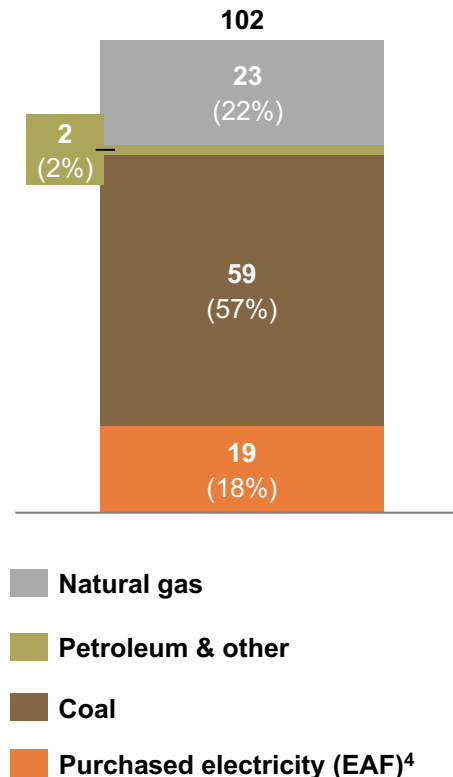
## Total energy consumption (2018)<sup>1</sup>

Trillion Btu



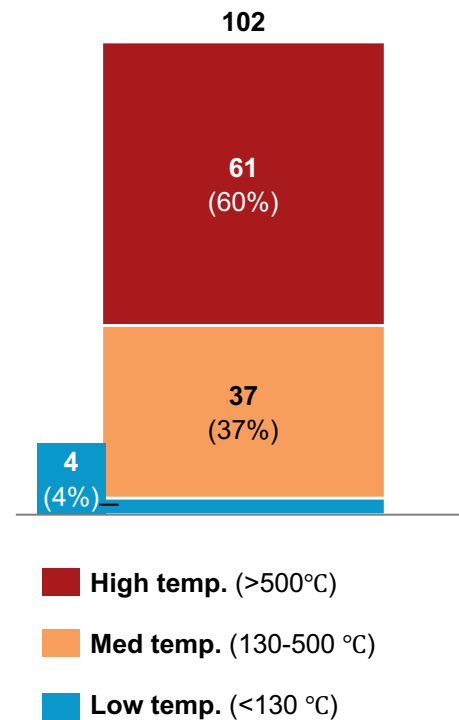
## Thermal emissions (2018)<sup>2</sup>

Million Tonnes of CO<sub>2</sub>e



## Estimated thermal emissions by process temperature (2018)<sup>3</sup>

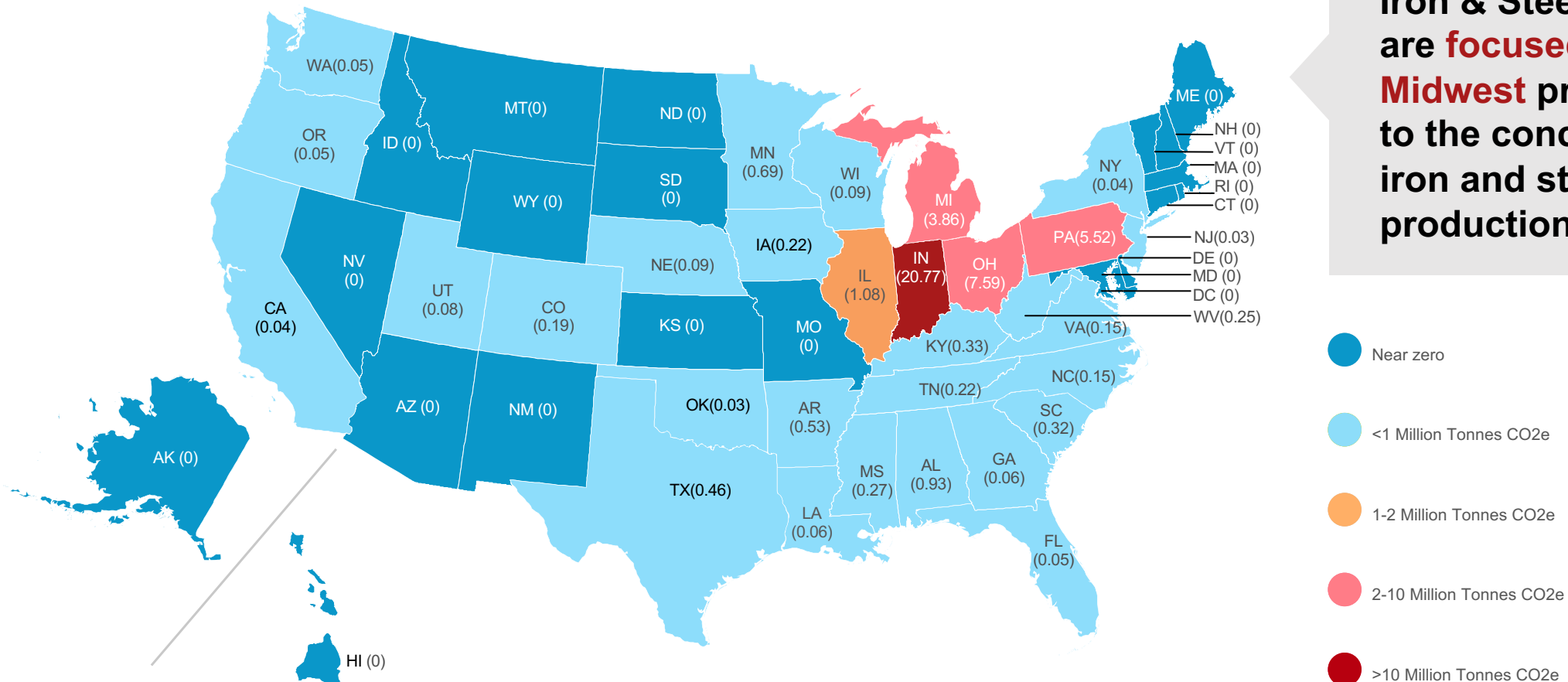
Million Tonnes of CO<sub>2</sub>e



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 CO<sub>2</sub>e/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

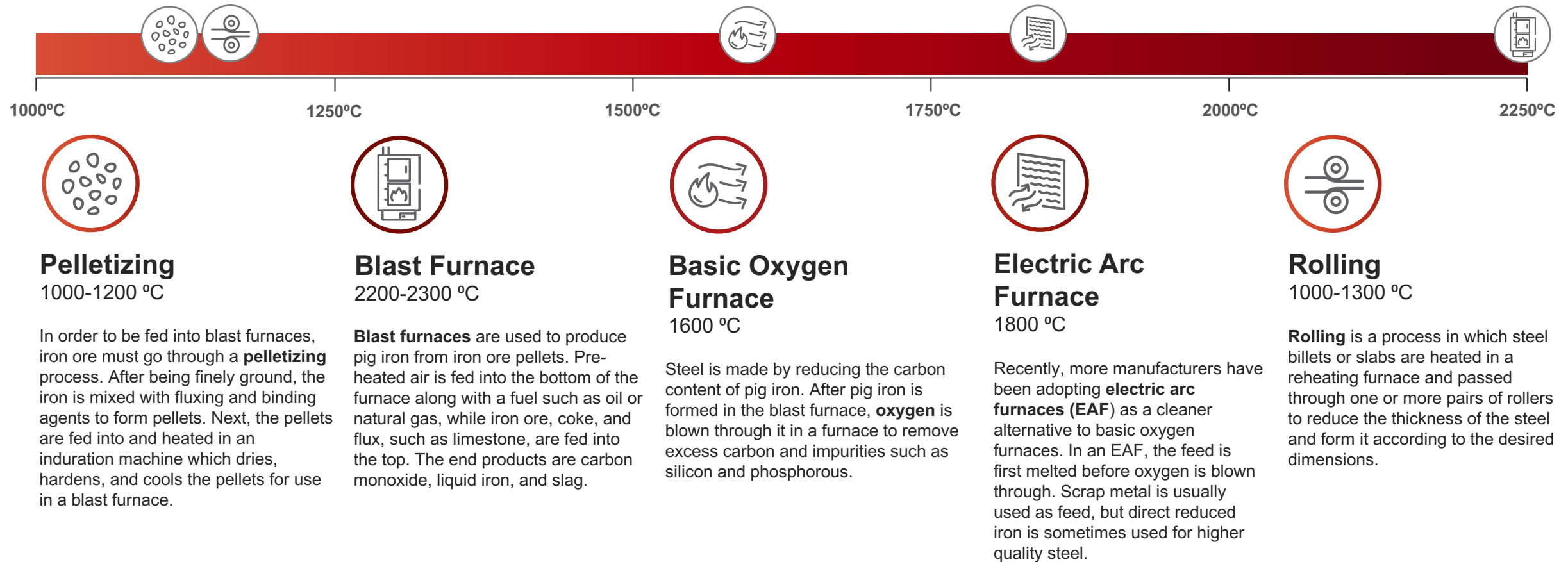
# Thermal emissions are concentrated in the Midwest

## Iron & Steel thermal emissions by state (Million Tonnes of CO<sub>2</sub>e)<sup>1</sup>



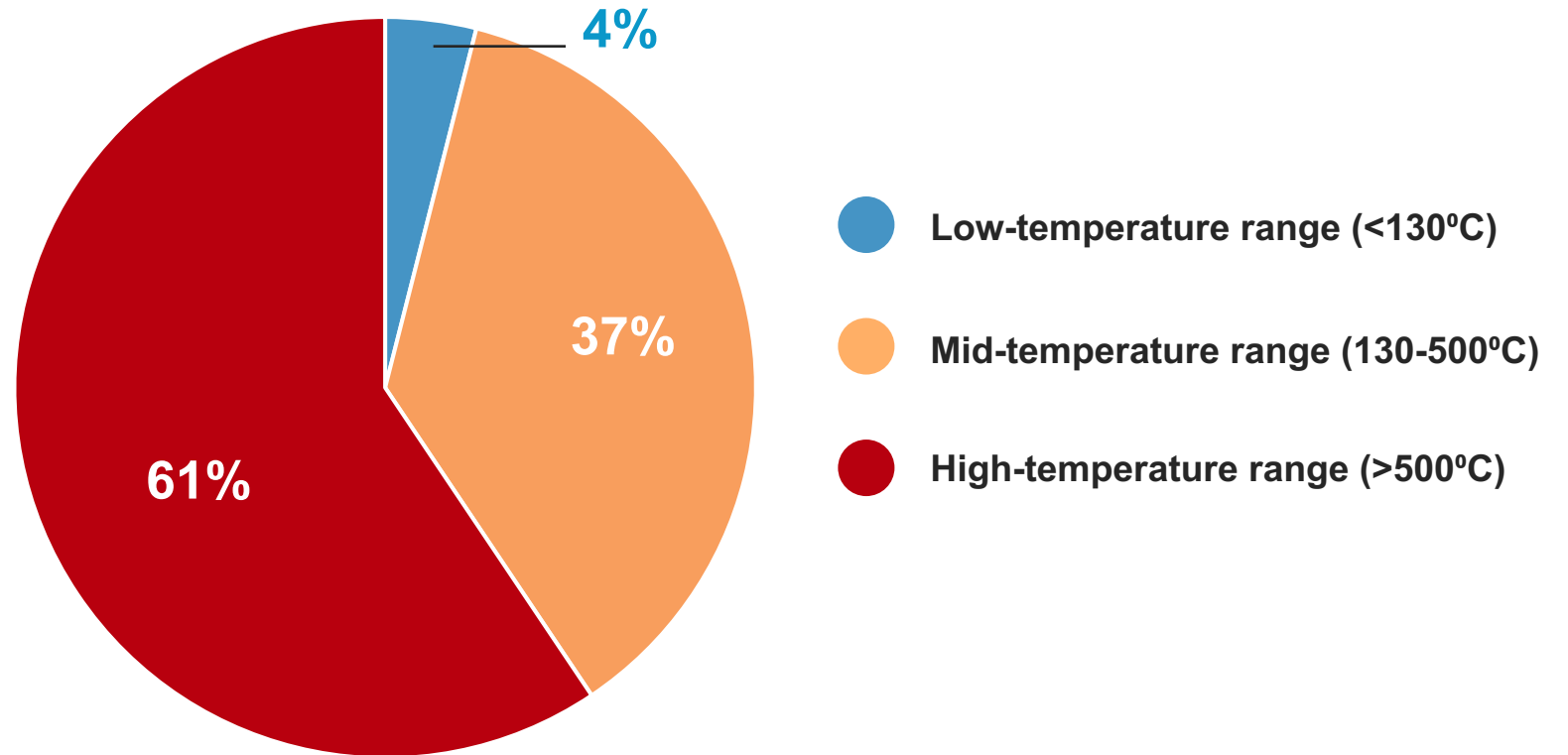
1. EPA GHGRP Inventory FLIGHT Database (2018); captures actual onsite reported emissions for large emitters emitting >25K tonnes of CO<sub>2</sub>e/year

# Core applications occur at high temperatures



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

**Thermal energy consumption (TBtu) by heat temperature range (°C)<sup>1</sup>**



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<sup>1</sup>

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<sup>1</sup>**

## **Scrap-EAF**

(scrap metal with electric arc furnace)

~100 facilities

EAFs produce steel by heating metal feedstock to temperatures up to 1800°C

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

**~23% of thermal emissions**

## **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

## US BF-BOF & DRI-EAF locations

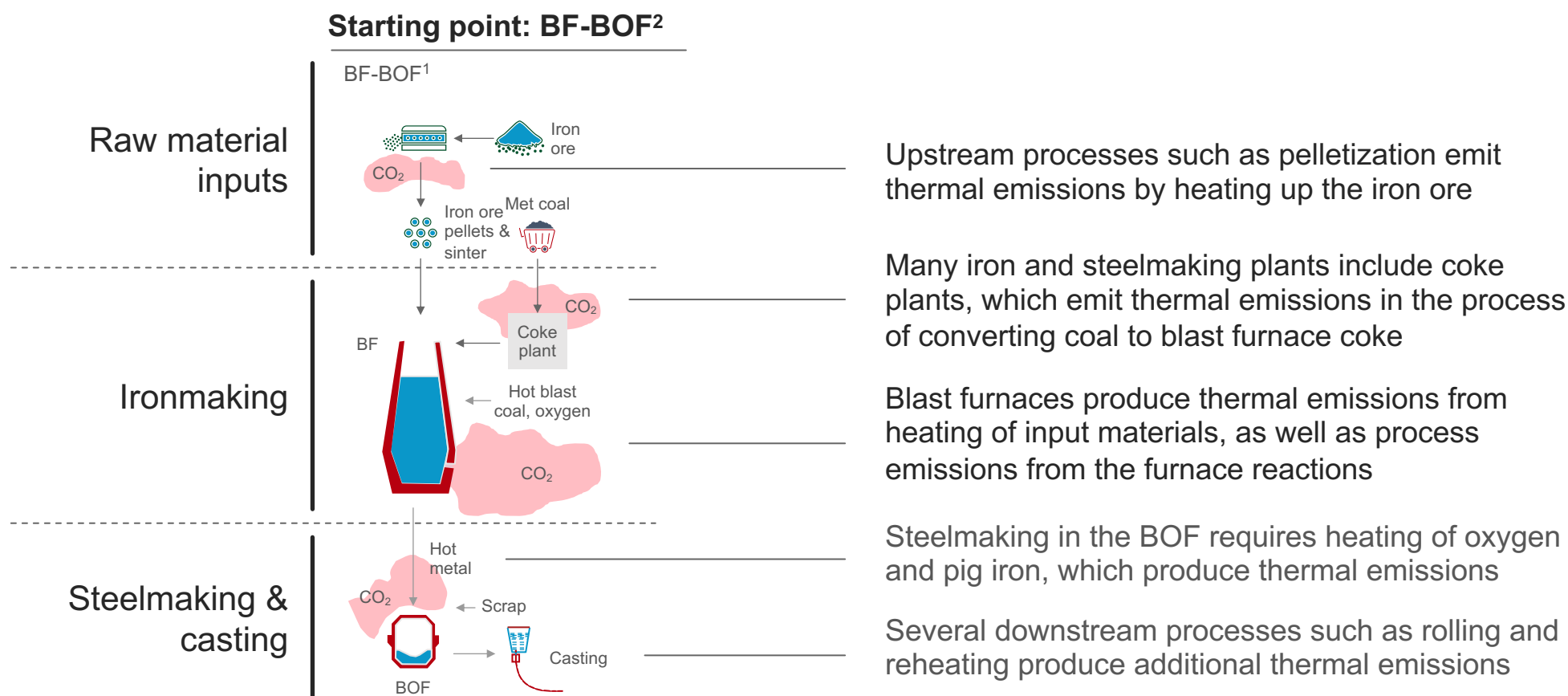


★ US BF-BOF with coal    ★ US DRI-EAF with natural gas

1. There were 10 active plants running BF-BOFs in the US in 2018, representing 34 million tonnes of CO<sub>2</sub>e 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<sup>1</sup>



1. There were 10 active plants running BF-BOFs the US in 2018, representing 34 million MT of CO<sub>2</sub>e 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

 Area represents amount of CO<sub>2</sub> emissions

# Primary decarbonizing approaches divide in two main pathways

BF-BOF plants  
(~77% of  
emissions)



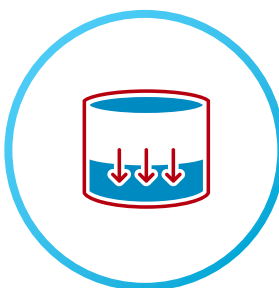
## Switch to DRI-EAF with H<sub>2</sub>

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<sub>2</sub>** 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

EAF plants  
(~23% of  
emissions)

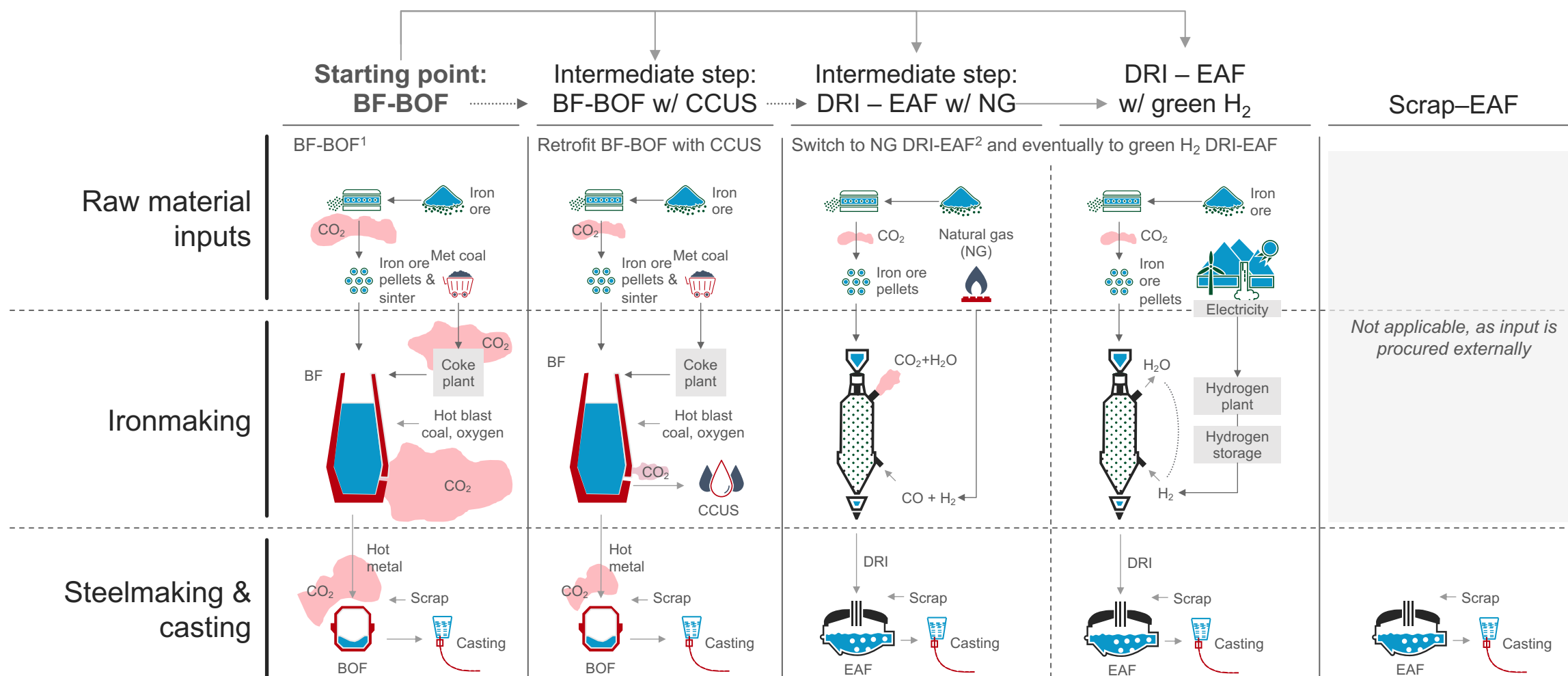


## Eliminate fossil fuel combustion

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



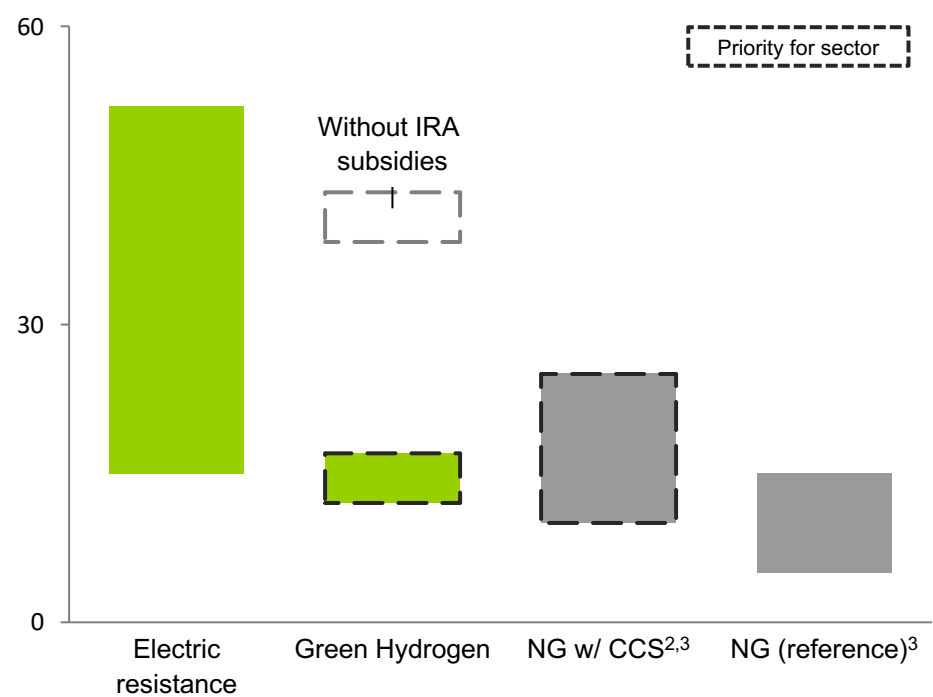
1. Blast Furnace-Basic Oxygen Furnace 2. Direct Reduced Iron-Electric Arc Furnace  
Source: BCG analysis

 Area represents amount of CO<sub>2</sub> emissions

# 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

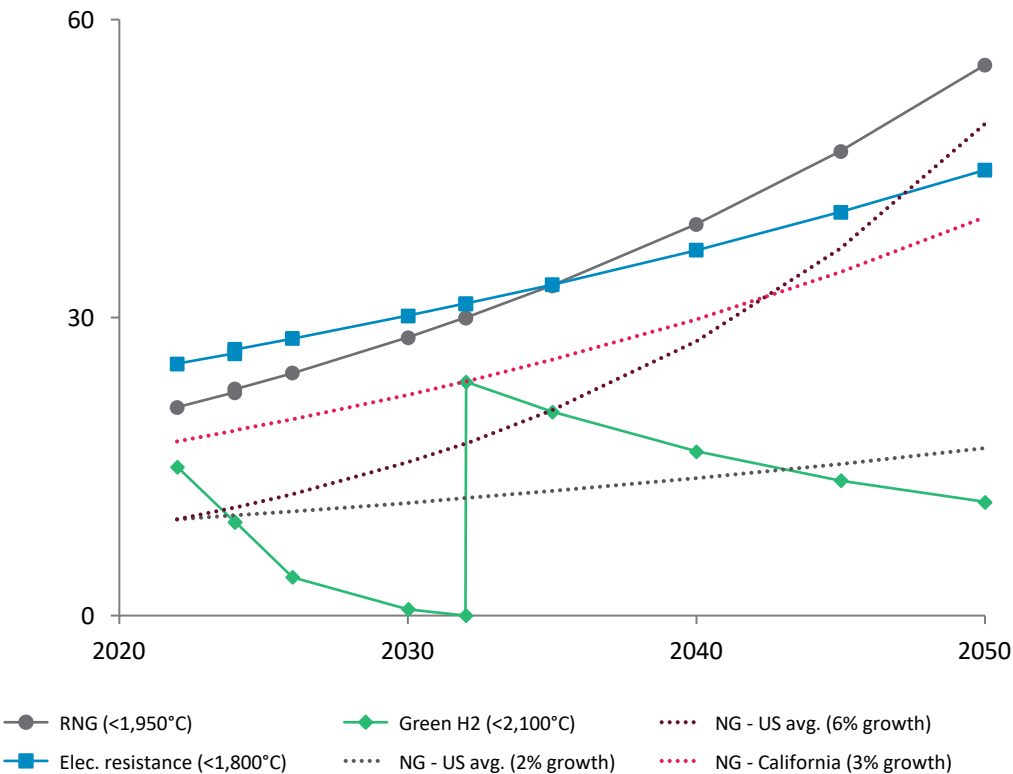
2022 LCOH for relevant technologies<sup>1</sup>

(\$/MMBtu)



Projected LCOH for relevant technologies<sup>1</sup>

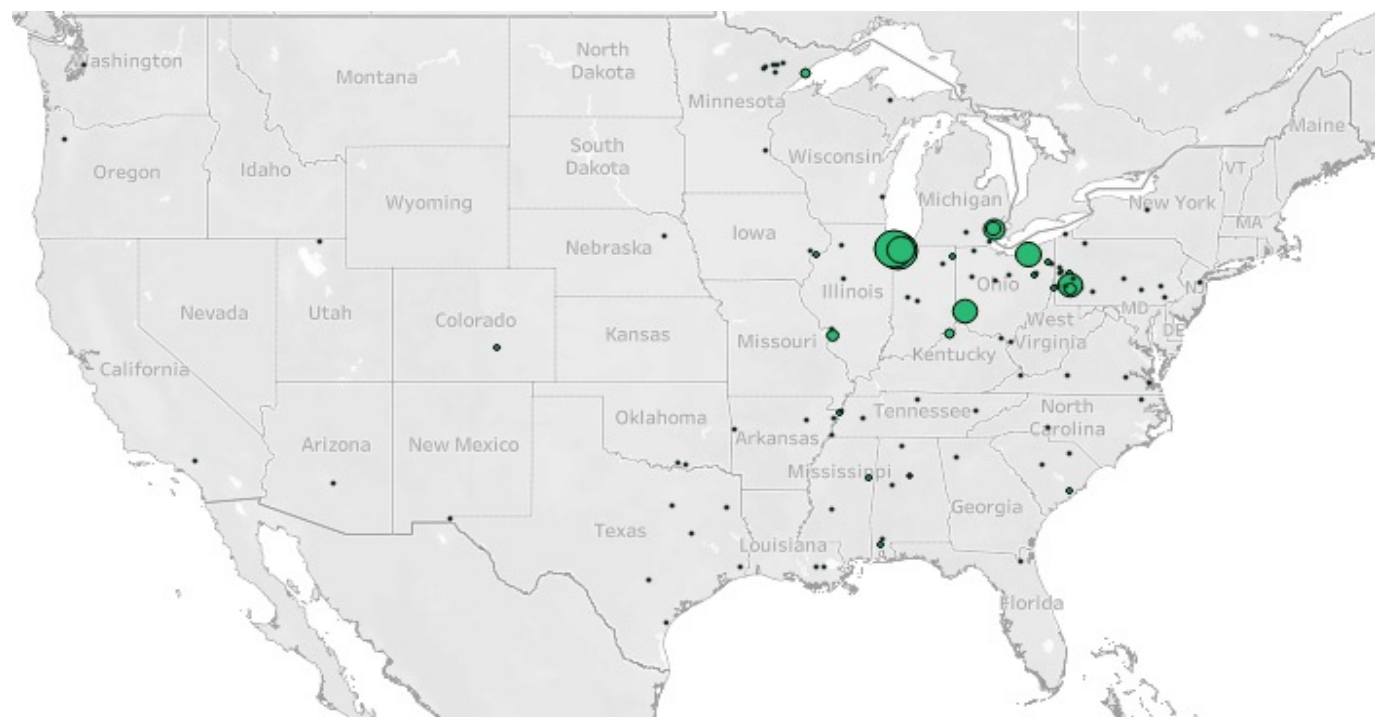
Average US LCOH (\$/MMBtu)



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

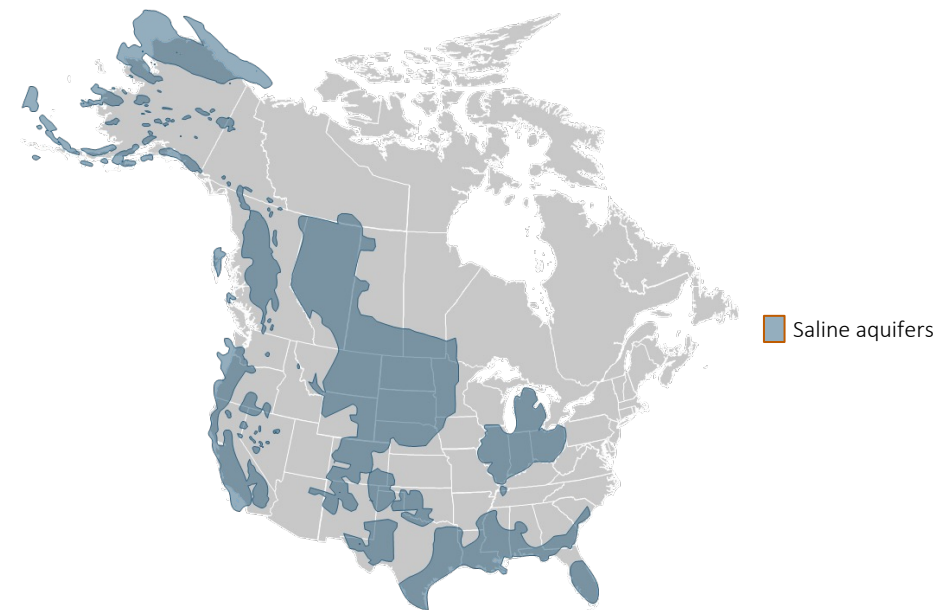
# Hydrogen and CCS are projected to be available in heavy-emissions areas

## US Iron & Steel sector thermal emissions by zip code<sup>1</sup>



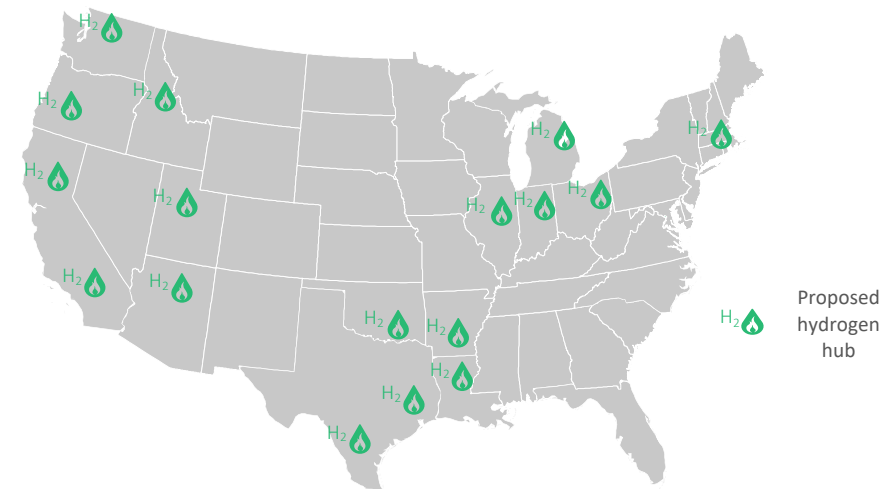
- 1.0 Million Tonnes CO<sub>2</sub>e
- 2.0 Million Tonnes CO<sub>2</sub>e
- 4.0 Million Tonnes CO<sub>2</sub>e
- 6.0 Million Tonnes CO<sub>2</sub>e

## CCS sequestration geographies<sup>2</sup>



Saline aquifers

## Proposed hydrogen hubs<sup>3</sup>



Proposed hydrogen hub



# 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

2022

2050

### Considerations

Iron and steel making value chain (i.e., simultaneous deployment of DRI with EAF), grid or PPA supports emissions savings

Adequate supply of fuel

Concentration of CO<sub>2</sub> in flue gas, government subsidies

### Target First Movers

End-of-life or greenfield steel mills, ability to procure inexpensive electricity

Regions with grid RNG blending (Midwest, Southeast)

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

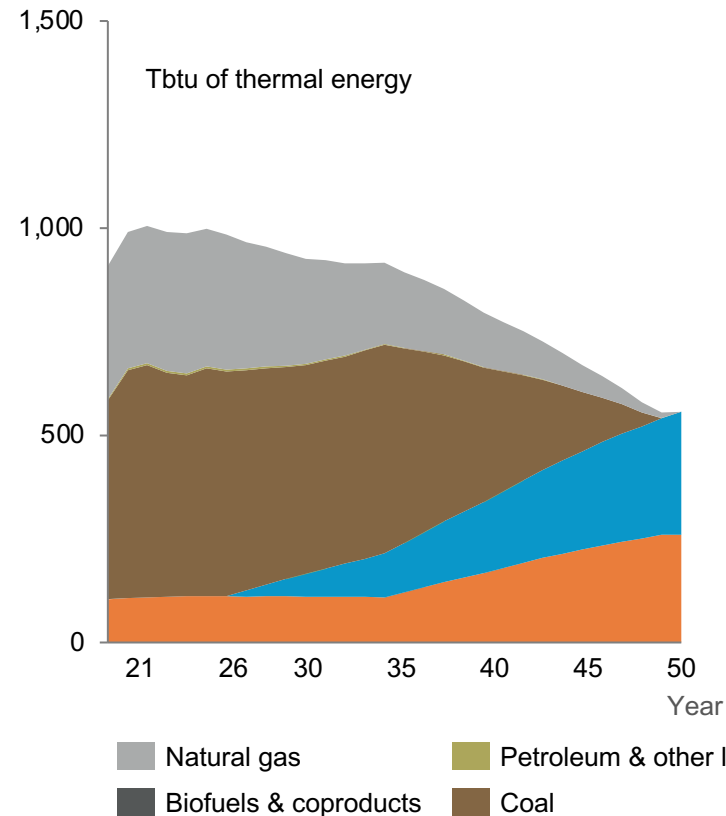
**More than 2/3 of US steel facilities today use EAFs**, and only ~10 facilities remain operating ~14 total blast furnaces - these facilities generated 77% of total thermal emissions for the sector in 2018

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.

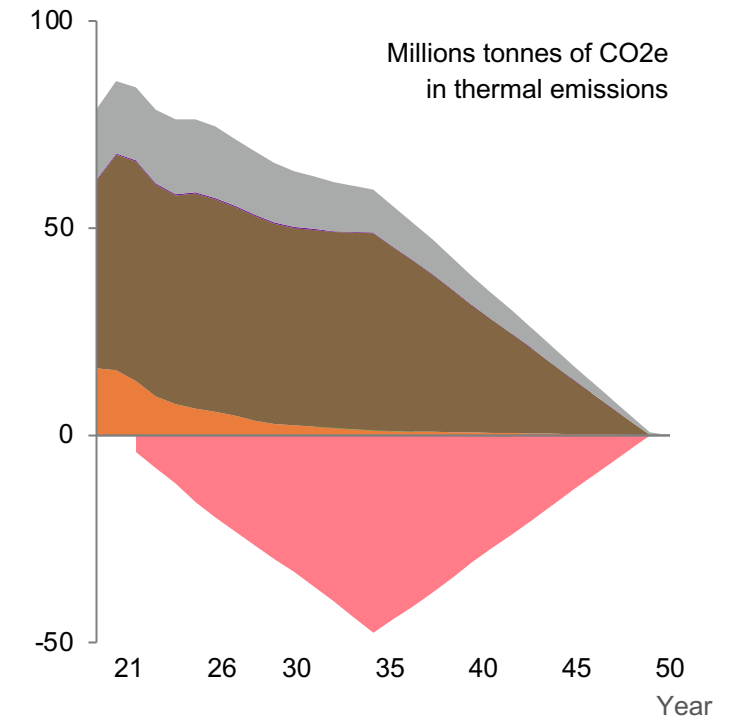
**In the interim period, the sector should deploy CCS to capture emissions** while the transition to DRI-EAF w/ green hydrogen occurs, upon which CCS can be phased out

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**

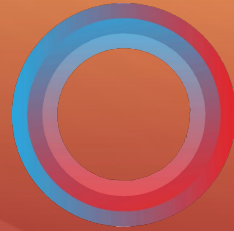
## Thermal energy consumption<sup>1</sup>



## Thermal emissions<sup>2</sup>



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 CO<sub>2</sub>e 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



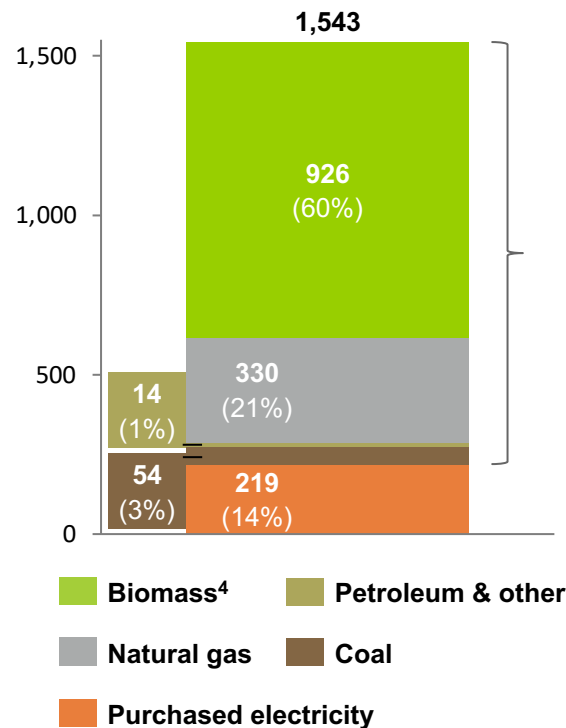
# Paper

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)<sup>1</sup>

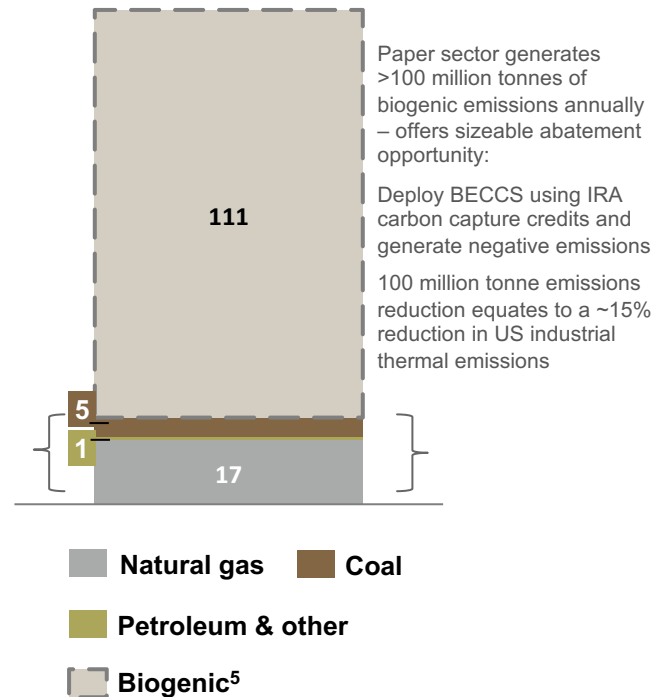
Trillion Btu



## Thermal emissions (2018)<sup>2</sup>

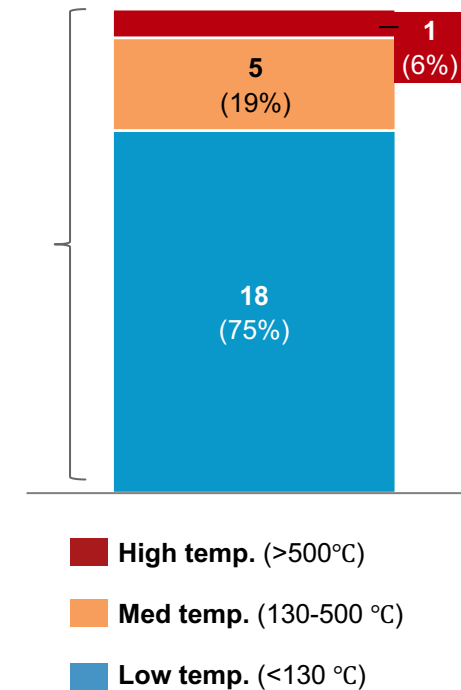
Million Tonnes of CO2e

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



## Estimated thermal emissions by process temperature (2018)<sup>3</sup>

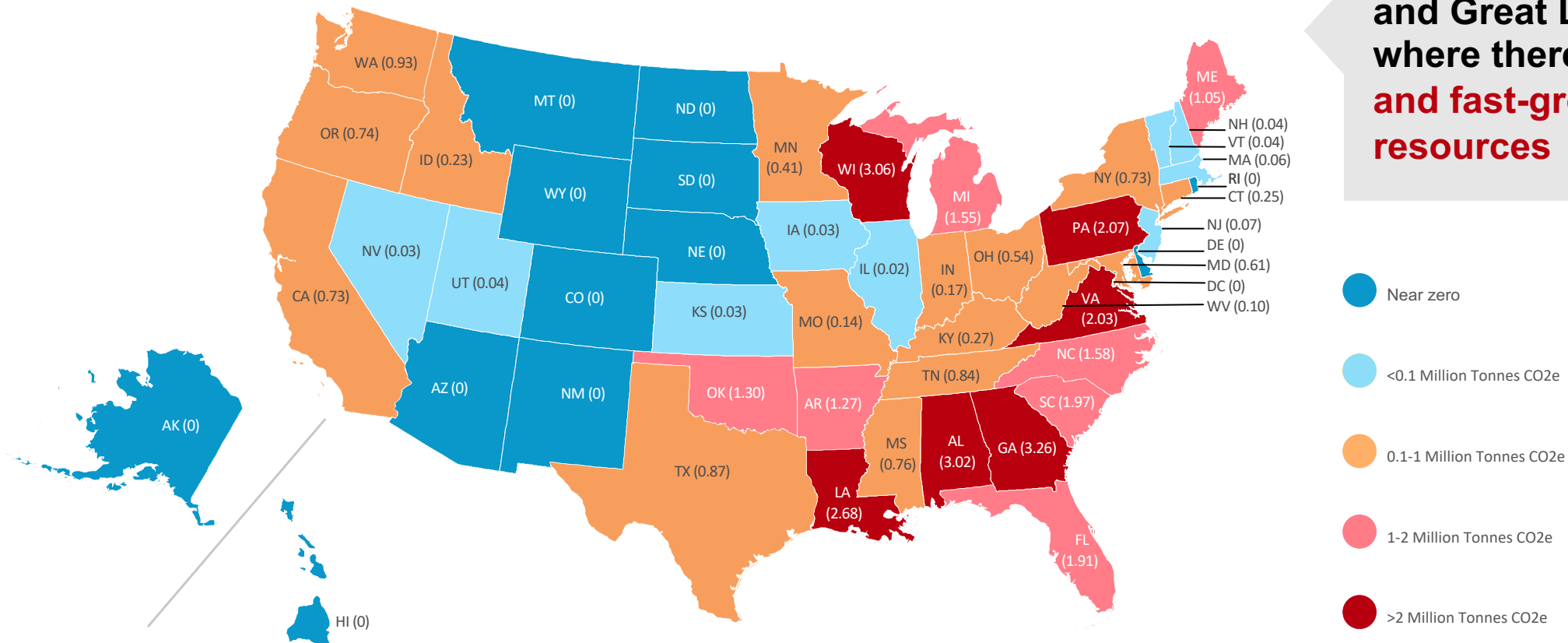
Million Tonnes of CO2e



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 CO<sub>2</sub>e)<sup>1</sup>

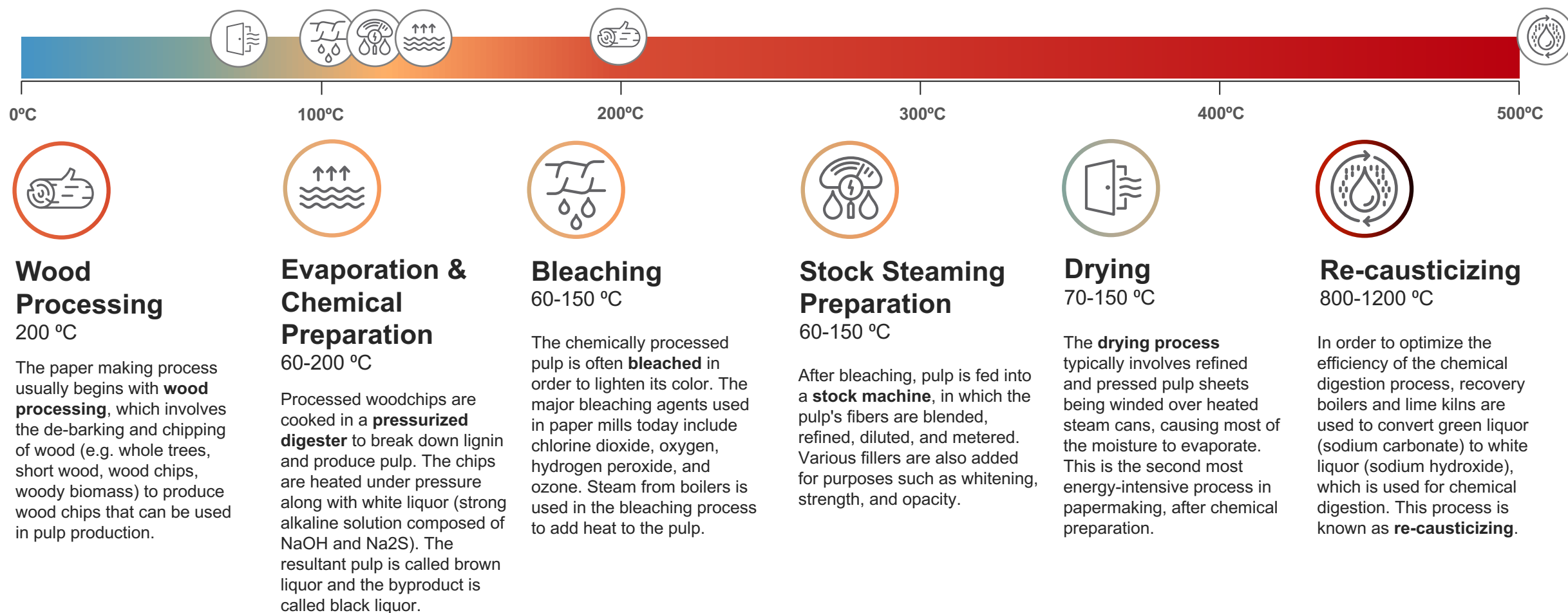


Paper industries are focused in the Southeast and Great Lakes regions, where there are **abundant and fast-growing wood resources**

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



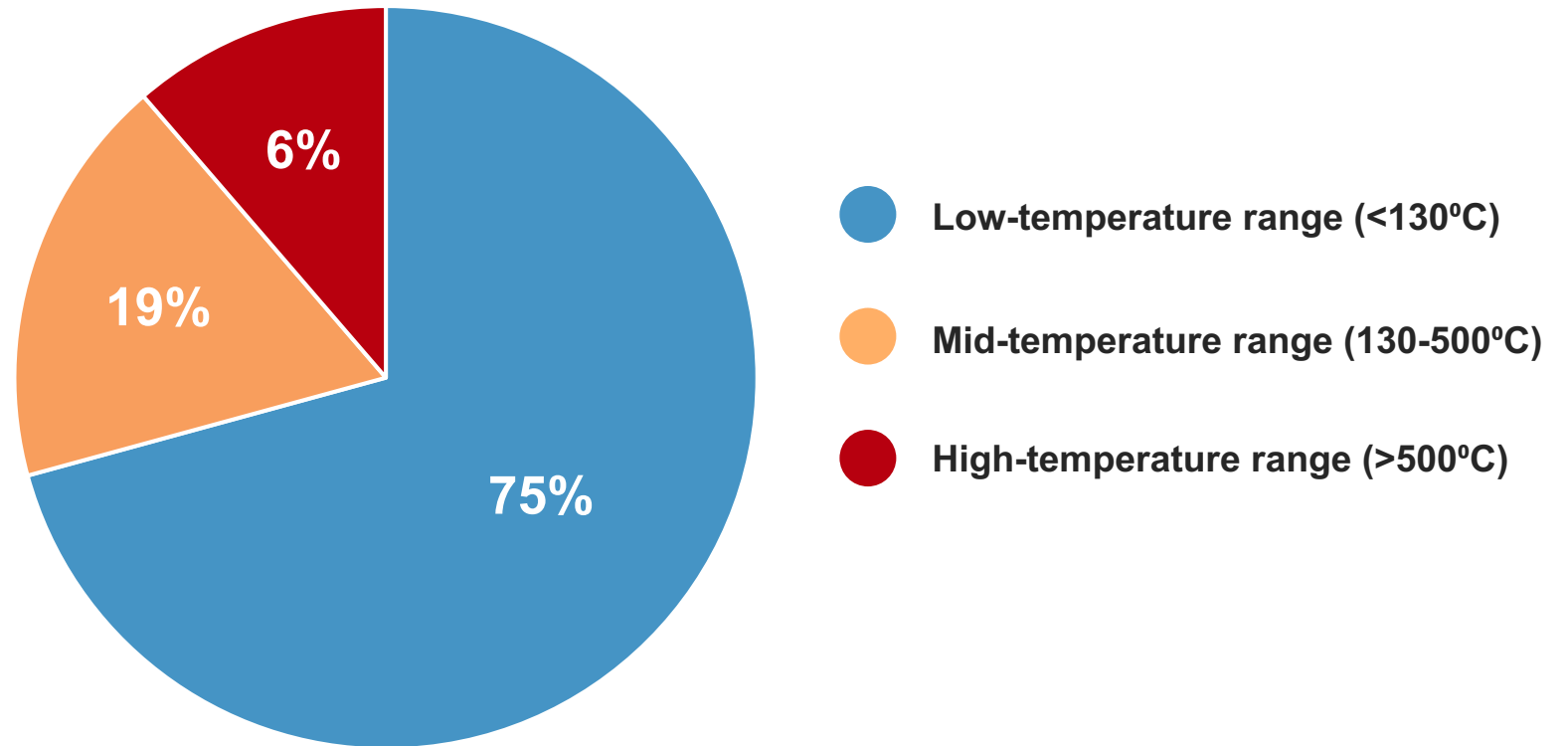
# Key heat applications require low & medium temperatures and can be electrified; several processes are already electrified at some facilities



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

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

**Thermal energy consumption (TBtu) by heat temperature range (°C)<sup>1</sup>**

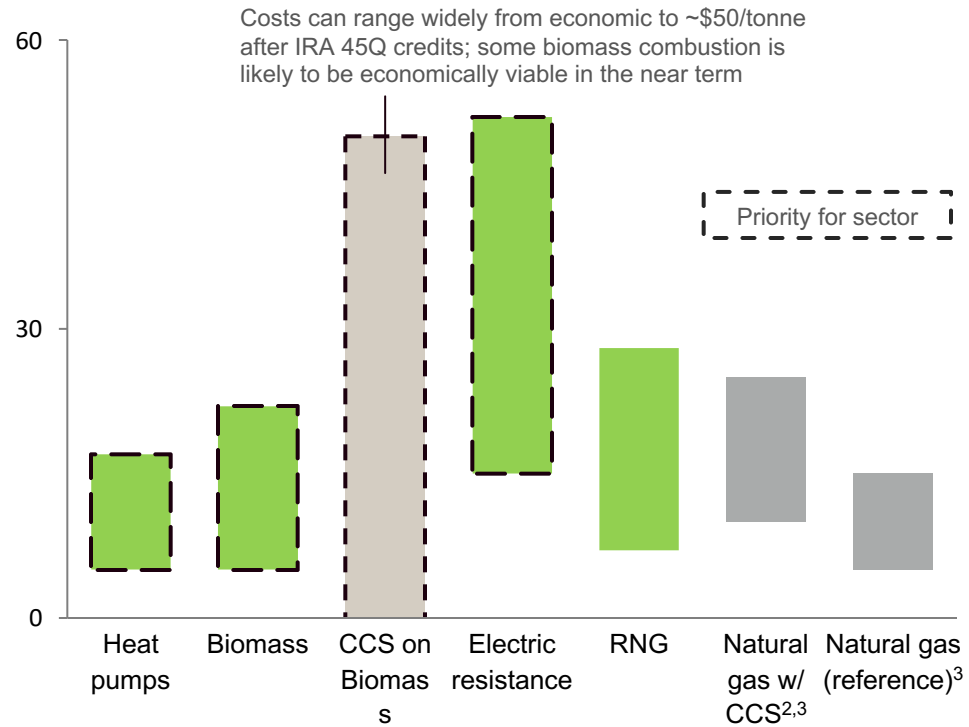


1. NREL Manufacturing Thermal Energy Use in 2014  
Source: DOE (2022), industry reports and papers, BCG analysis

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

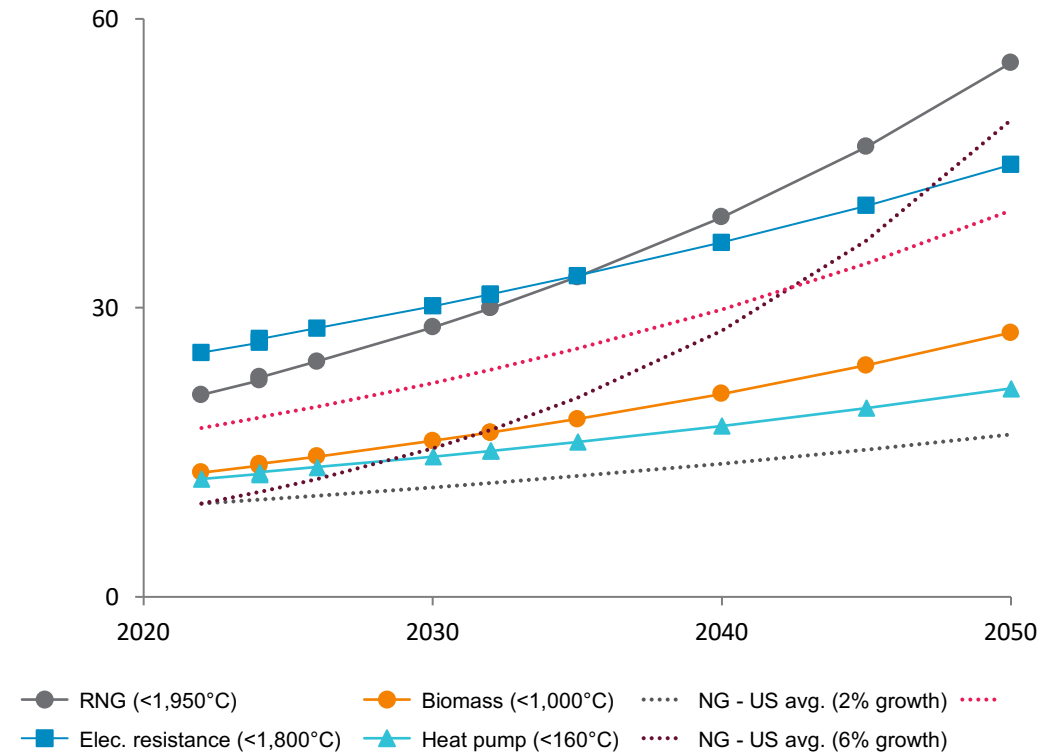
## 2022 LCOH for relevant technologies<sup>1</sup>

(\$/MMBtu)



## Projected LCOH for relevant technologies<sup>1</sup>

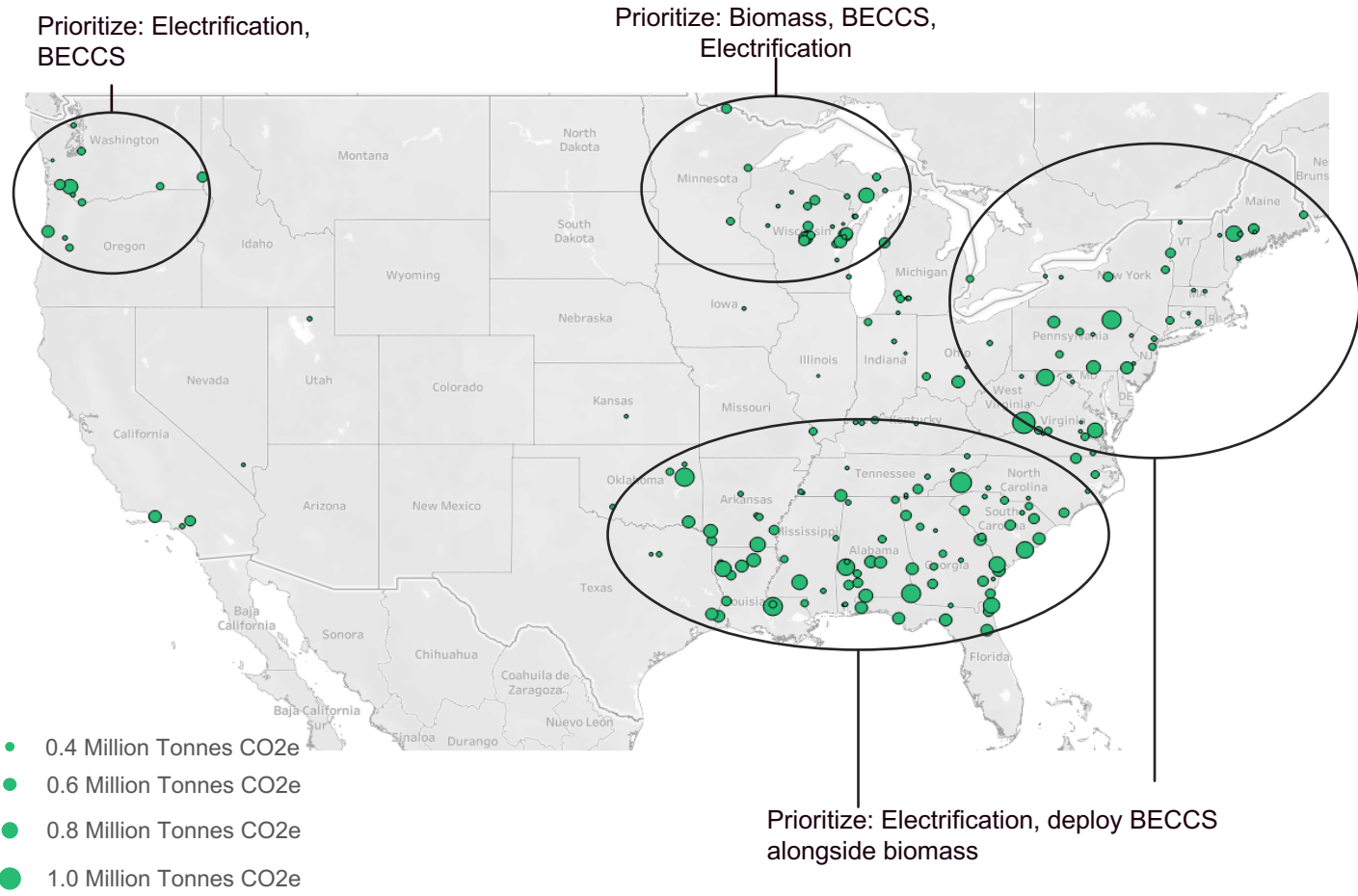
Average US LCOH (\$/MMBtu)



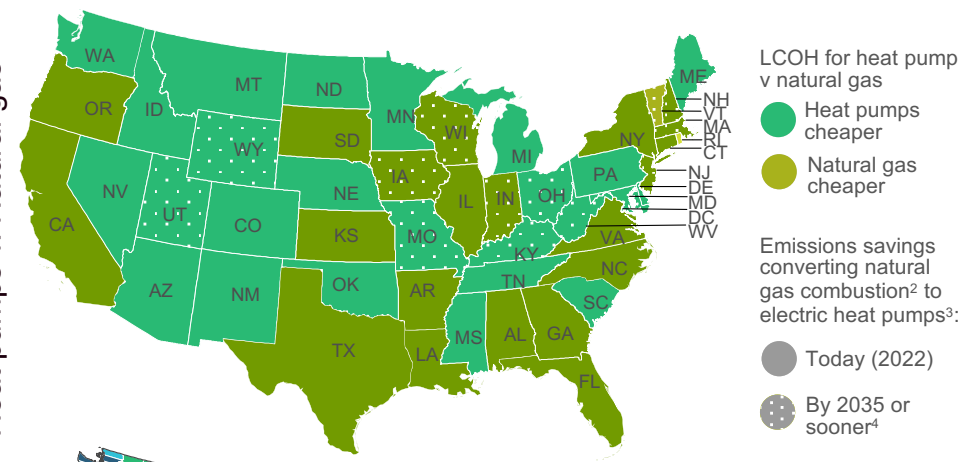
1. LCOH compares project lifetime costs against lifetime energy produced; costs include capital expense of equipment, fuel costs, and maintenance expense assumptions over the usable life of the energy asset. Electricity and natural gas pricing is based on national weighted average wholesale industrial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

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

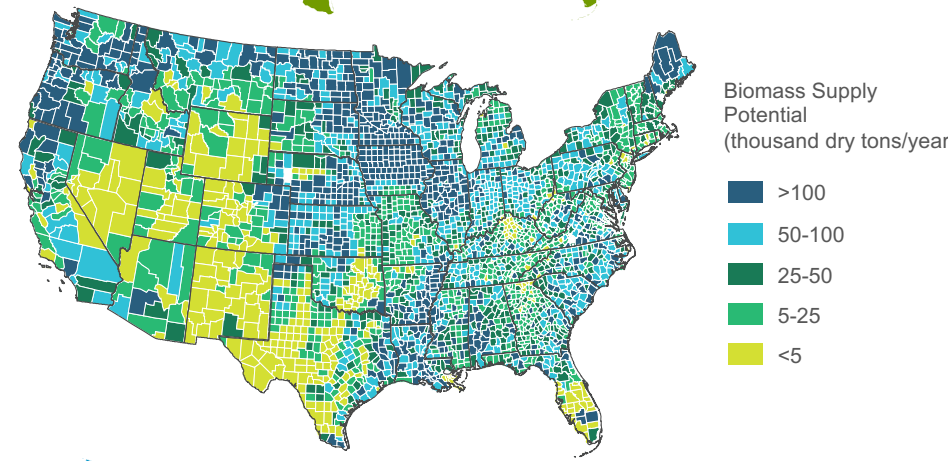
## US Paper Sector thermal emissions by zip code<sup>1</sup>



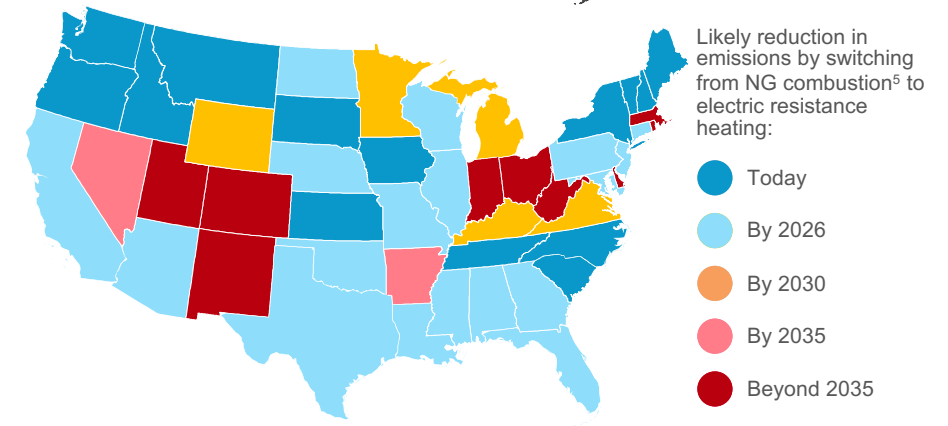
Heat pumps v. Natural gas<sup>2,4</sup>



Biomass supply<sup>3</sup>



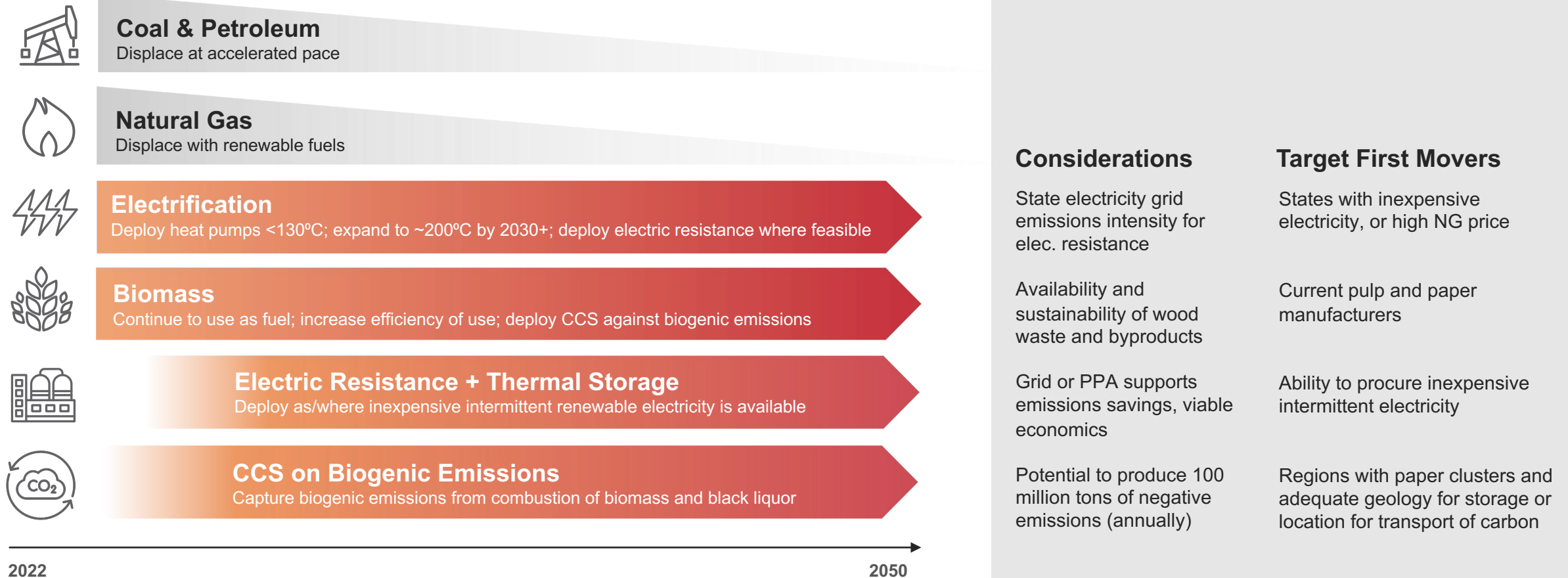
Elec. resistance emissions v. NG<sup>4</sup>



1. EPA GHGRP Inventory FLIGHT Database (2018); captures actual onsite reported emissions for large emitters emitting >25k tons of CO<sub>2</sub>e 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



**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 CO<sub>2</sub>e 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

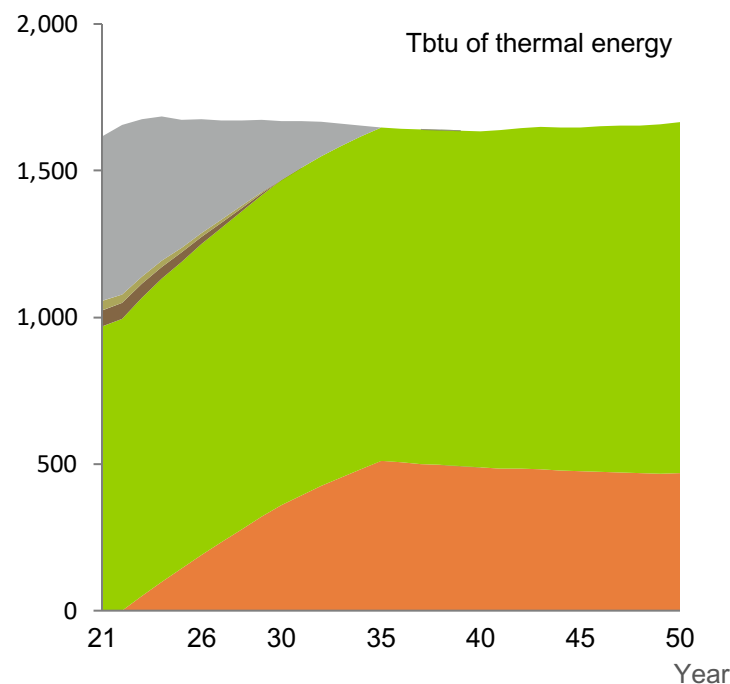
**94% of industrial heat** is in low (75%) and medium (19%) temperature ranges, which can be **decarbonized on an accelerated timeline** with electrification and heat pumps

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

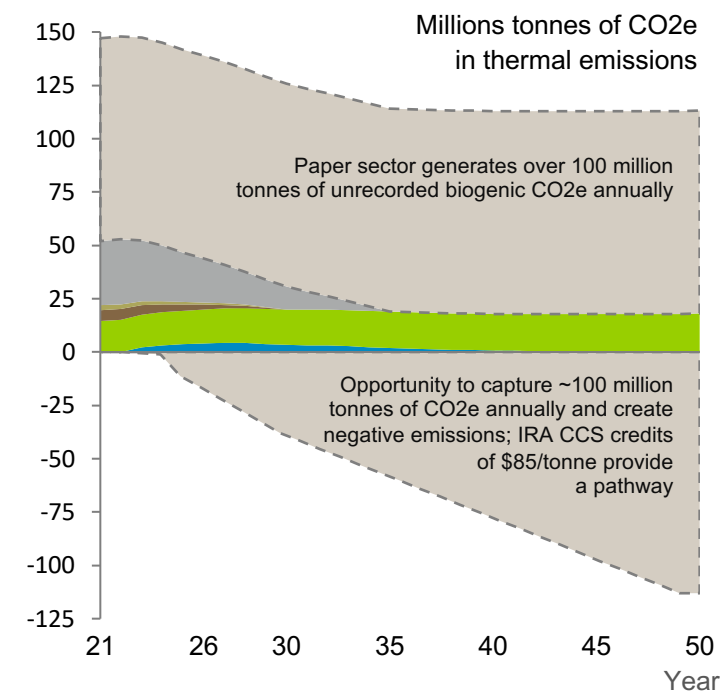
The sector generated 111 million tonnes of biogenic CO<sub>2</sub>e<sup>3,4</sup> in 2018 primarily due to combustion; while these emissions are unreported, there is an opportunity for the sector to capture this carbon, which would equate to a ~15% reduction in total industrial thermal emissions.

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<sup>1</sup>



## Thermal emissions<sup>2</sup>



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 CO<sub>2</sub>e 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



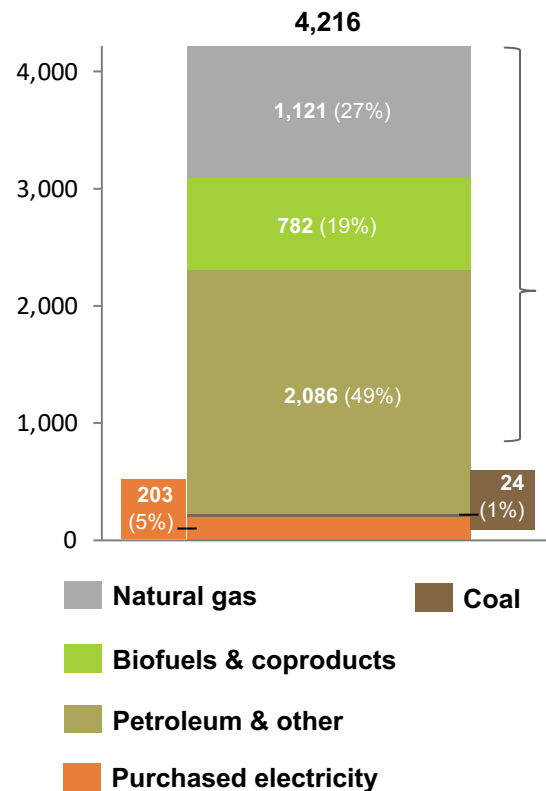
# Refineries

Sector Perspectives

# ~88% of emissions are generated <500°C but majority of thermal energy is fueled by refinery fossil byproducts<sup>4</sup>, which have few alternative uses

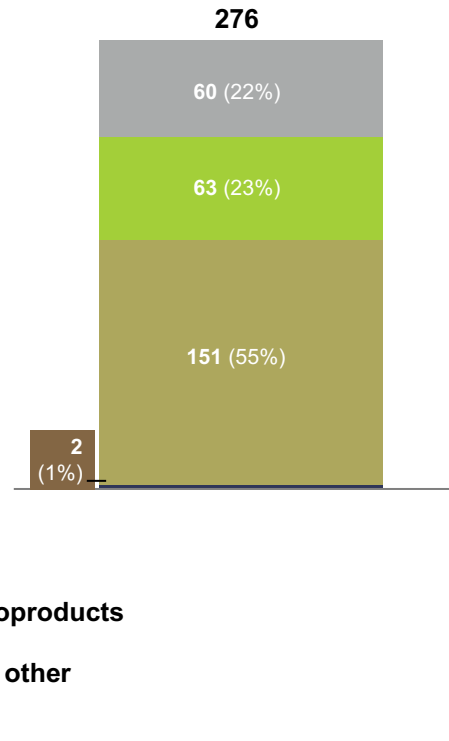
## Total energy consumption (2018)<sup>1</sup>

Trillion Btu



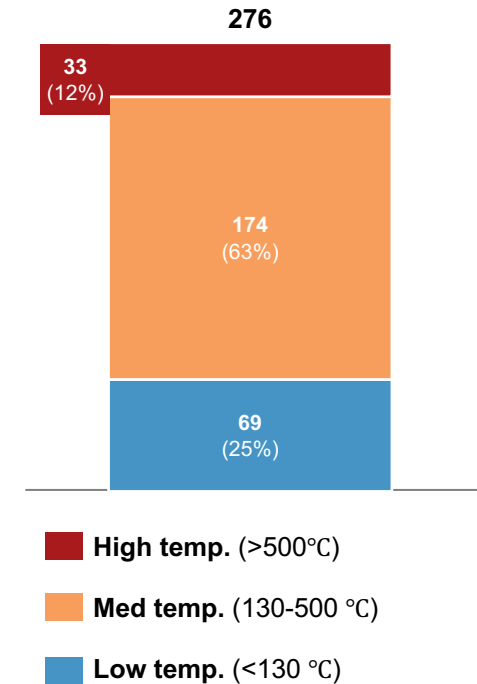
## Thermal emissions (2018)<sup>2</sup>

Million Tonnes of CO<sub>2</sub>e



## Estimated thermal emissions by process temperature (2018)<sup>3</sup>

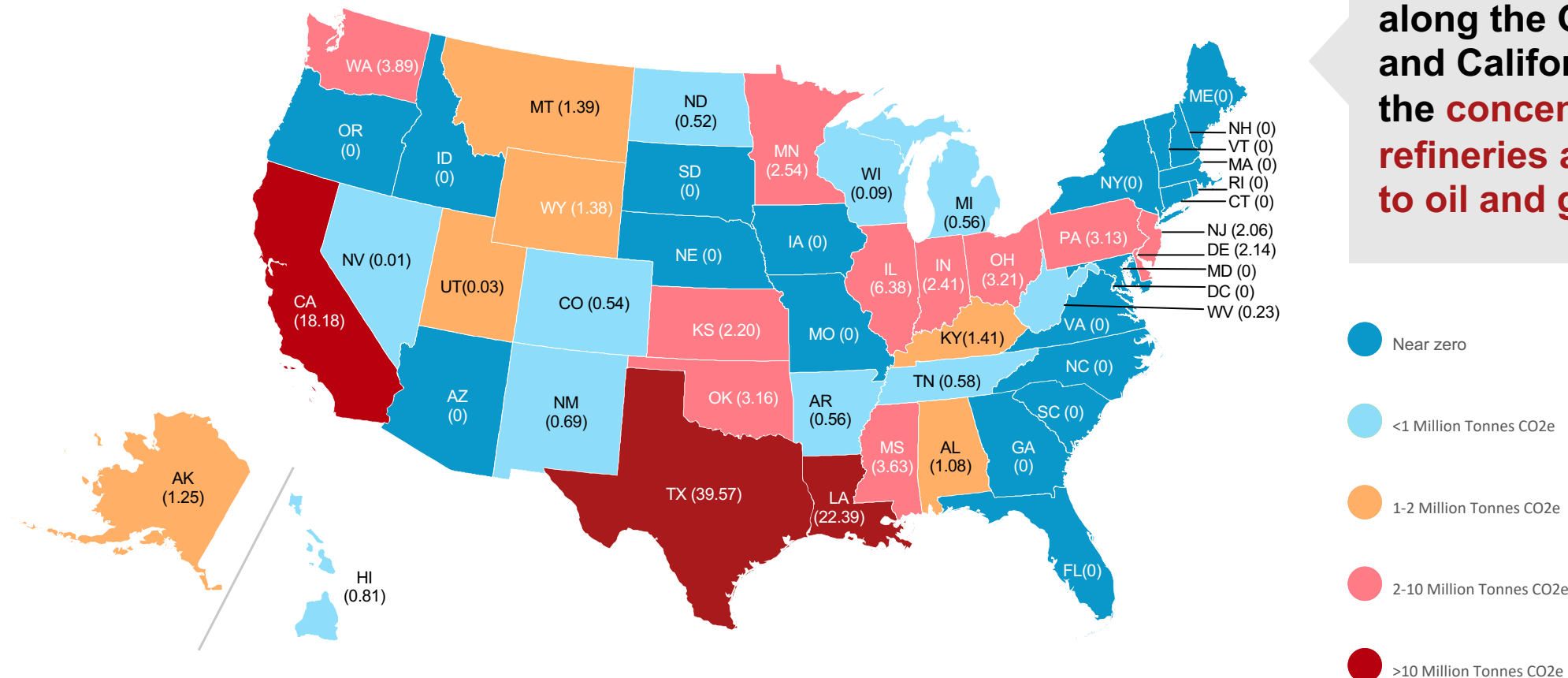
Million Tonnes of CO<sub>2</sub>e



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 CO<sub>2</sub>e/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)<sup>1</sup>



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 °C

**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.



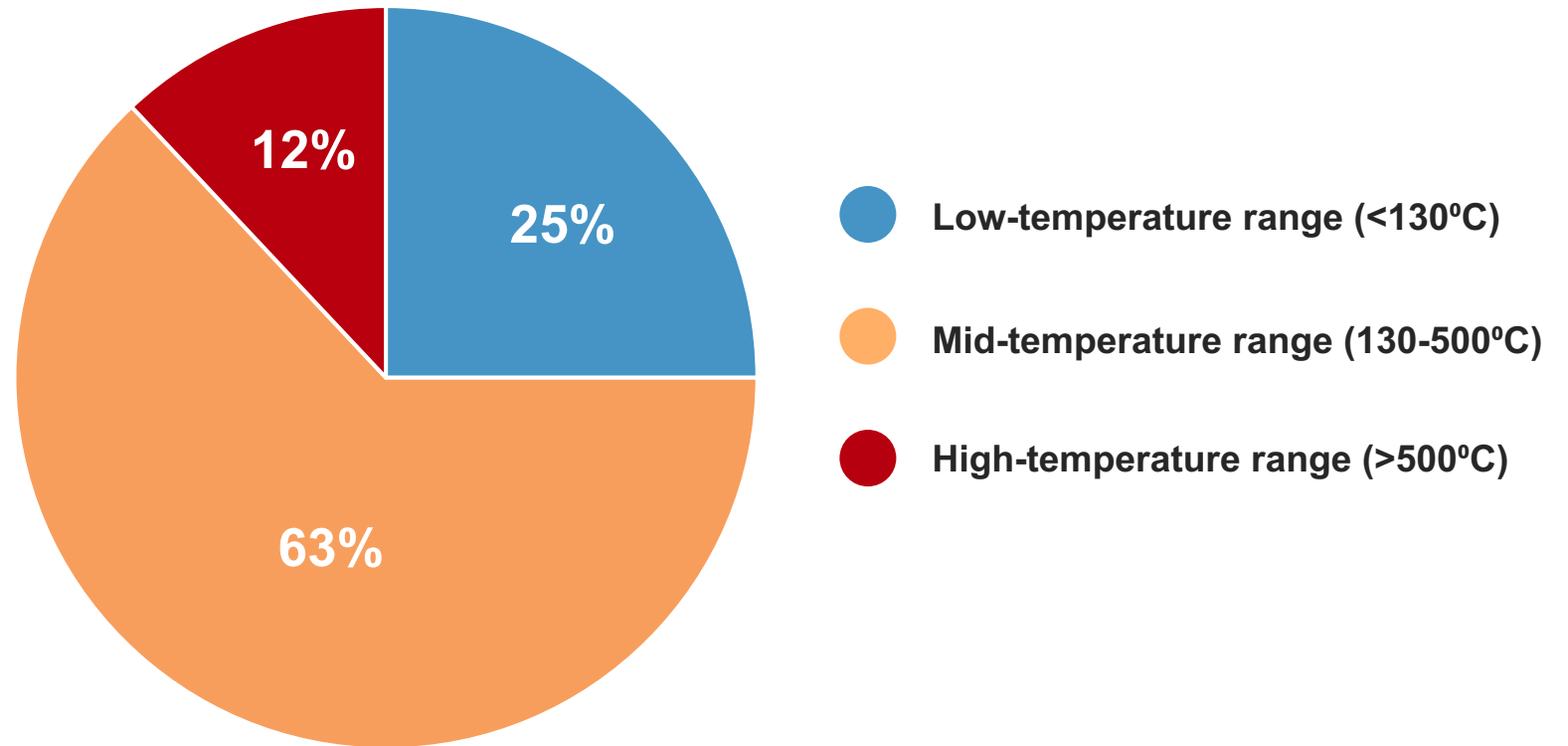
## Reactors | ~260-480 °C

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.



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

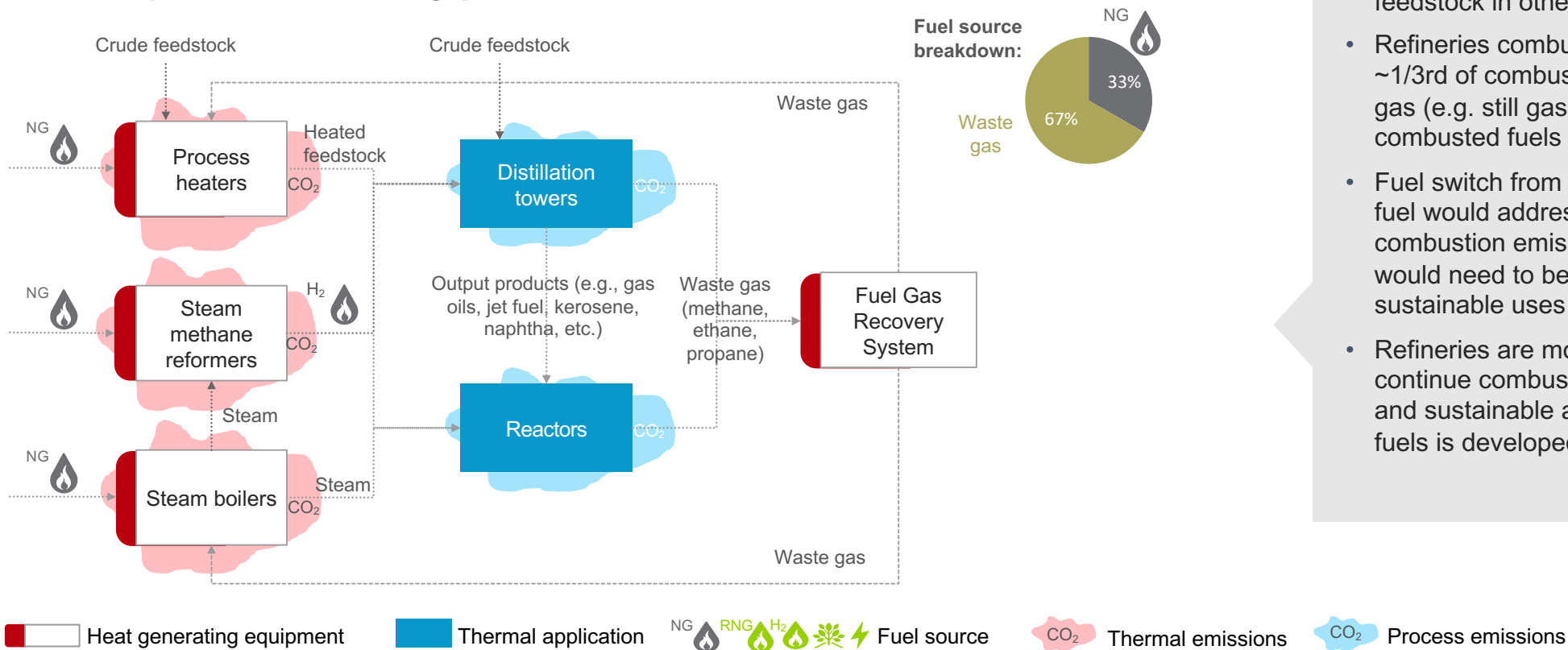
**Thermal energy consumption (TBtu) by heat temperature range (°C)<sup>1</sup>**



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

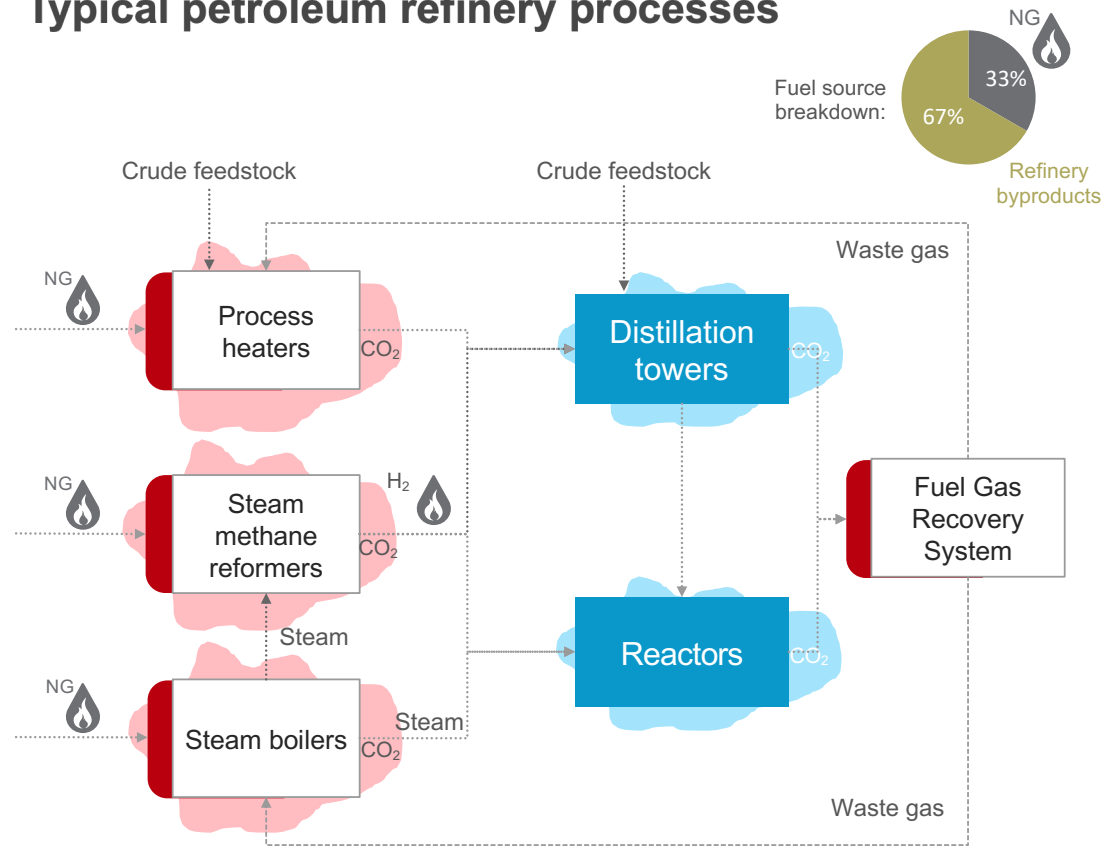
## Current petroleum refinery processes



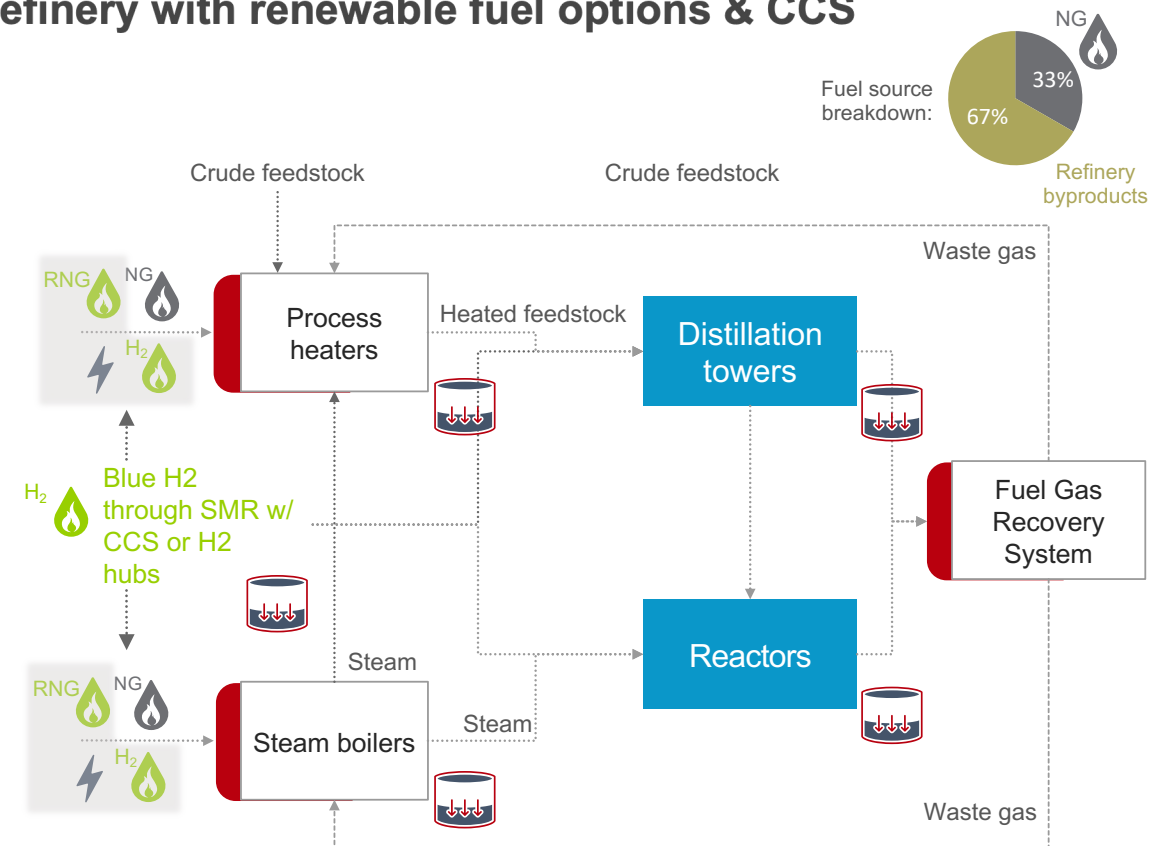
- Petroleum refineries typically use process heaters and steam boilers that burn natural gas to create steam heat, which is moved around the facility through a steam network system distributing heated steam to applications
- Natural gas is also used in steam methane reformers to produce hydrogen; NG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

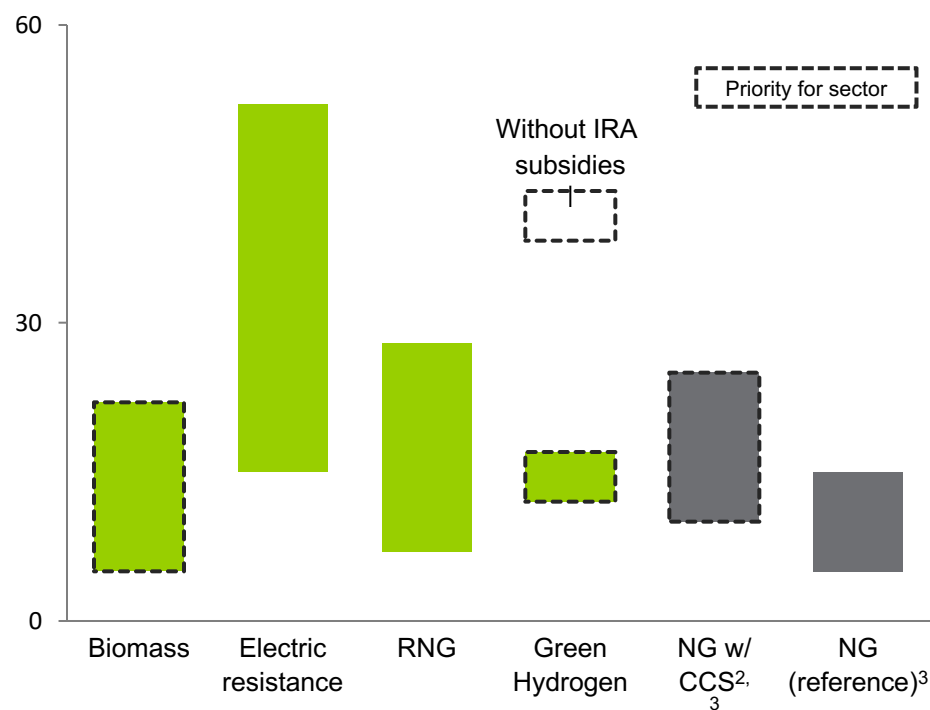


Heat generating equipment Thermal application Fuel source Thermal emissions Process emissions CCS

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

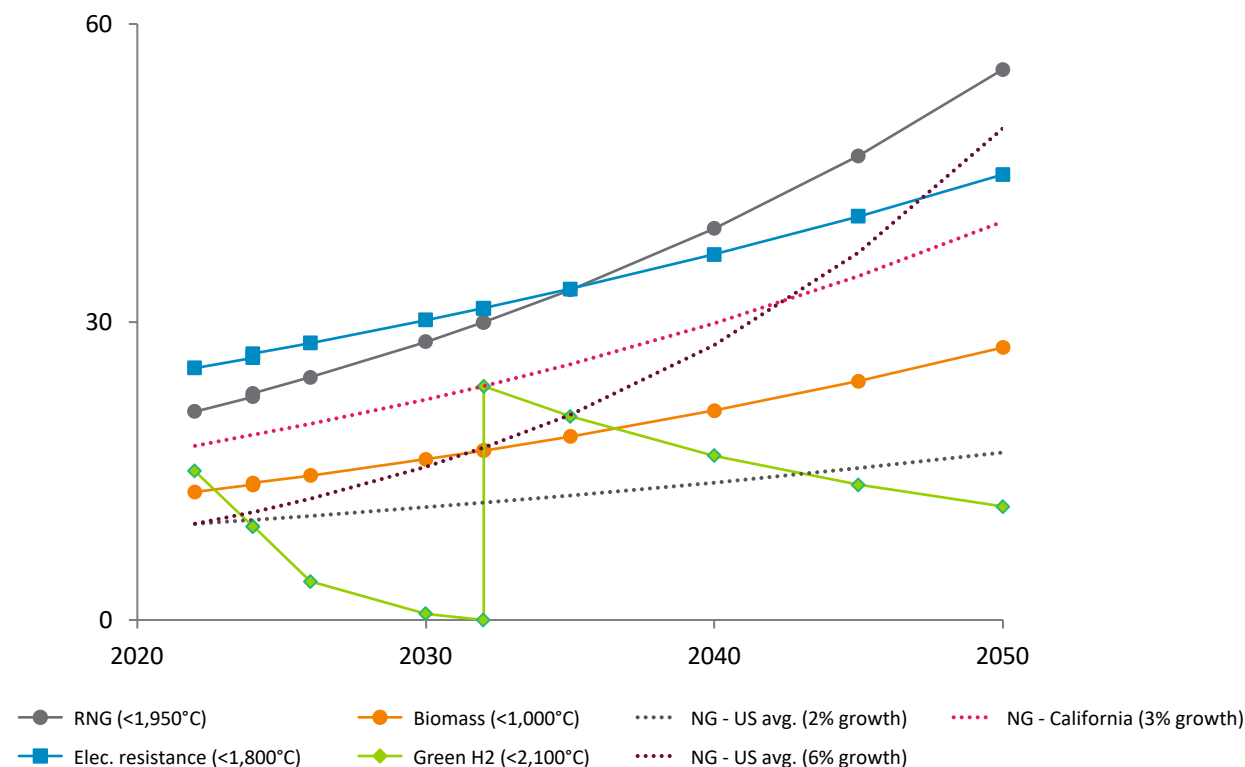
## 2022 LCOH for relevant technologies<sup>1</sup>

(\$/MMBtu)



## Projected LCOH for relevant technologies<sup>1</sup>

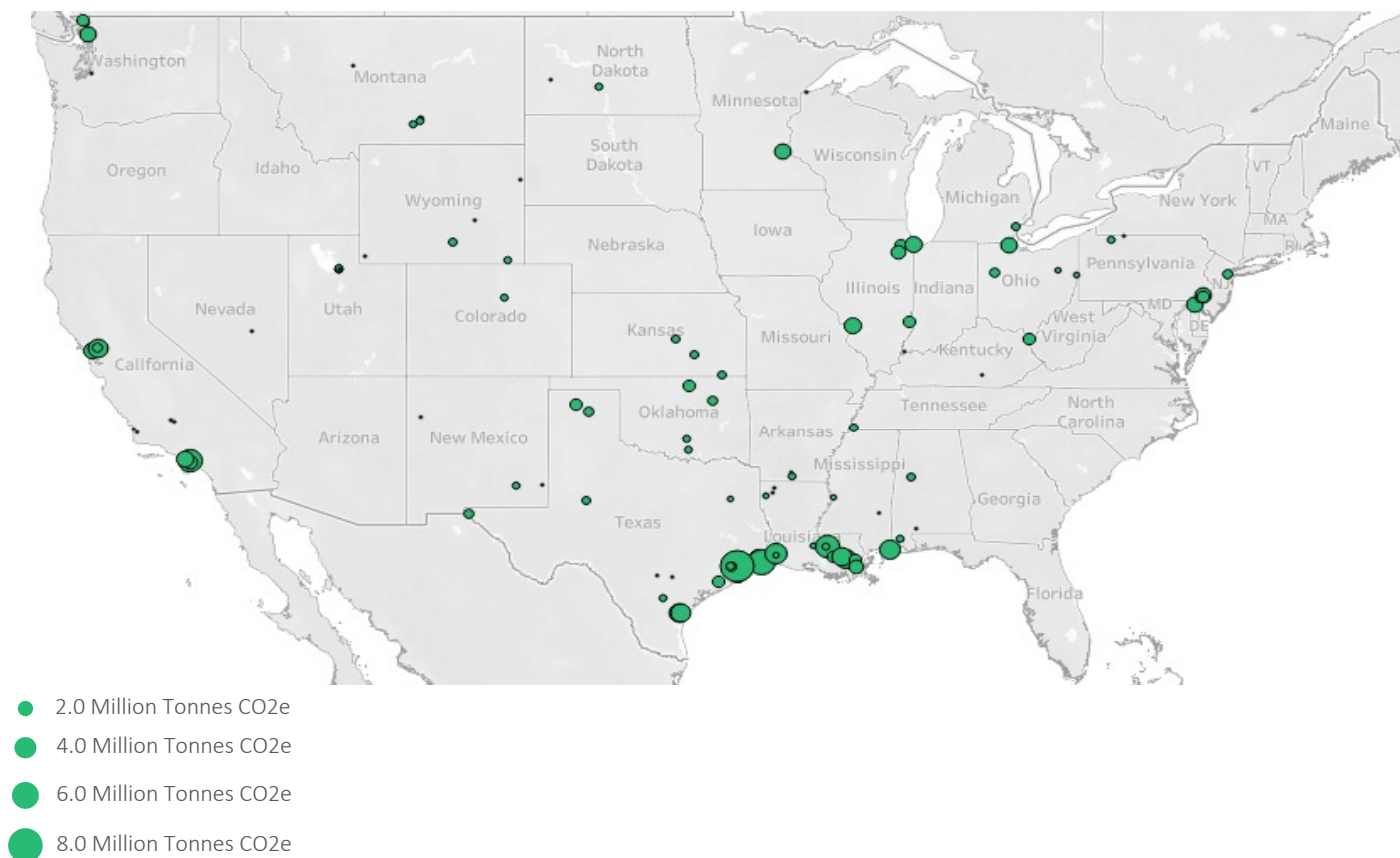
Average US LCOH (\$/MMBtu)



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<sup>1</sup>

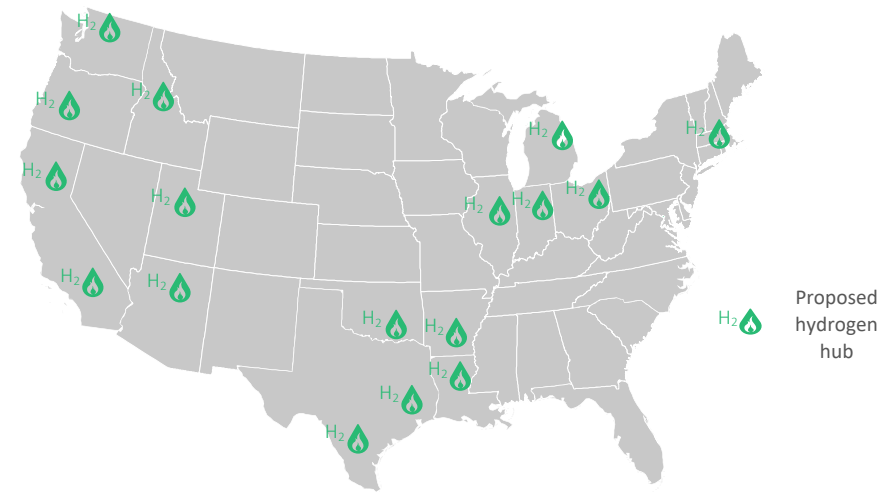


1. EPA GHGRP Inventory FLIGHT Database (2018); captures actual onsite reported emissions for large emitters emitting >25k tonnes of CO<sub>2</sub>e per year

CCS sequestration geographies<sup>2</sup>



Proposed hydrogen hubs<sup>3</sup>



Proposed hydrogen hub

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

Concentration of CO<sub>2</sub> in flue gas, government subsidies

### Target First Movers

Regions with refinery clusters and adequate geology for storage

Approximately  $\frac{2}{3}$  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

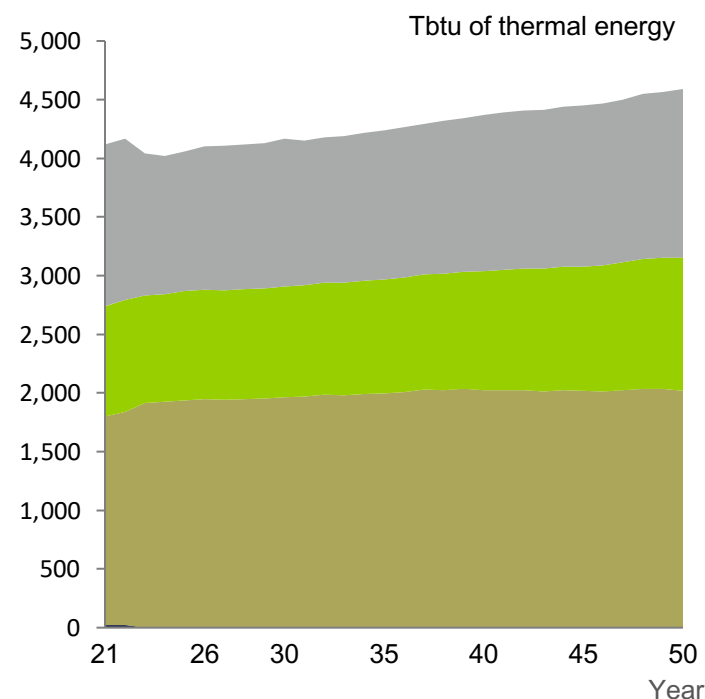
Refineries generate process heat by burning natural gas as well as refinery byproducts such as still gas. **Byproducts form the majority of combusted fuels, representing ~2/3rds of total fuel combustion; natural gas combustion represents ~1/3rd**

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**

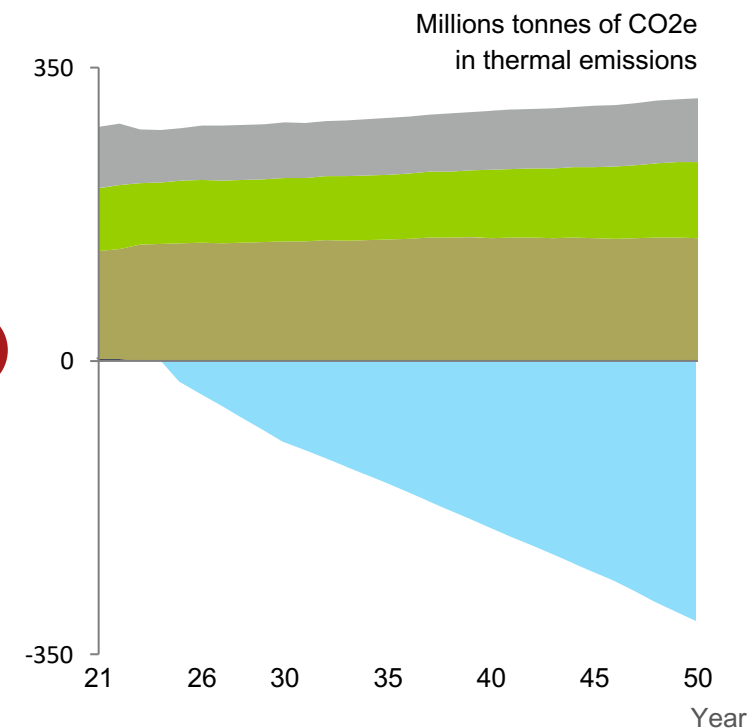
Natural gas combustion in refineries can be switched to low carbon fuels, but such fuels are supply constrained and may be better prioritized for other sectors (e.g., the refinery demand for green hydrogen to displace natural gas combustion would rival the demand for green hydrogen to replace NG combustion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

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

## Thermal energy consumption<sup>1</sup>

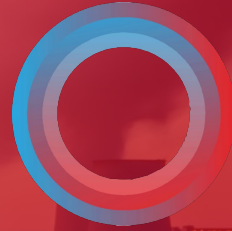


## Thermal emissions<sup>2</sup>



Legend: Natural gas (grey), Biofuels & coproducts (green), Petroleum & other (olive), Coal (brown), CCS (blue)

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 CO<sub>2</sub>e 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

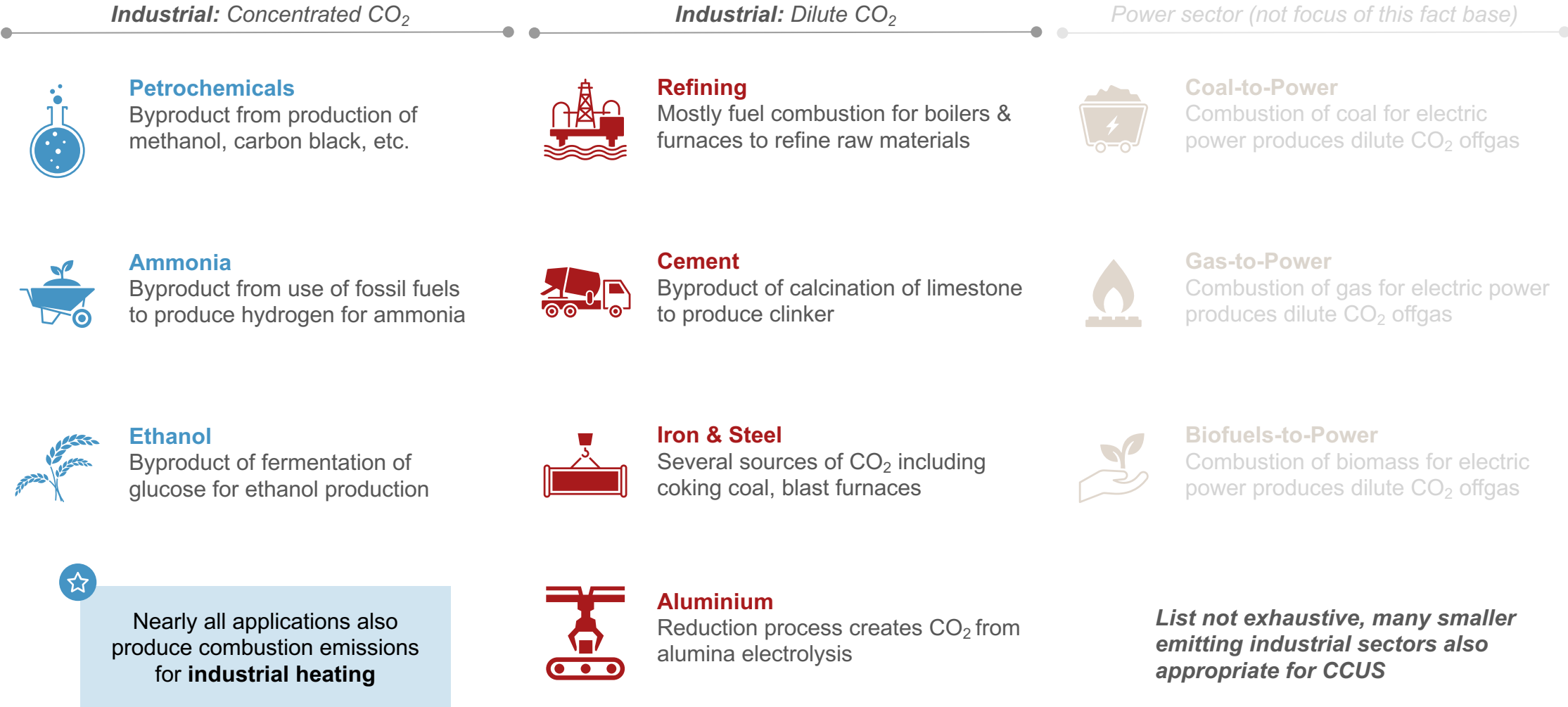


# Carbon capture for use or sequestration

Renewable Thermal Technology

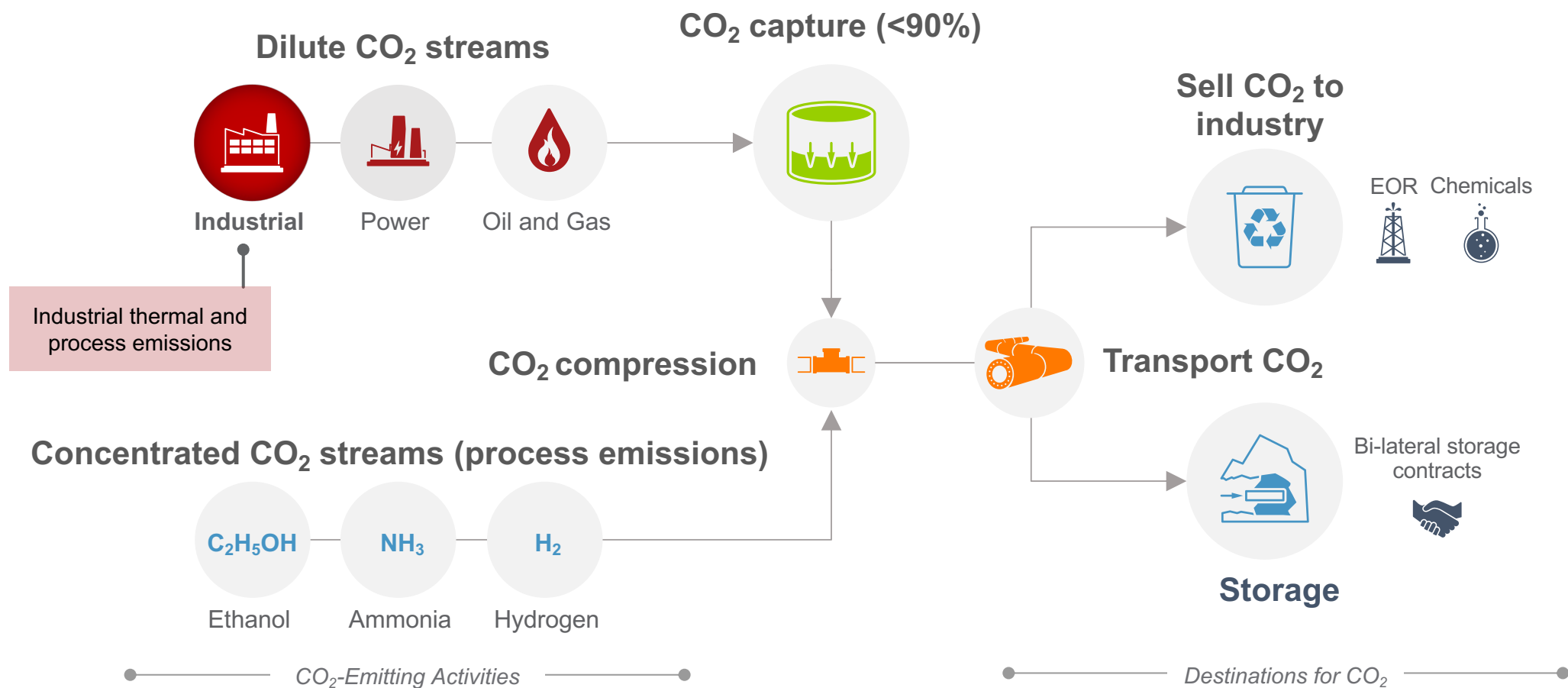


# Carbon capture is applicable for a range of large stationary combustion and process emitters





# CCUS captures up to 90% of CO<sub>2</sub> 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 CO<sub>2</sub> in capture stream



## Location

- CO<sub>2</sub> source location important for:
  - aggregating emission streams
  - transport of captured CO<sub>2</sub>
  - storage or use of CO<sub>2</sub>



## Source of Heat

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



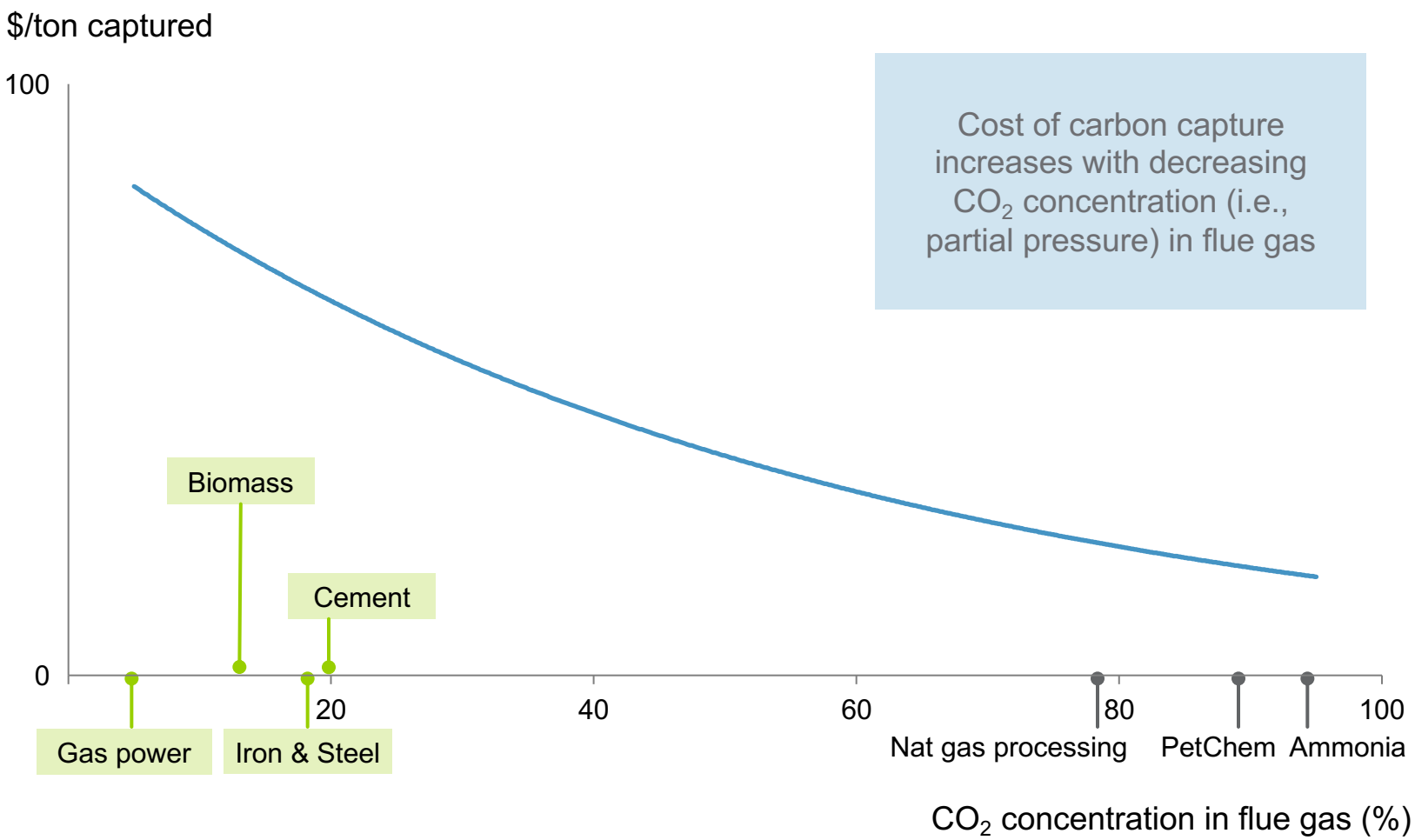
## Process Emissions

- Opportunity to simultaneously capture non-combustion process emissions



# Concentration

## Level of CO<sub>2</sub> in flue gas is a key cost driver



- Flue gas from industrial thermal combustion typically contains <10% CO<sub>2</sub>, resulting in higher carbon capture costs relative to process emissions
- *Note: Cost of CO<sub>2</sub> capture (\$/ton) is independent of emissions intensity (kg CO<sub>2</sub> per MMBtu) and fuel costs*

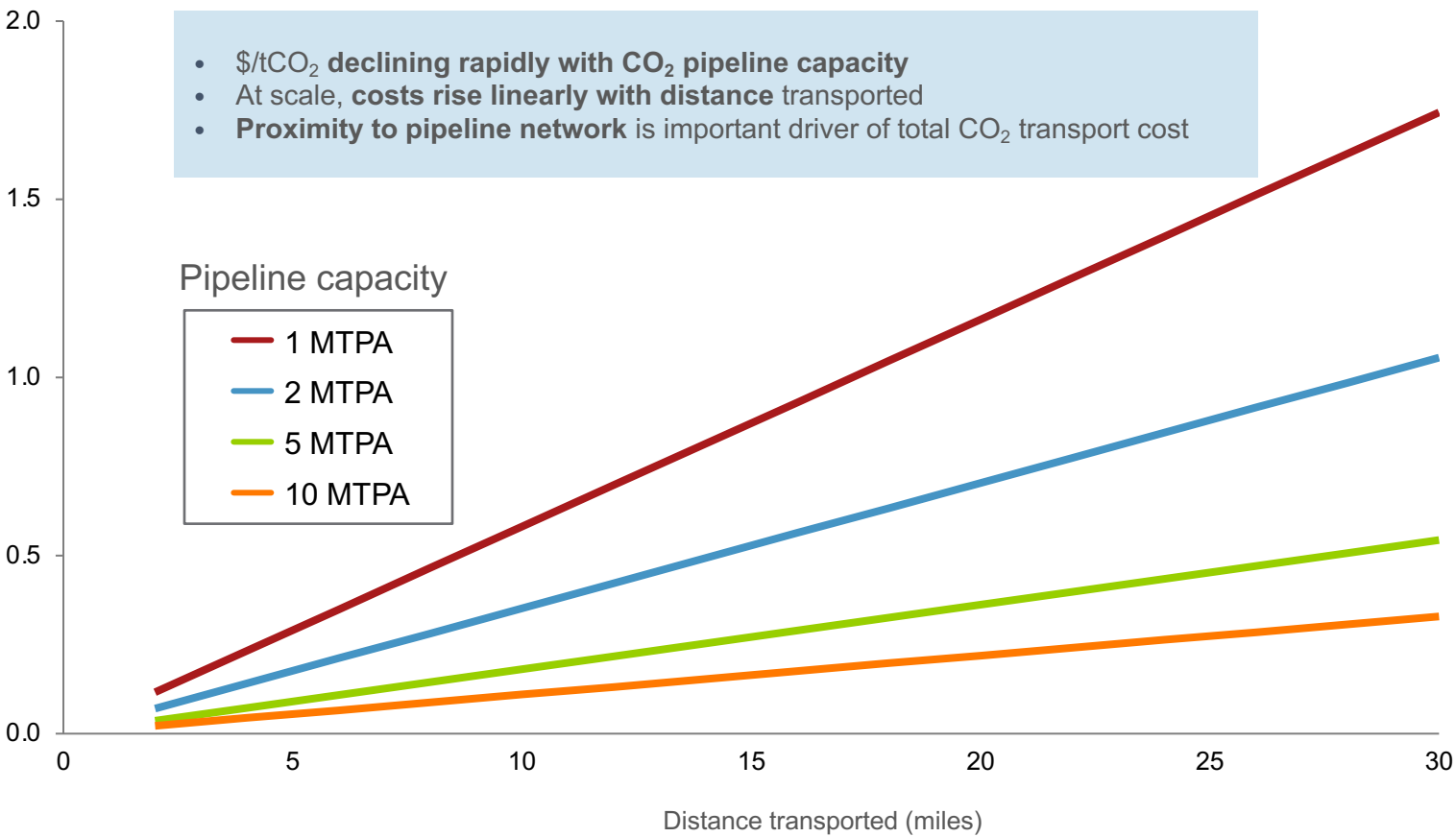
Note: Assuming 8% WACC, 85% utilization rate, 20-year lifetime  
Source: Industry Sources, NPC, IEAGHG, BCG Analysis



Location

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

Trunk pipeline total cost (\$/tCO<sub>2</sub>)

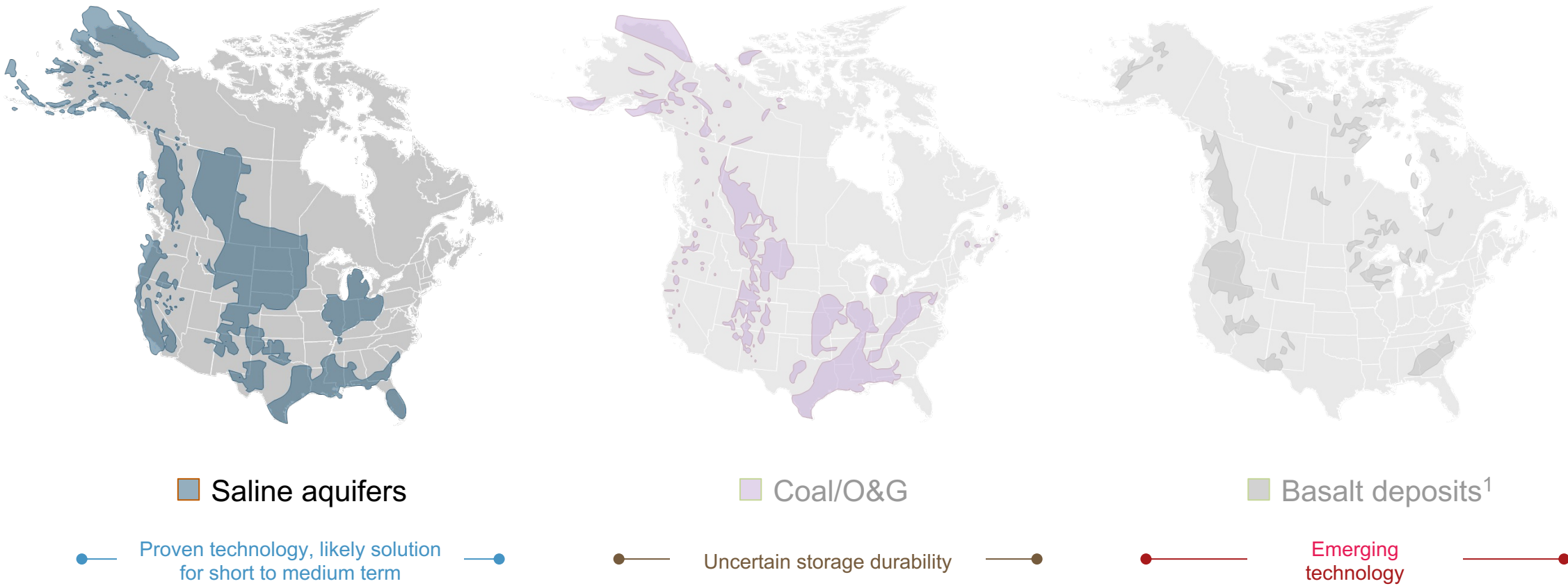


- Pipeline network development is likely necessary to unlock CCS potential for a wider set of industrial players.
- Joint or national development of CO<sub>2</sub> pipeline will accelerate CCS for industrials, who may be currently geographically challenged to deploy CCS



Location

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

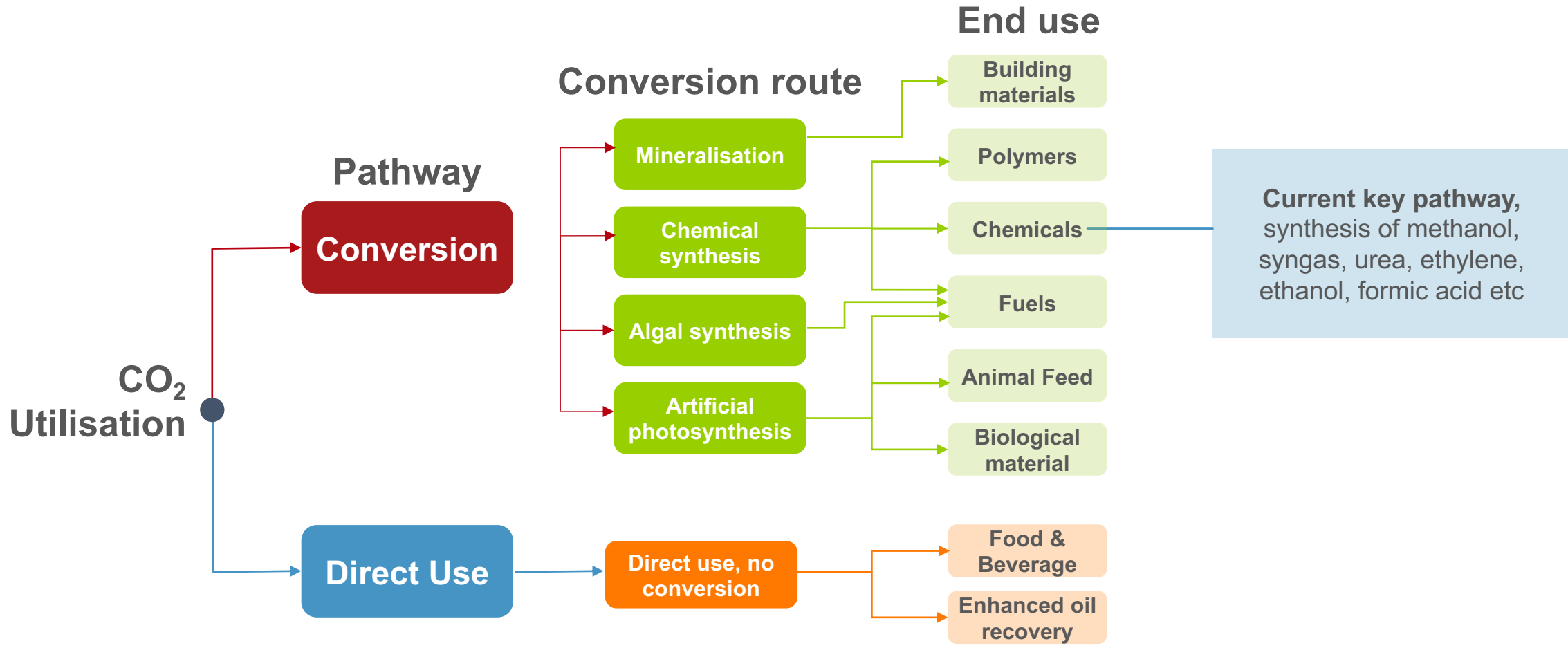


1. Not yet fully proven but with high expectation as a form of permanent CO2 sequestration given the chemical reactions within basalt to form solid carbonates  
Source: USGS, NETL NATCAB



Location

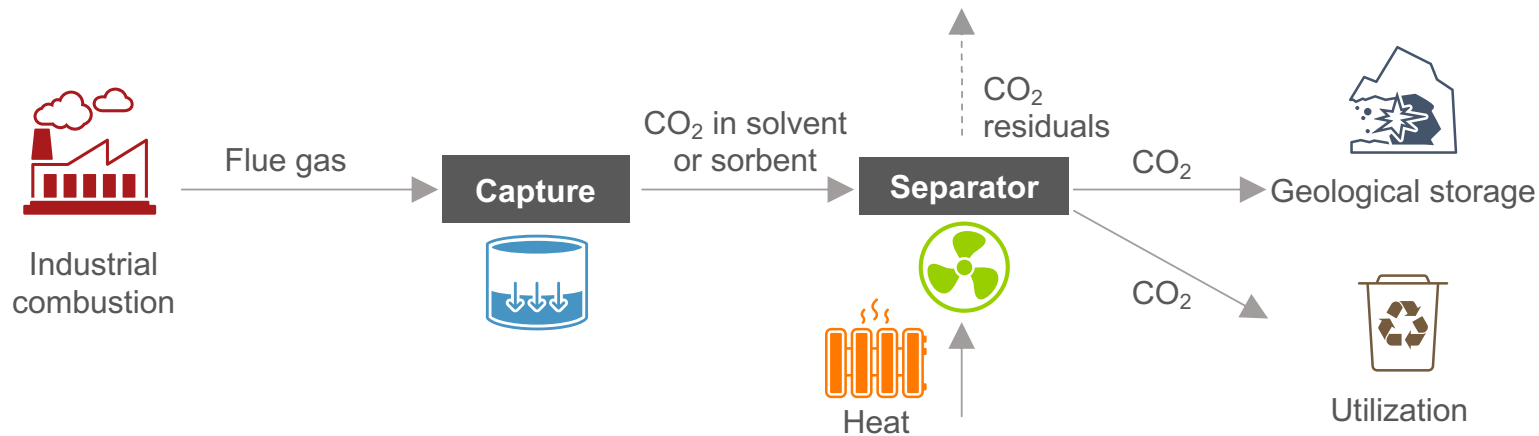
**Similar to storage, utilization of captured CO2 also depends on proximity between source of emissions and end use location**





## Source of Heat

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



- Existing CCUS systems typically use a solvent (e.g., MEA) to capture CO<sub>2</sub>, while novel CCUS systems are being developed using pressure-swing or electrification processes
- Heat at approximately 120°C is applied to the solvent to release CO<sub>2</sub>
- Depending on flue gas CO<sub>2</sub> 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<sub>2</sub>
- Waste heat streams is the most effective way to provide heat to drive the carbon capture process

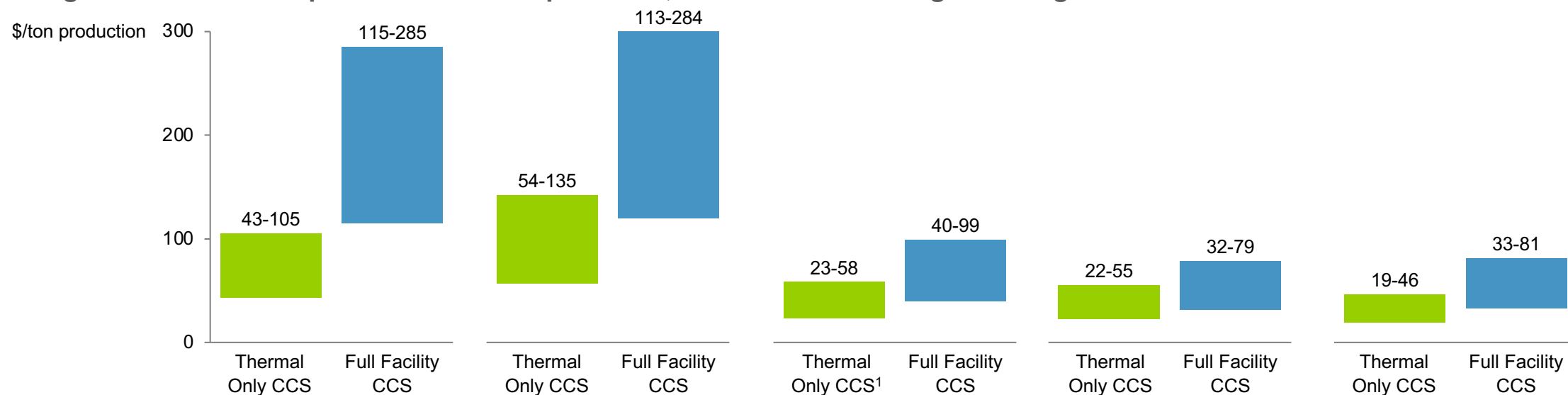
## Forms of regeneration heat (in order of descending cost)

- 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



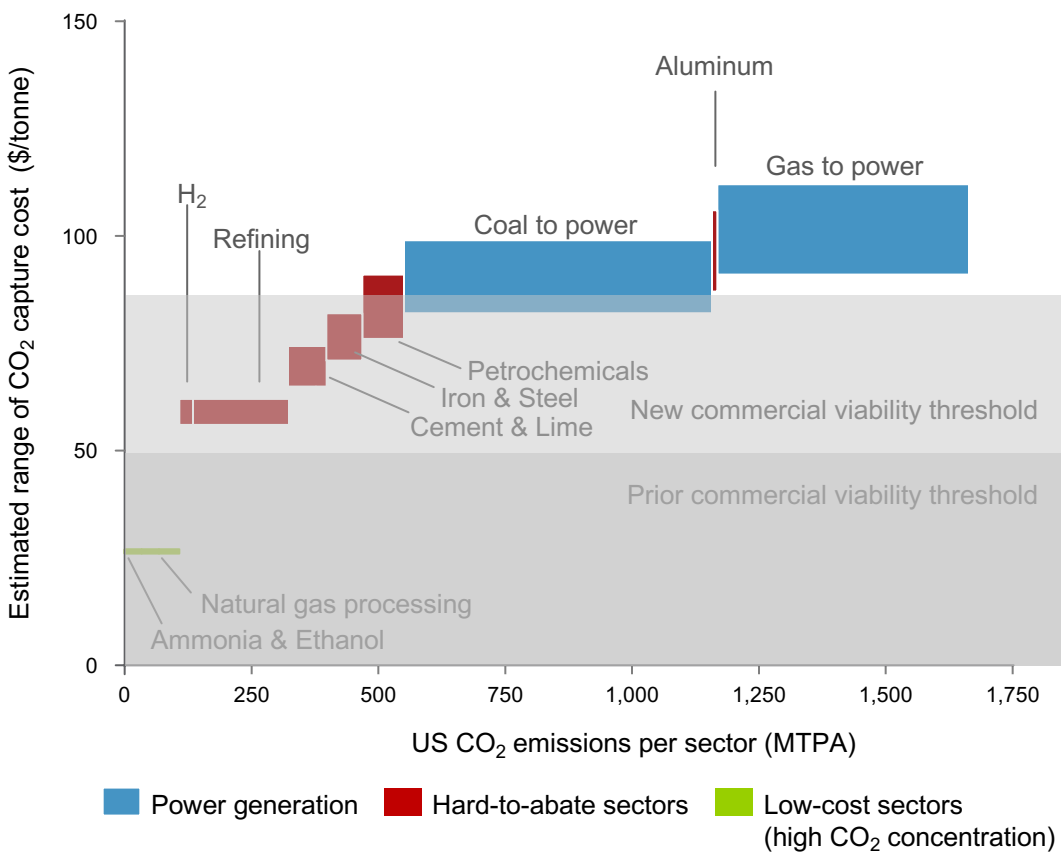
|                                        | Ammonia                | Steel                            | Cement clinker | Glass           | Methanol        |
|----------------------------------------|------------------------|----------------------------------|----------------|-----------------|-----------------|
| 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

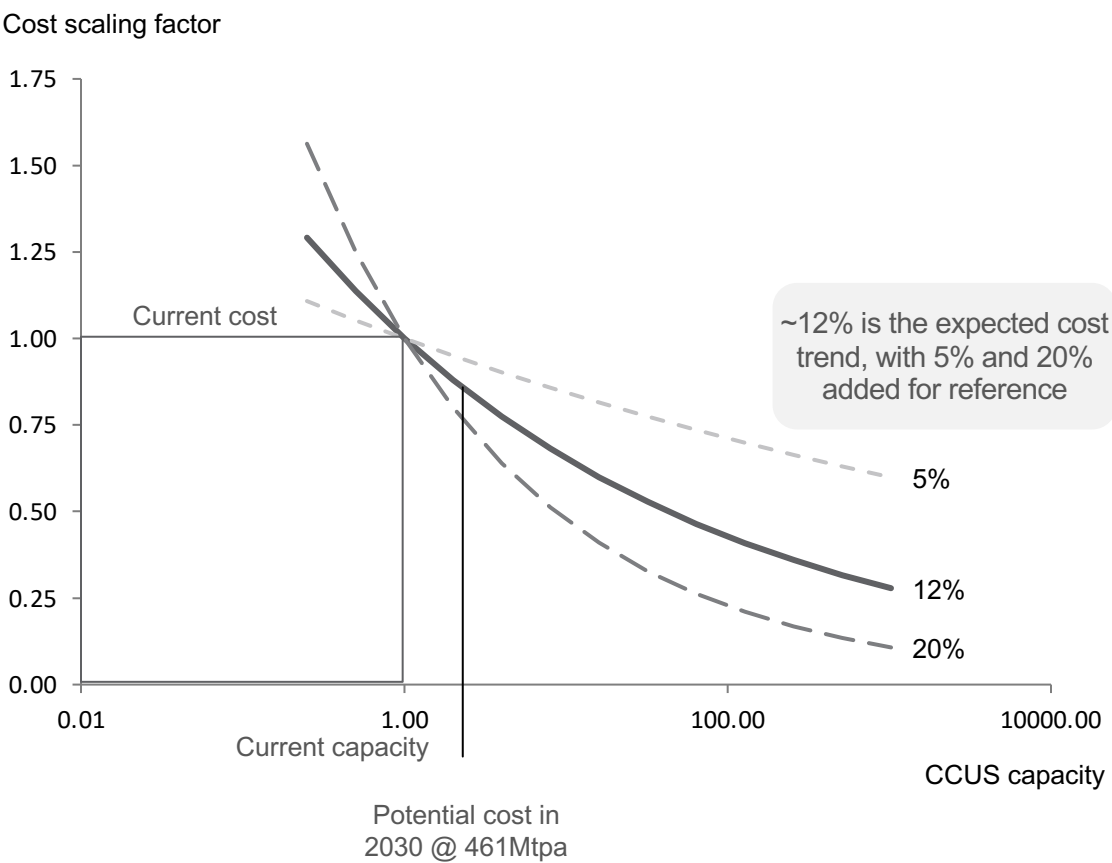


# Inflation Reduction Act increases 45Q tax credits to \$85/t making CCUS potentially viable for refining, hydrogen, cement, & steel sectors

\$85/ton incentives significantly expand CCUS commercial viability

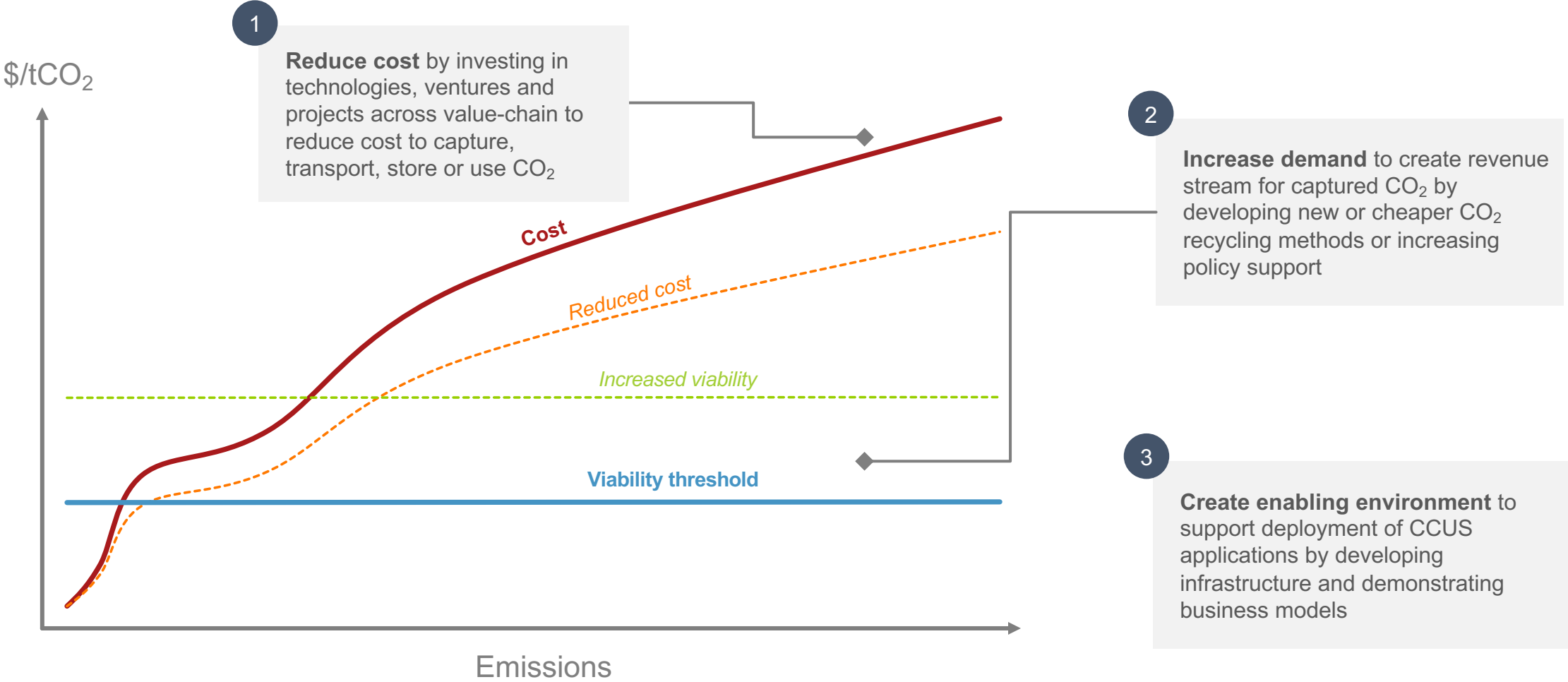


...and further cost reductions of ~12% are expected as deployment doubles, making coal+CCUS potentially viable



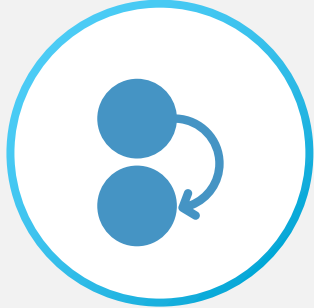


# Three broad strategies can increase the viability of CCUS for industrial heating decarbonization



# 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



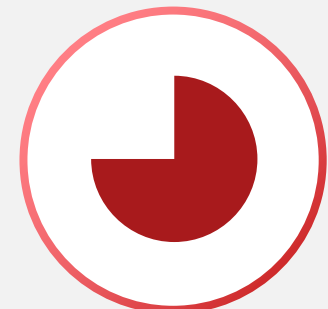
Cost can be high and does not add value unless there is a price on carbon



Extensive supplemental infrastructure required



Non-renewable and not a long-term solution



Does not capture 100% of CO2 emissions





# Clean Hydrogen

Renewable Thermal Technology



# 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<sub>2</sub> 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<sub>2</sub> and are non-renewable (i.e., blue and grey H<sub>2</sub>).
- 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<sup>1</sup>



Hydrogen combustion boilers<sup>2</sup>



Hydrogen catalyzed boilers<sup>3</sup>

*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 °C
  - 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 °C 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<sub>2</sub> 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<sub>2</sub> hubs**
  - **Other potential application (partial decarbonization)**
    - ☆ Blending (up to 15% H<sub>2</sub>) 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*

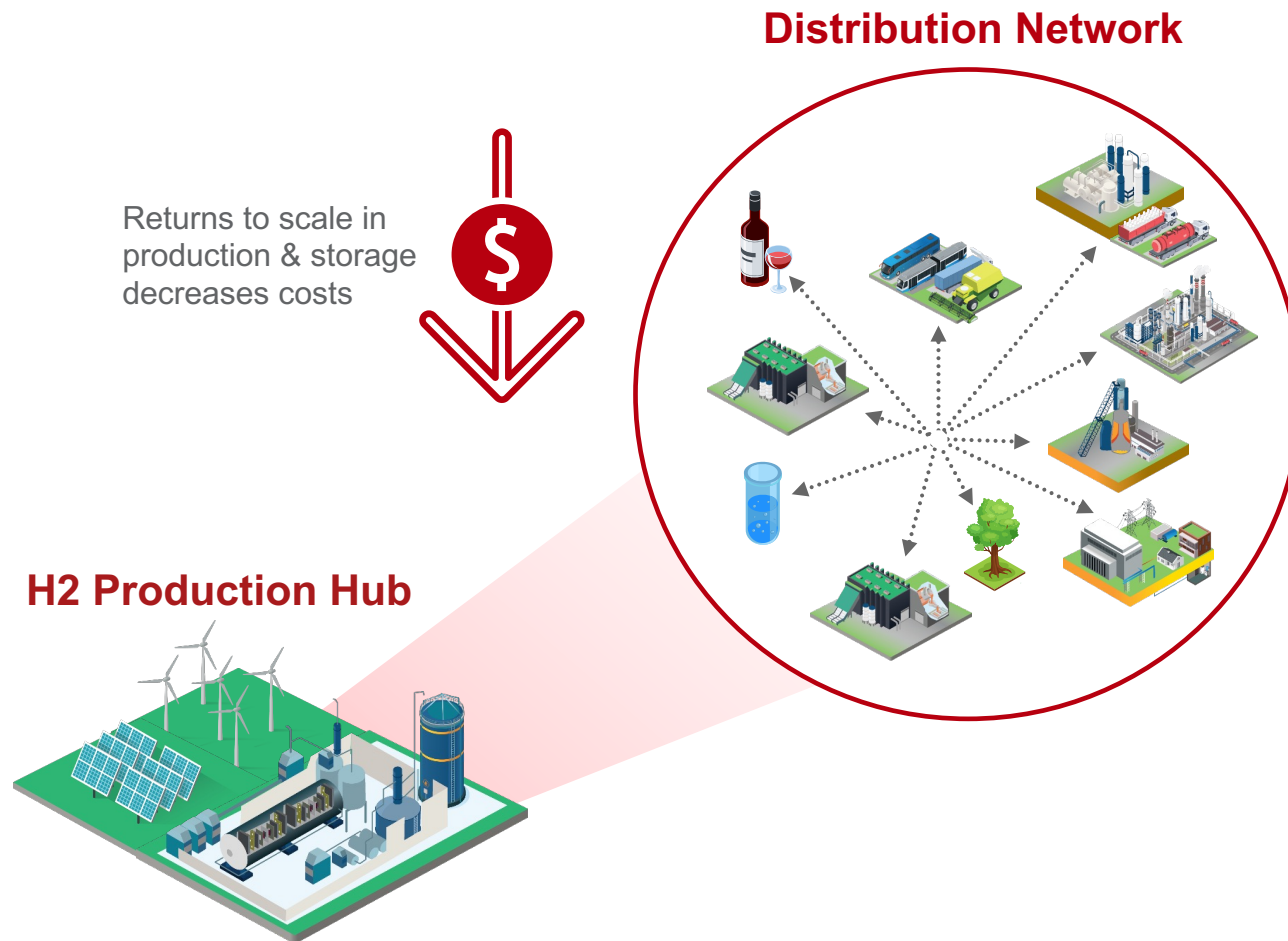




# Central hubs are cost advantaged compared to onsite hydrogen production

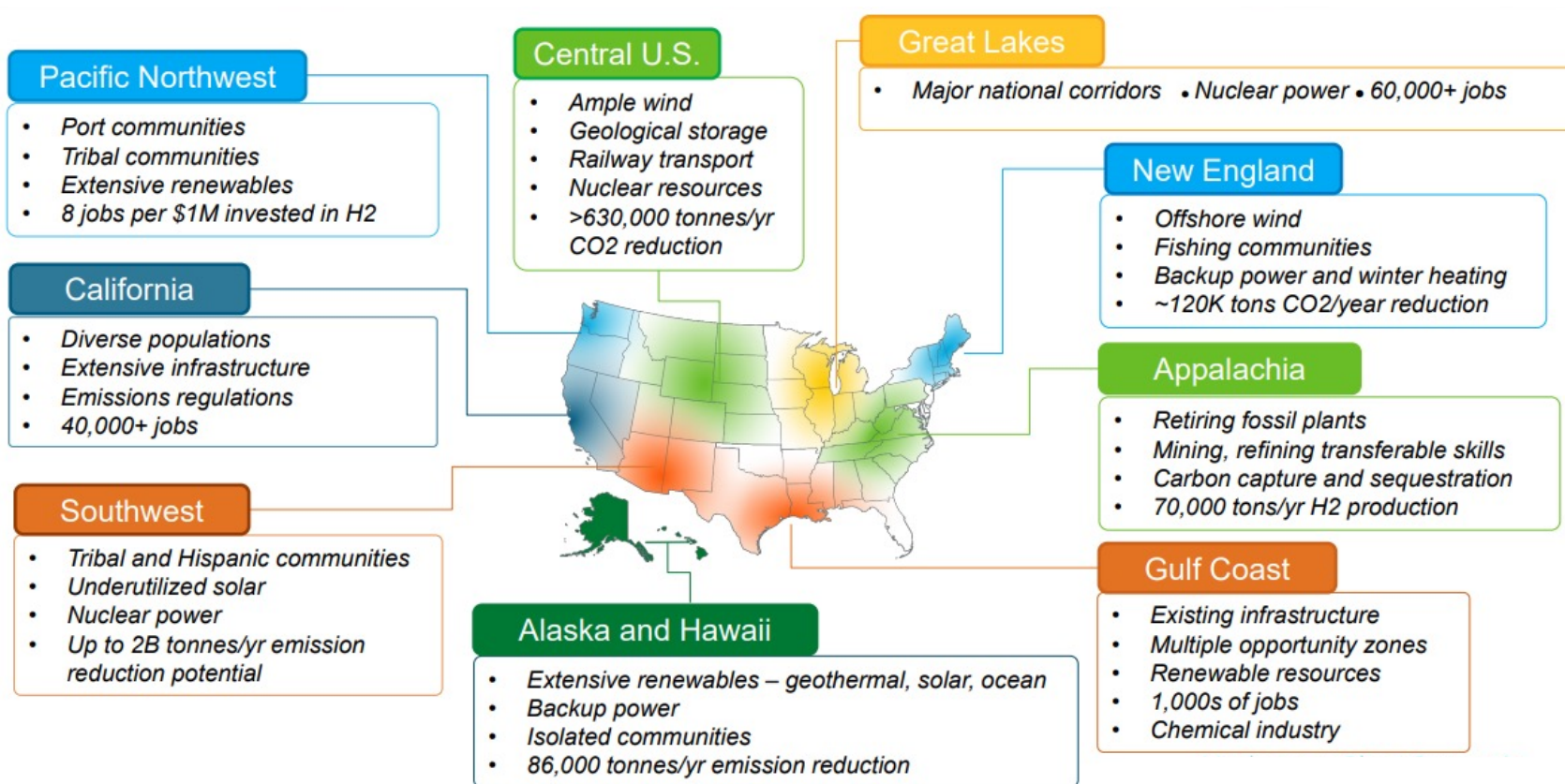
**Adding additional demand sites to the hub decreases cost through returns to scale**

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.





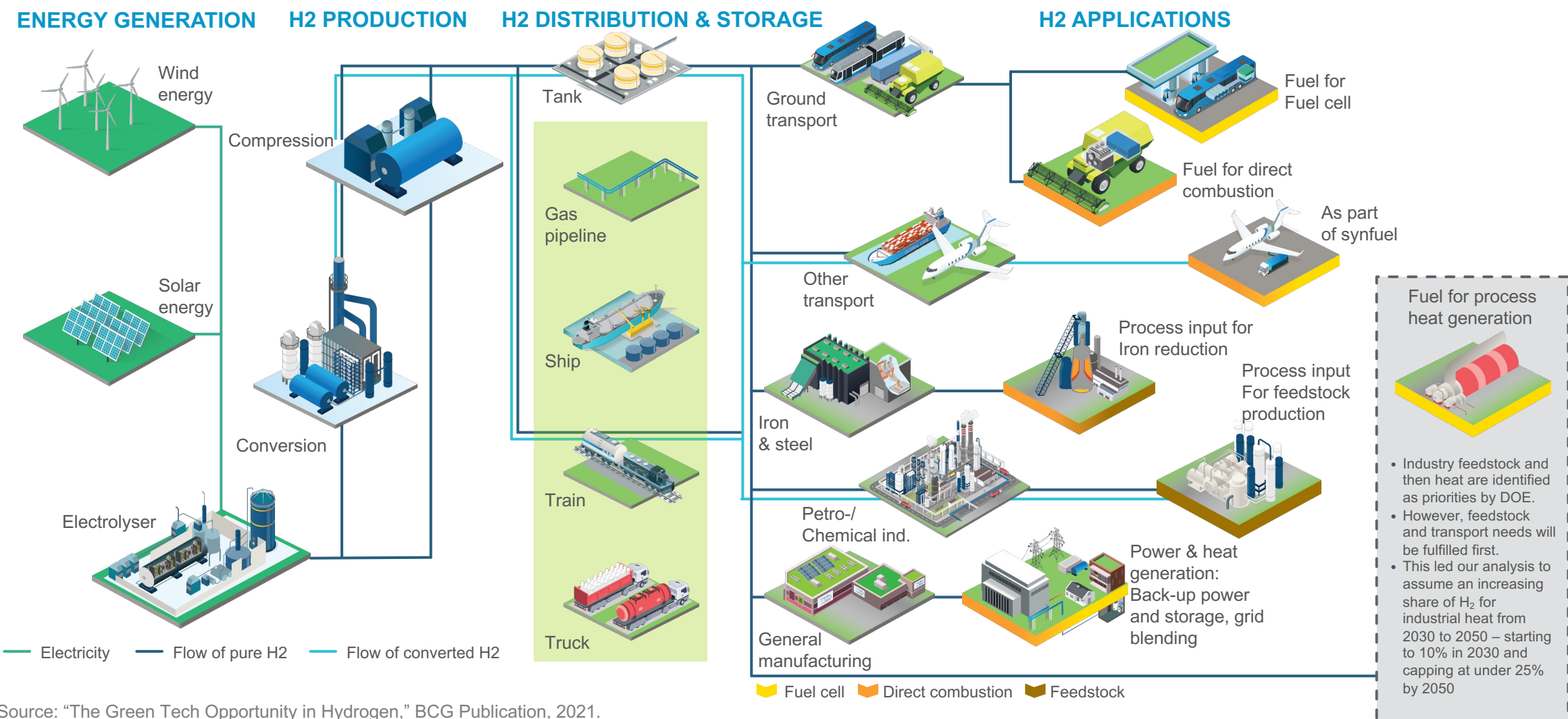
# DOE identified 9 potential regional hubs for clean hydrogen production to accelerate decarbonization across sectors and geographies



**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



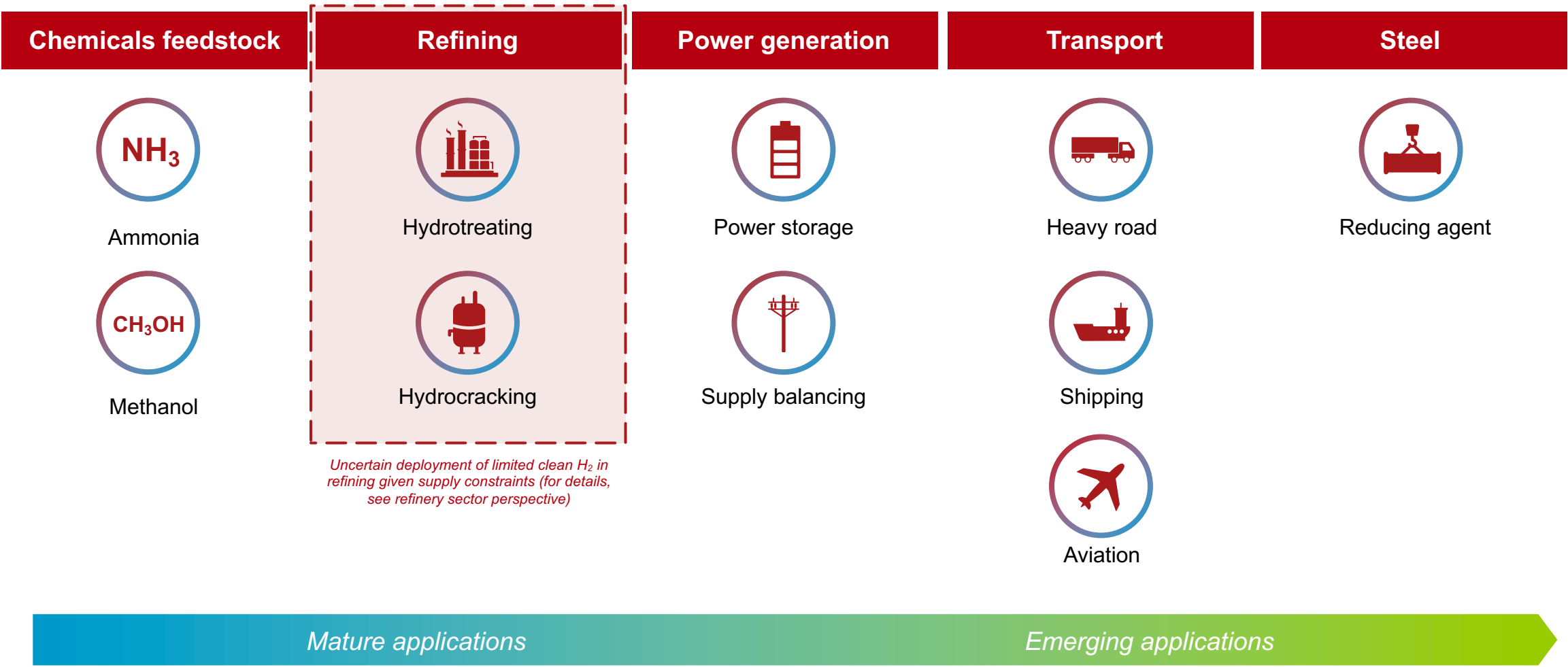
# Hubs centralize the production, storage & distribution of hydrogen to supply various current and emerging consumers of hydrogen



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

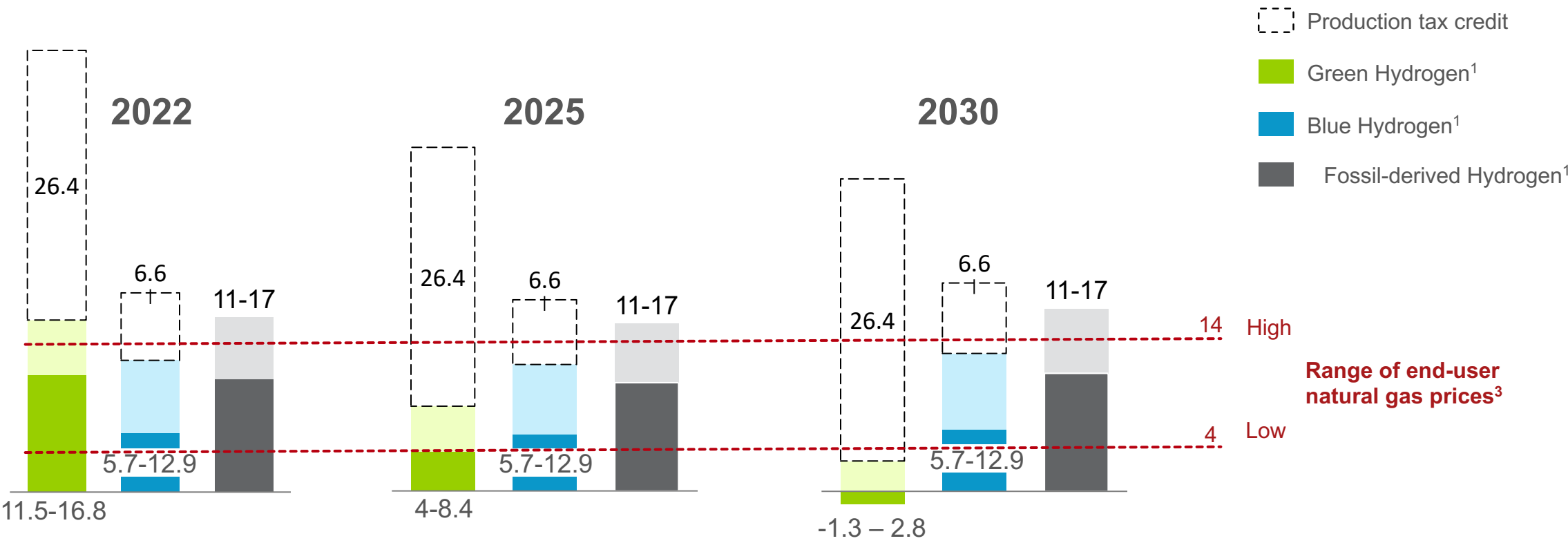




# With Inflation Reduction Act subsidies, hydrogen prices are expected to be competitive relative to natural gas prices today

## United States Levelized Cost of Hydrogen (\$/MMBtu, production cost plus T&D costs)<sup>1</sup>

Lighter shades reflects range of cost uncertainty<sup>2</sup>

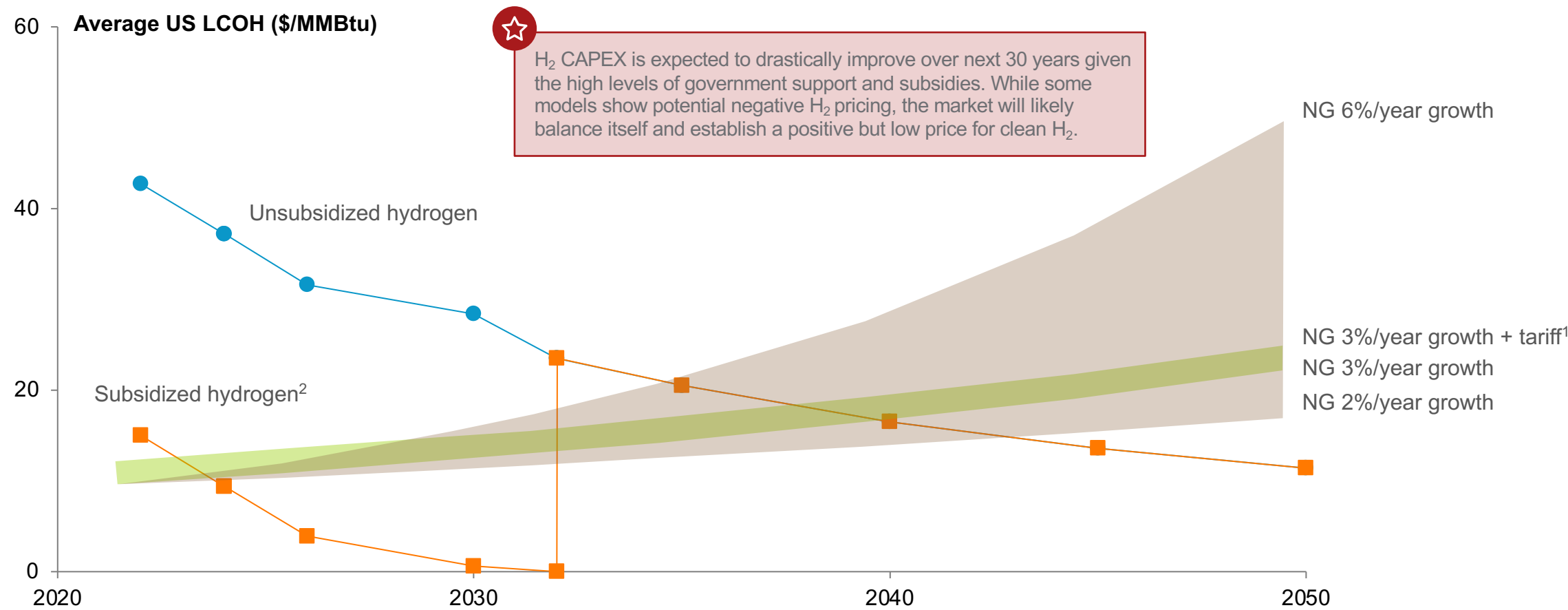


1. Lighter shade reflects pricing uncertainty regarding natural gas (lower limit \$2/MMBTU, upper limit \$5/MMBTU) and electricity; 2. Starts at \$0.4/kg H<sub>2</sub> for 60-75% greenhouse gas reduction vs fossil-derived hydrogen, goes up to \$0.75/kg H<sub>2</sub> for 75-85% greenhouse gas reduction;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

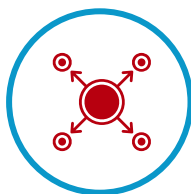


1. Based on \$51/tonne CO<sub>2</sub> social cost of carbon; 2. Inflation Reduction Act hydrogen production tax credit and investment tax credits



**Significant  
advancements will be  
required for green H<sub>2</sub>  
to become competitive  
for decarbonization of  
industrial thermal  
applications**

## Key advancements needed to achieve green H<sub>2</sub> feasibility



### Develop H<sub>2</sub> hubs

Industrial players should support and invest in H<sub>2</sub> hubs now to secure future H<sub>2</sub> supplies



### Reduced power price

Resulting in OPEX reduction (e.g., from wind / solar reduced costs, cost exemptions<sup>1</sup>)



### 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<sub>2</sub> price)



### High levels of VRE

More variable renewable energy disrupting the grid & requiring new solutions (e.g., storage)

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



# Industrial heating using H<sub>2</sub> 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

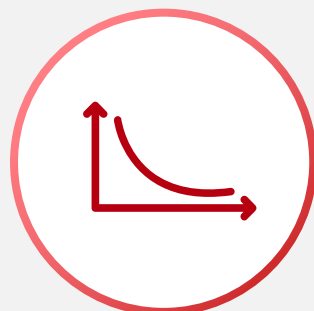
## Barriers



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



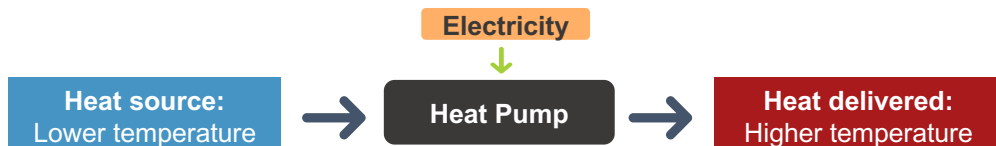
RENEWABLE  
THERMAL  
COLLABORATIVE



# 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<sup>2</sup>



Water source heat pump<sup>3</sup>



Absorption heat pump<sup>4</sup>

## Technical characteristics

- **Temperature range:** Up to 160 °C
  - Most heat pumps can deliver heat up to 100 °C at high efficiency
  - Meets low temperature industrial heating requirements (e.g., drying, washing, preheating)
  - Systems capable of providing temperatures above 200 °C 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

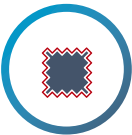
Key properties of solar thermal heating include:



160 °C 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:



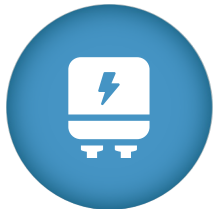
## Emissions and operating cost savings

- 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 <130°C 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

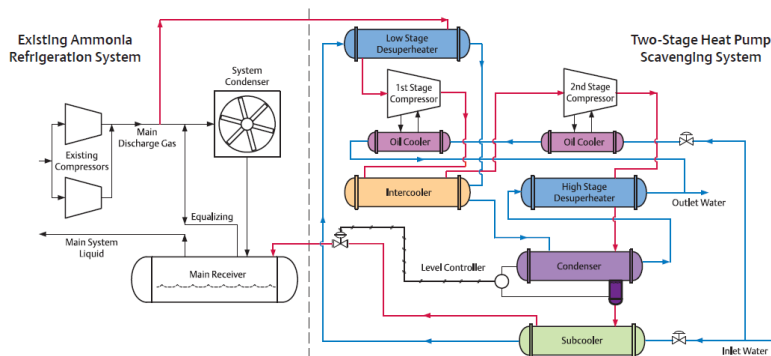
# Two case studies of industrial electric heat pumps show the range from mature to emerging application areas

## 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 °C to 88 °C 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.

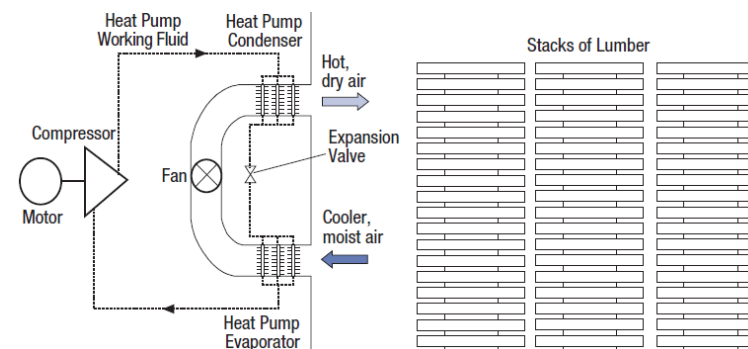


## Case study 2: Lumber Drying

- **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.





# 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<sup>1</sup>

|     | 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  | 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)

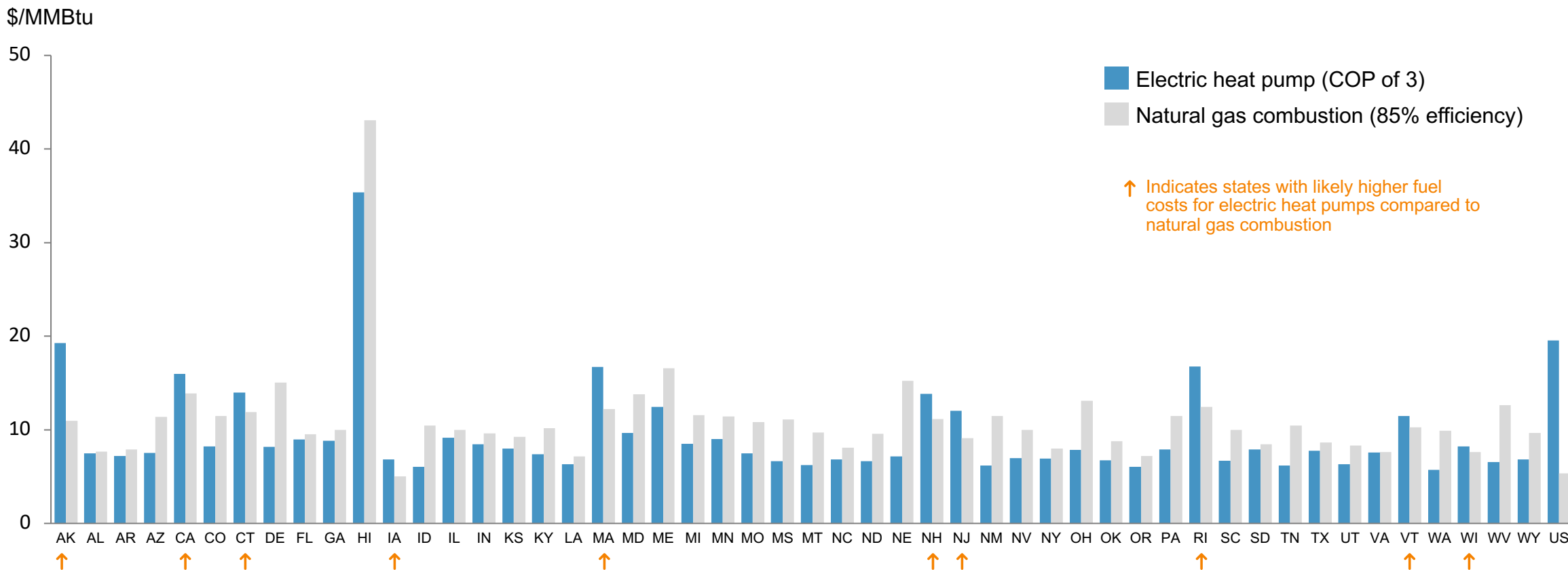
E.g., COP of 3 indicates an efficiency of 300%, by which every unit of electricity input yields 3 units of thermal energy output

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



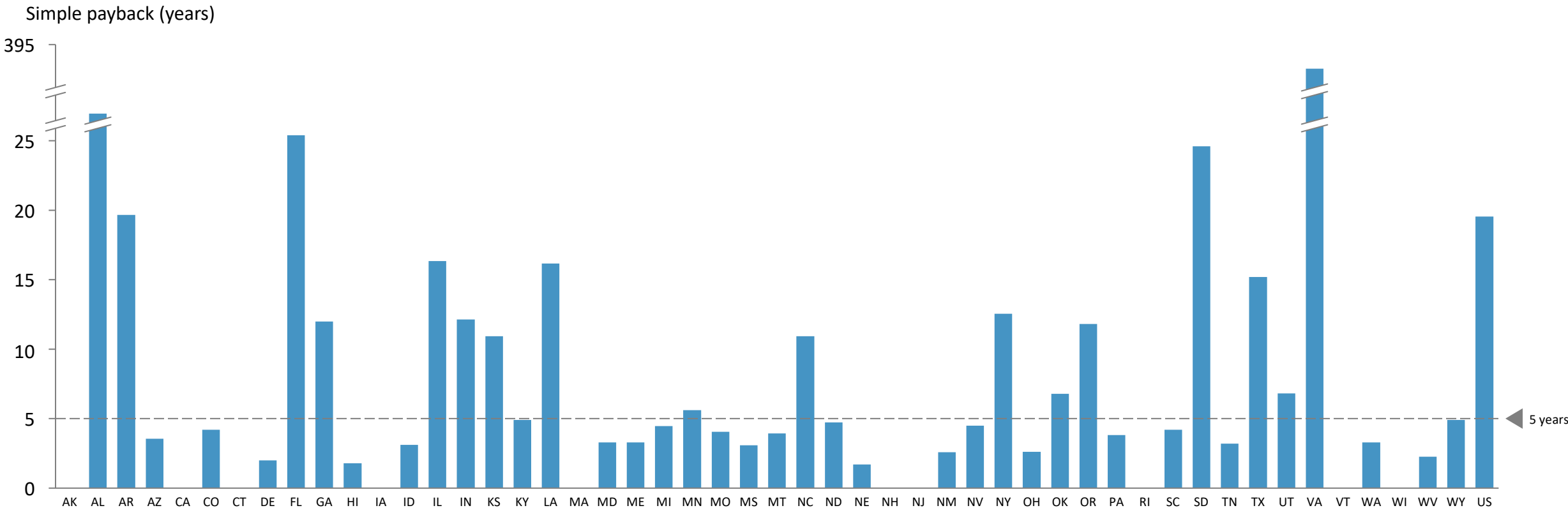
Note: Analysis assumes a moderate natural gas combustion efficiency of 85%, and a conservative heat pump COP of 3  
Source: US EIA Industrial Electricity Prices (May 2022), US EIA Industrial Natural Gas Prices (May 2022)





# 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



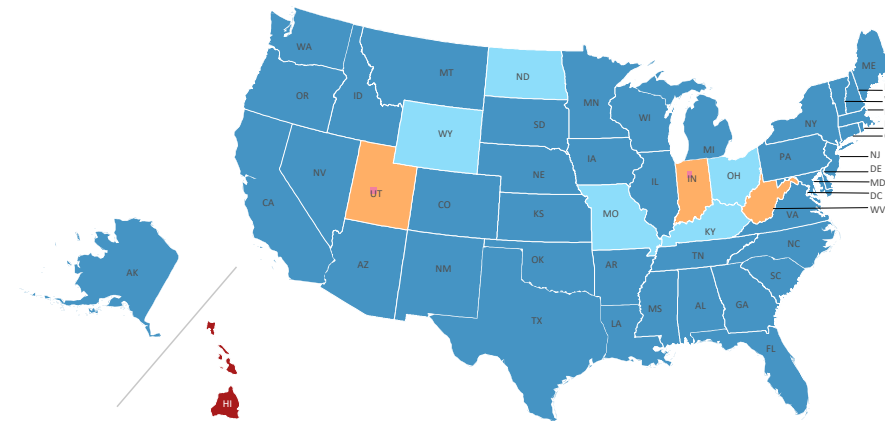
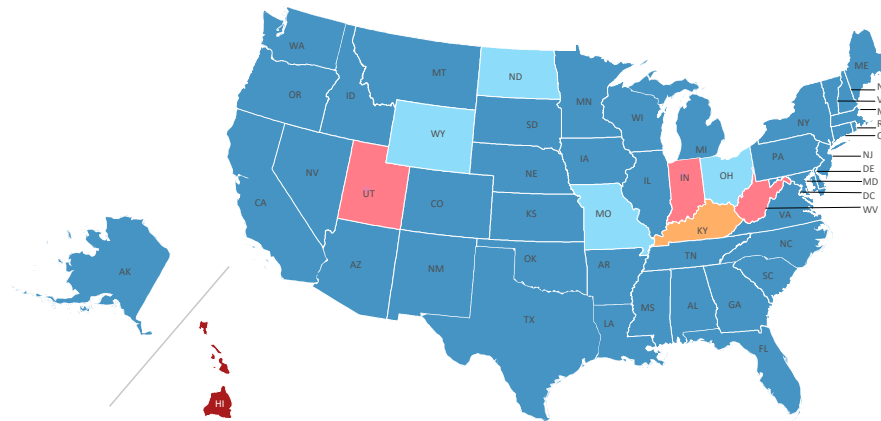
# Emissions savings are expected in nearly all states today by switching from natural gas combustion to electric heat pump heating

Scenario 1: 80% renewables by 2050

Scenario 2: 65% renewables by 2030

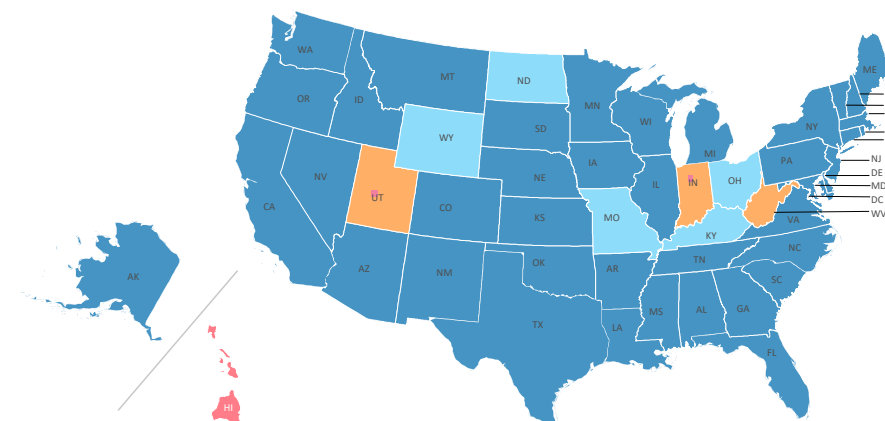
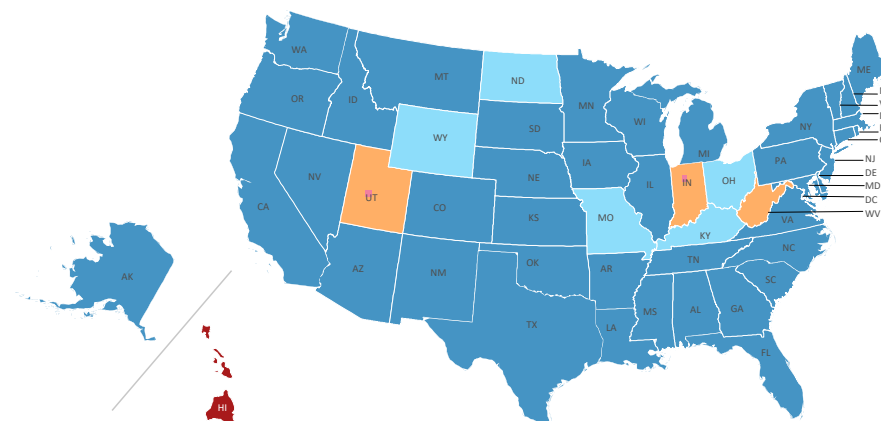
Likely reduction in emissions by switching from natural gas combustion<sup>1</sup> to electric heat pump<sup>2</sup> heating:

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



Scenario 3: 80% renewables by 2030

Scenario 4: Near 100% renewables by 2035





# 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

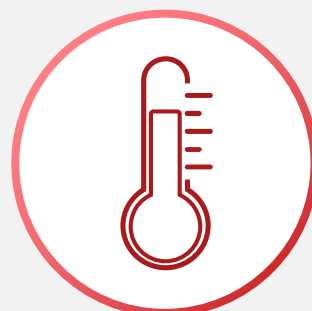
## Barriers



Higher capital costs relative to combustion equipment



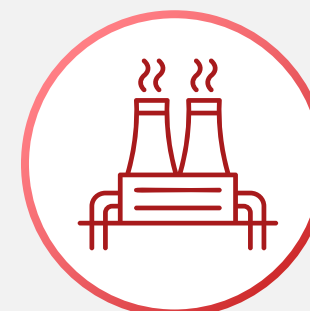
Rotating equipment leads to higher maintenance costs



Efficiency decreases beyond 100 °C, and cannot deliver >160 °C



Potential for high GWP<sup>1</sup> refrigerant leaks



Extensive electrical infrastructure upgrades may be required



# Electric Resistance

Renewable Thermal Technology



# 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<sup>4</sup>



Electric furnaces<sup>5</sup>



Electric boilers<sup>6</sup>



Electric air heaters<sup>7</sup>

*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 °C
  - 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<sub>2</sub>/MMBtu (VT) to 358 kg CO<sub>2</sub>/MMBtu (HI) depending on grid mix and system efficiency <sup>1</sup>
- **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 °C 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  |                  |         |                                             |

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 manufactures 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.

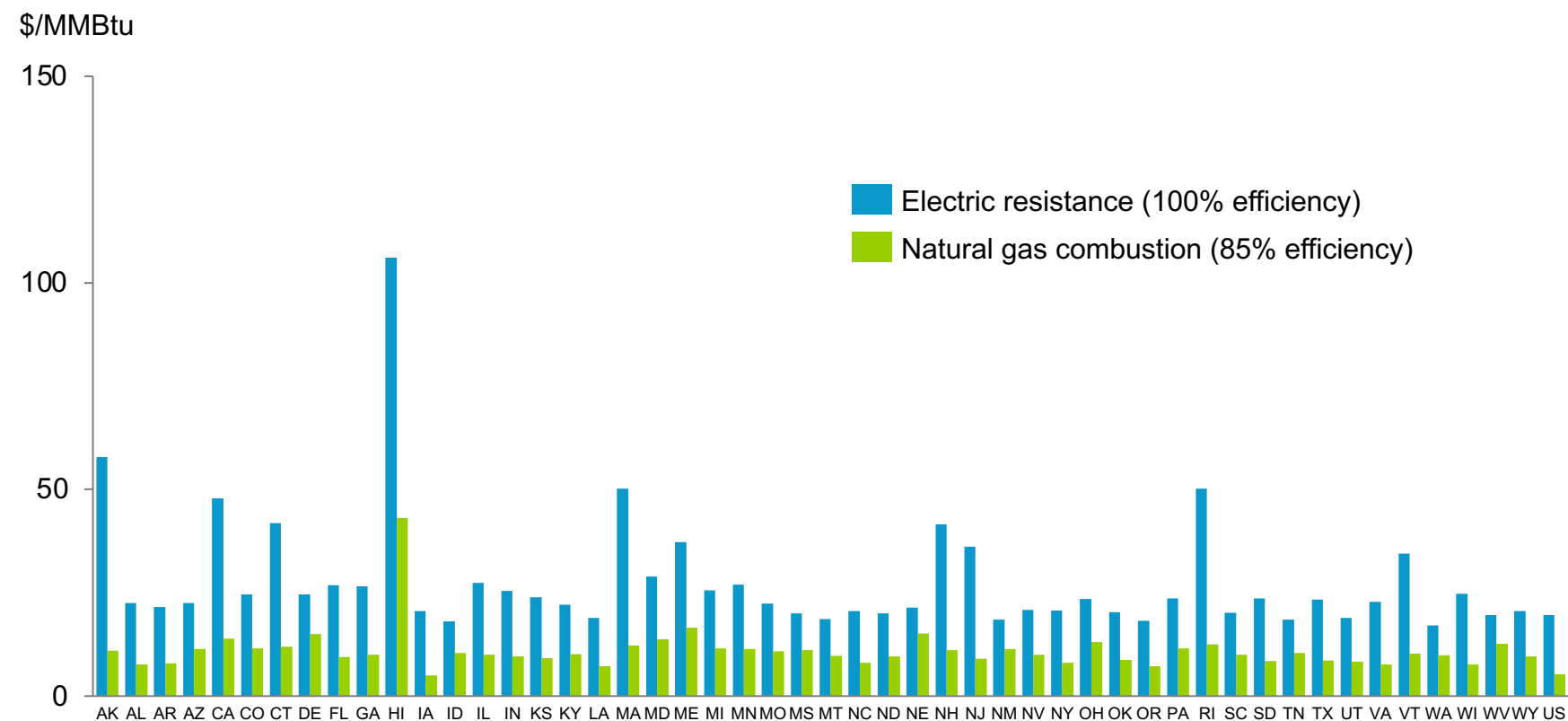
Initially, the boilers will operate with electricity purchased from the local grid. Norsk Hydro is examining options to acquire green electricity to power the boilers.





# 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,

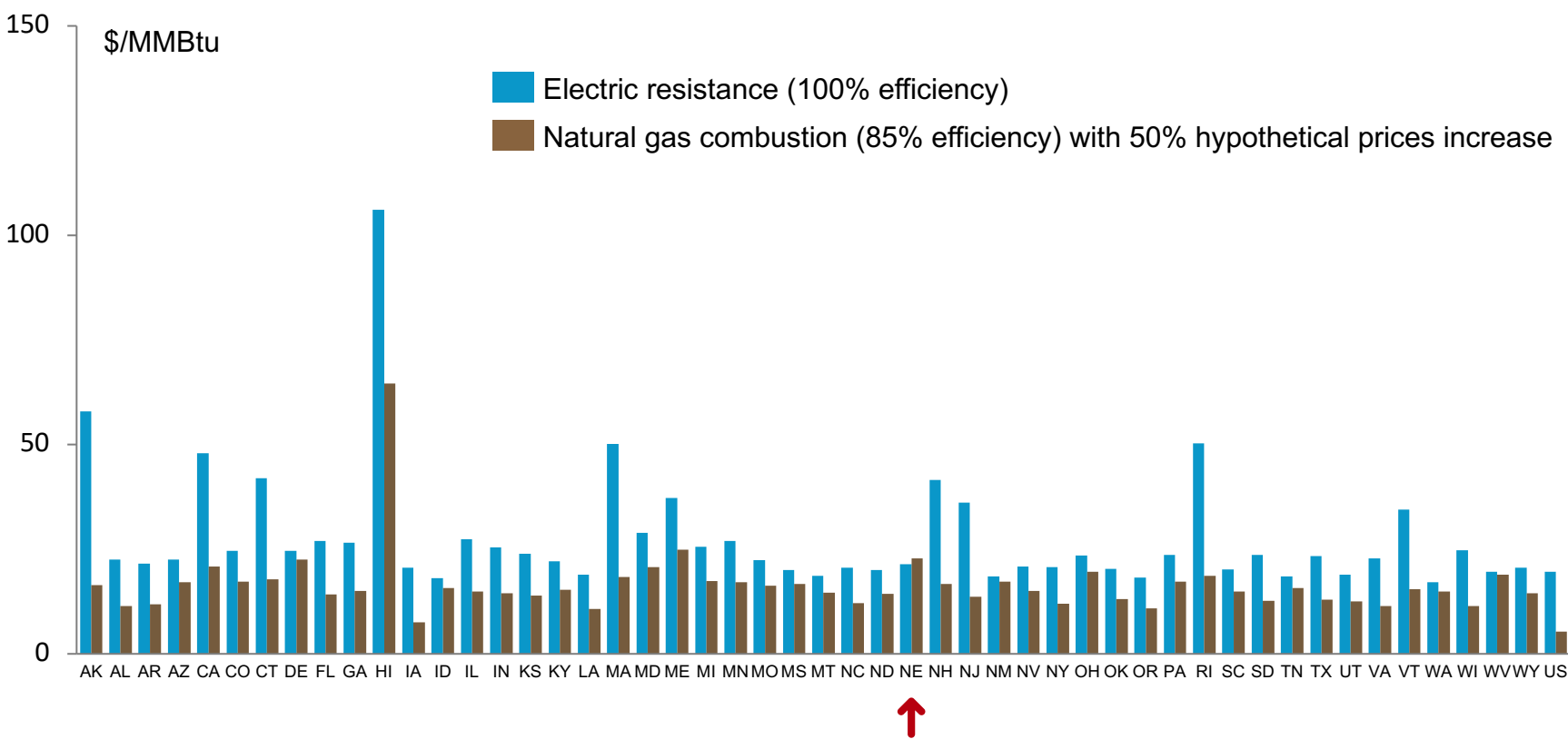
- Significant incentives must be provided to users of electric heating or
- Natural gas prices or tariffs need to increase substantially

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



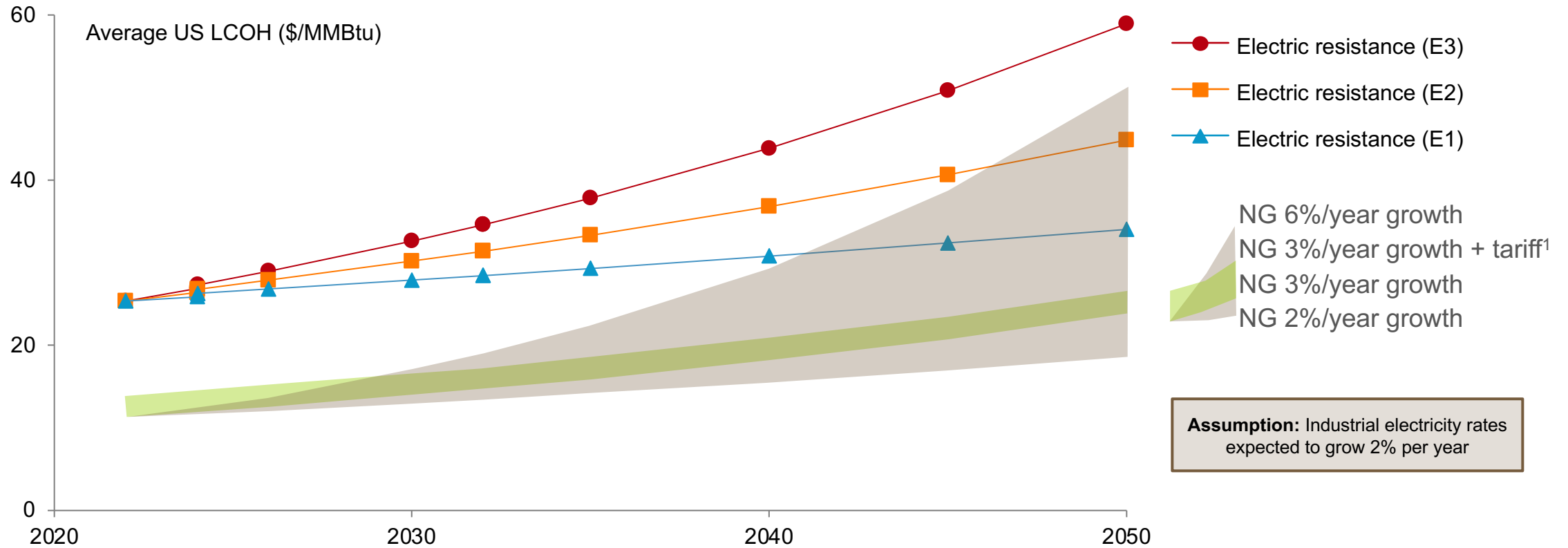
Electric resistance industrial heating using grid electricity is likely more expensive relative to natural gas

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

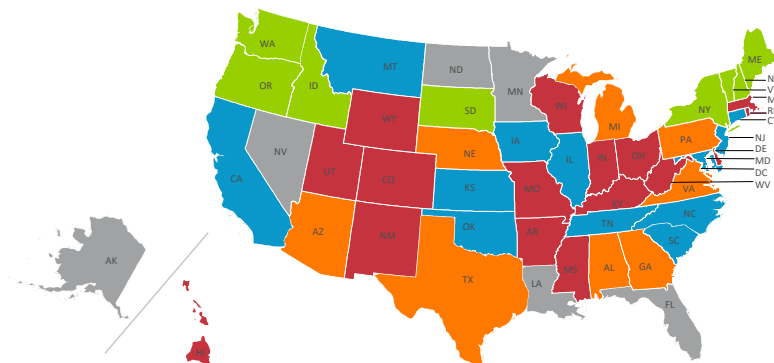


1. Based on \$51/tonne CO<sub>2</sub> social cost of carbon  
Note: Subsidized are shown in plots, subsidized and unsubsidized LCOHs are within 5%

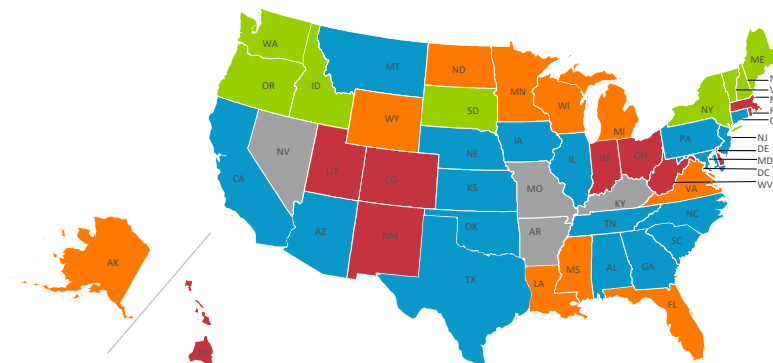


# In all scenarios by 2026, more than half of states may be able to reduce emissions by switching to electric resistance heating

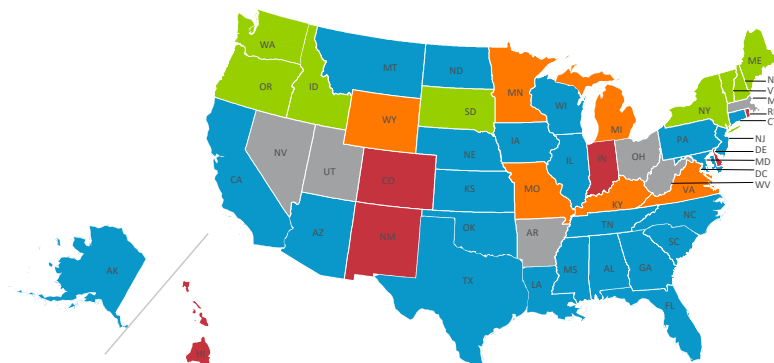
**Scenario 1: 80% renewables by 2050**



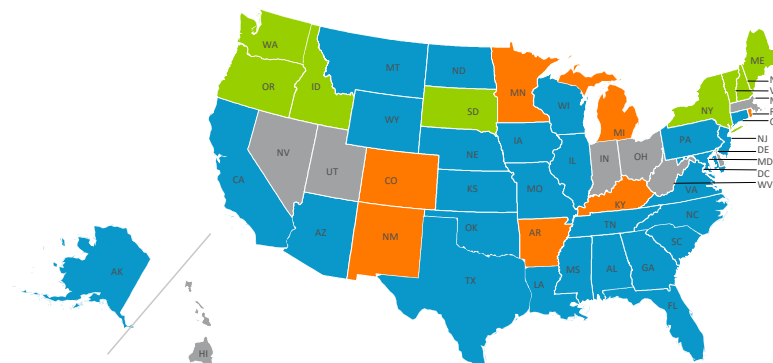
**Scenario 2: 65% renewables by 2030**



**Scenario 3: 80% renewables by 2030**



**Scenario 4: Near 100% renewables by 2035**



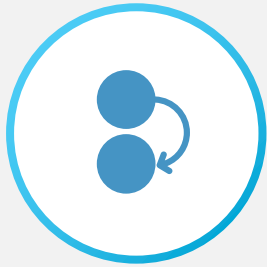
Likely reduction in emissions by switching from natural gas combustion<sup>1</sup> to electric resistance heating:

- Today
- By 2026
- By 2030
- By 2035
- Beyond 2035

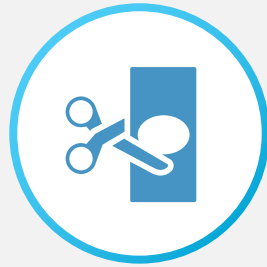


# Solar thermal industrial heating has several advantages, but faces several major hurdles to adoption

## Advantages



Minor modifications from combustion system



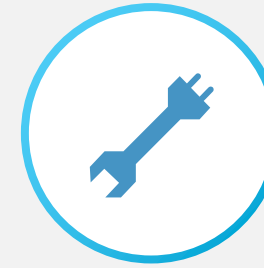
Capital costs equal to or below combustion



Precise control of temp. and heat input



Approaches 100% efficiency



Low maintenance requirements

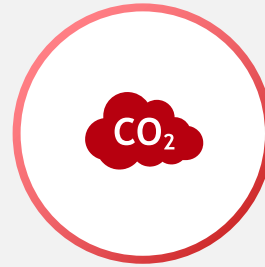


Improved health & safety due to lack of combustion

## 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



# 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<sub>2</sub> to produce methane (CH<sub>4</sub>). 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<sup>1</sup>



Gas furnaces<sup>2</sup>



Gas boilers<sup>3</sup>



Gas air heaters<sup>4</sup>

*Note: Example equipment not exhaustive*

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

## Technical characteristics

- **Temperature range:** Up to 1,950 °C
  - 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





# 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 °C max. temp.
-  High heat flux
-  Heats all materials

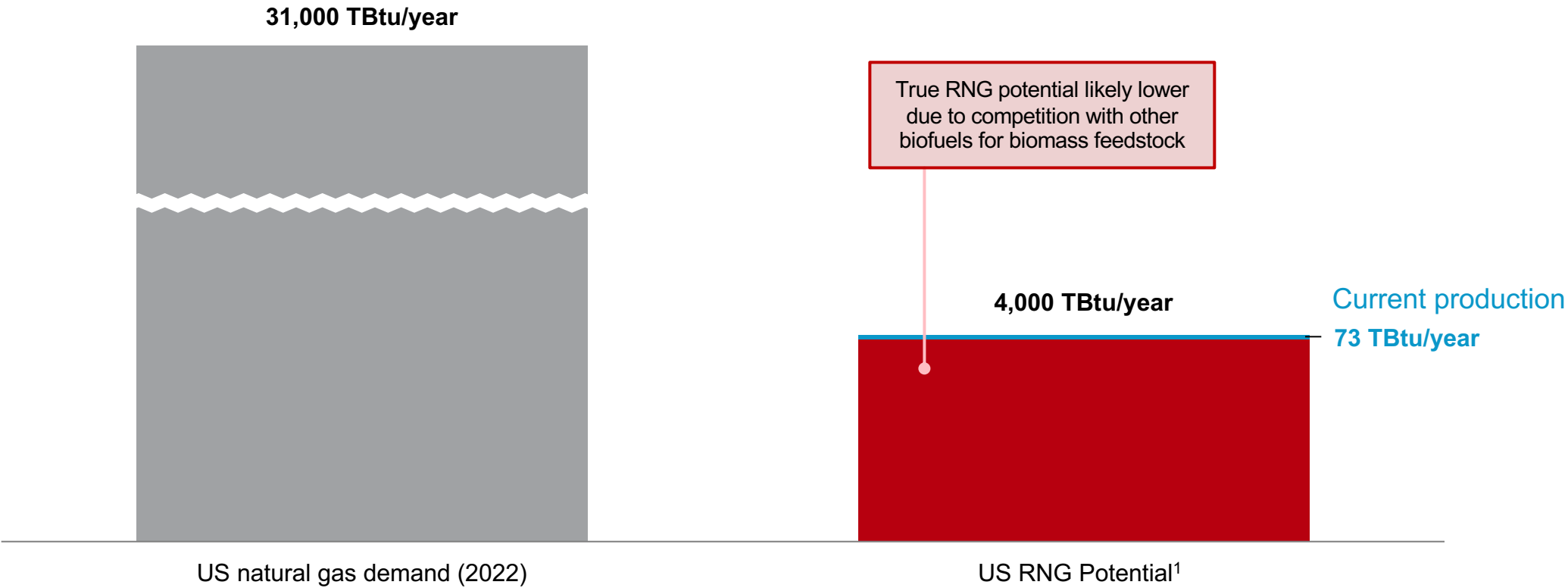
These properties align with requirements for several process heating applications.

| 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

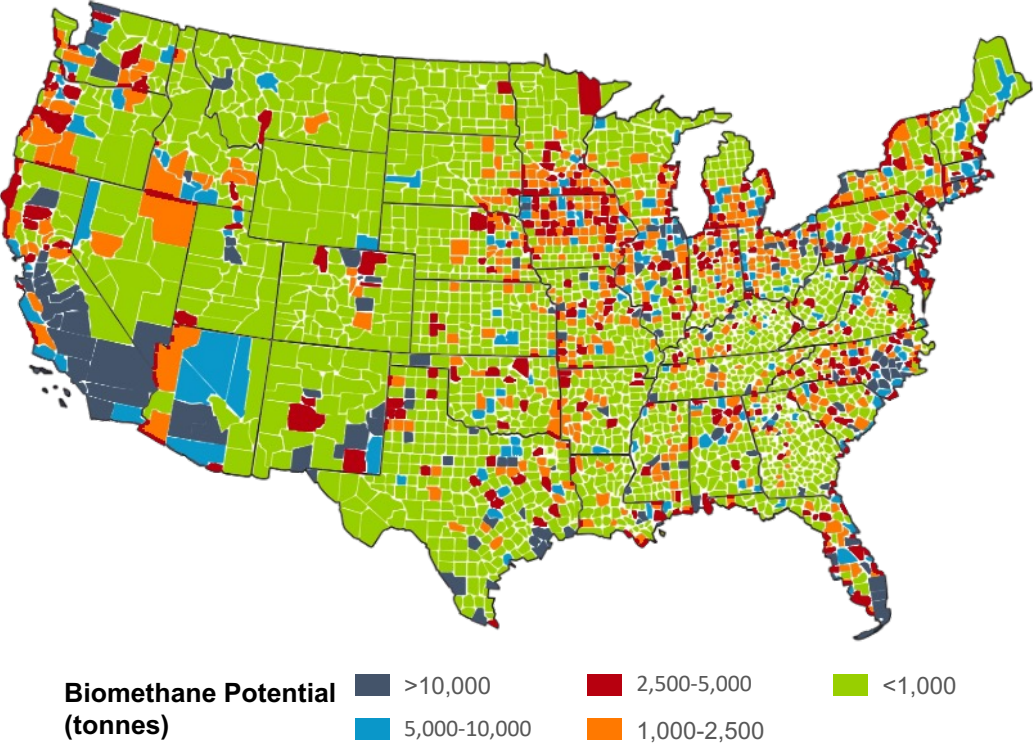


1. Assumes lignocellulosic biomass resources are used, does not account for competing uses (e.g., other fuels, power generation)  
Source: EIA, IEA, EPA, Argonne National Laboratory, MJB&A, California Bioenergy, BCG analysis

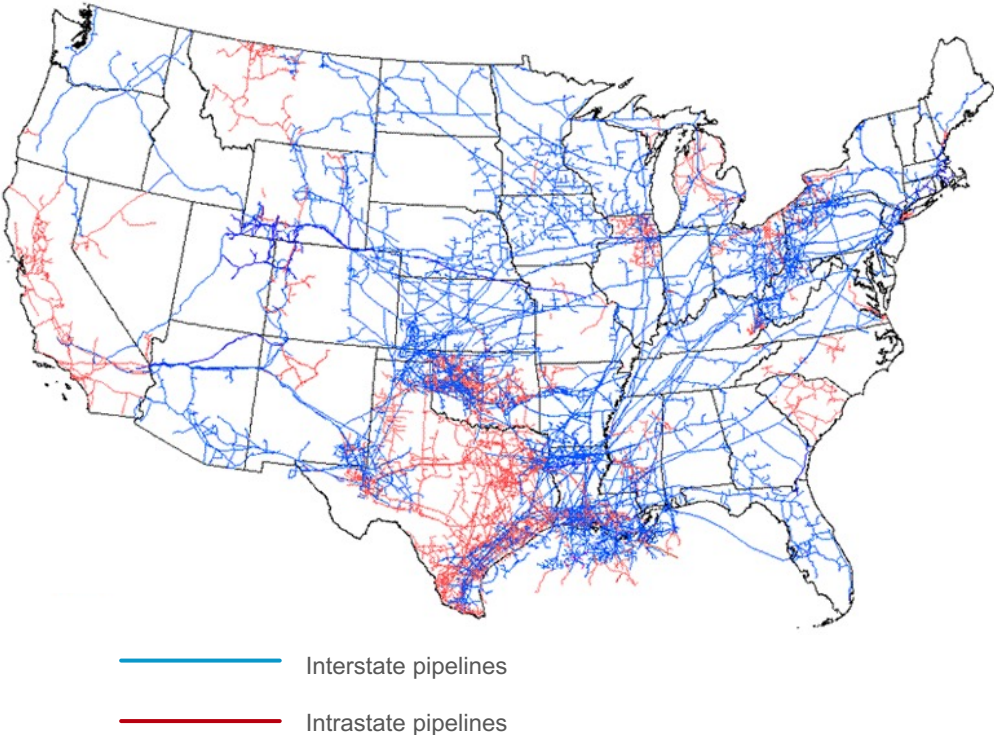


# RNG is likely to be consumed locally or regionally since RNG supply potentially does not directly align with existing gas pipeline infrastructure

Biomethane supply potential



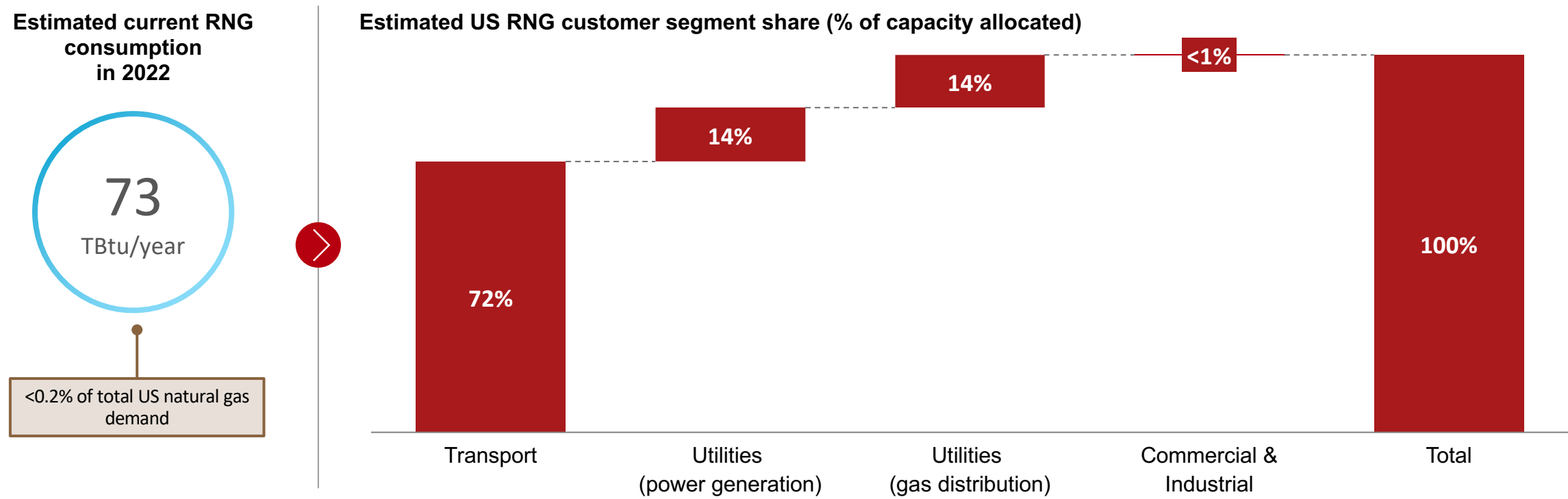
Interstate and intrastate natural gas pipelines



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

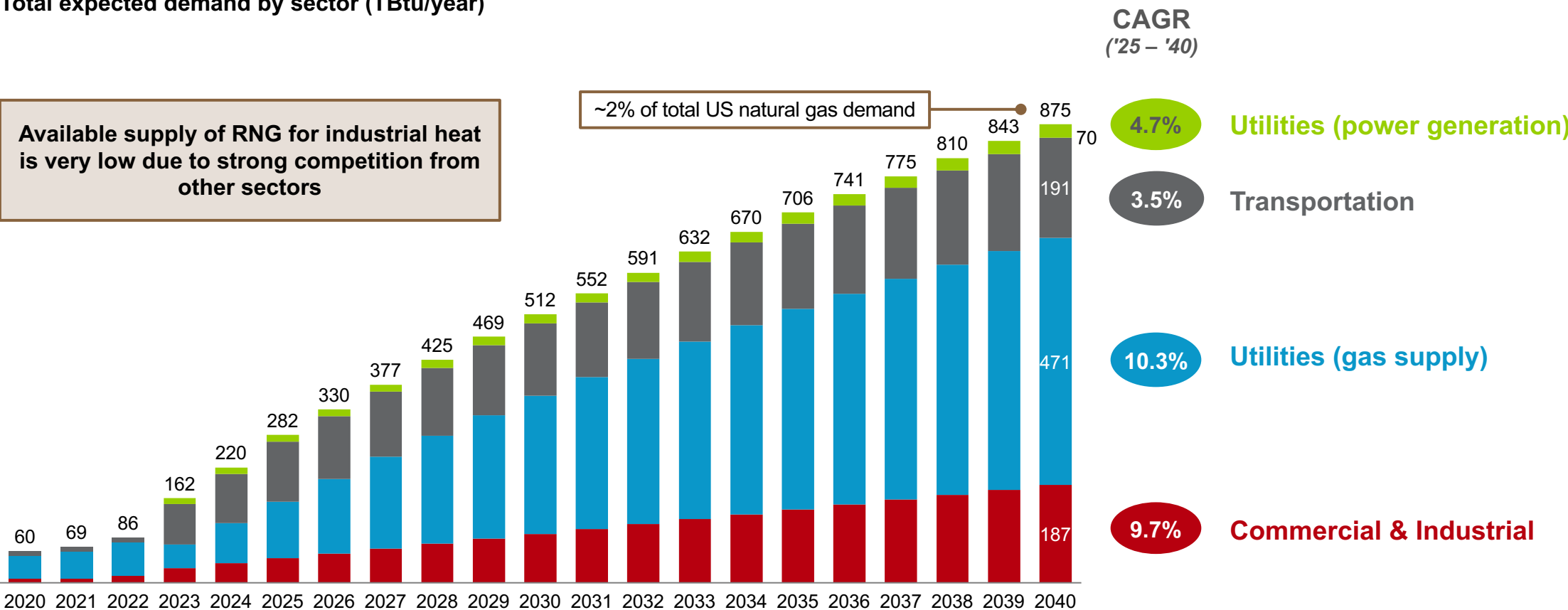


Includes LFG to RNG, agriculture sourced RNG, and wastewater sourced RNG; Projects without reported capacity estimated using benchmarks from the EPA and other sources listed below  
Source: IEA, EPA, Argonne National Laboratory, MJB&A, California Bioenergy, BCG analysis



# 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)

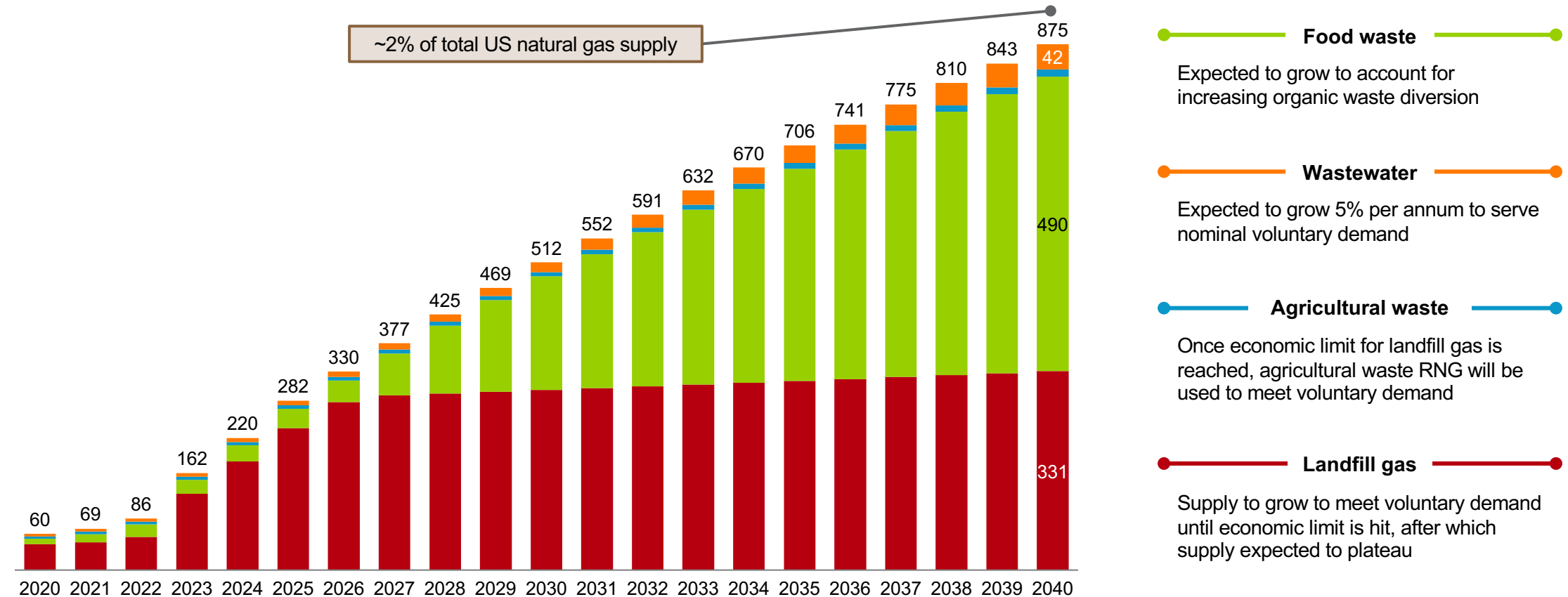


Source: BCG Analysis





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

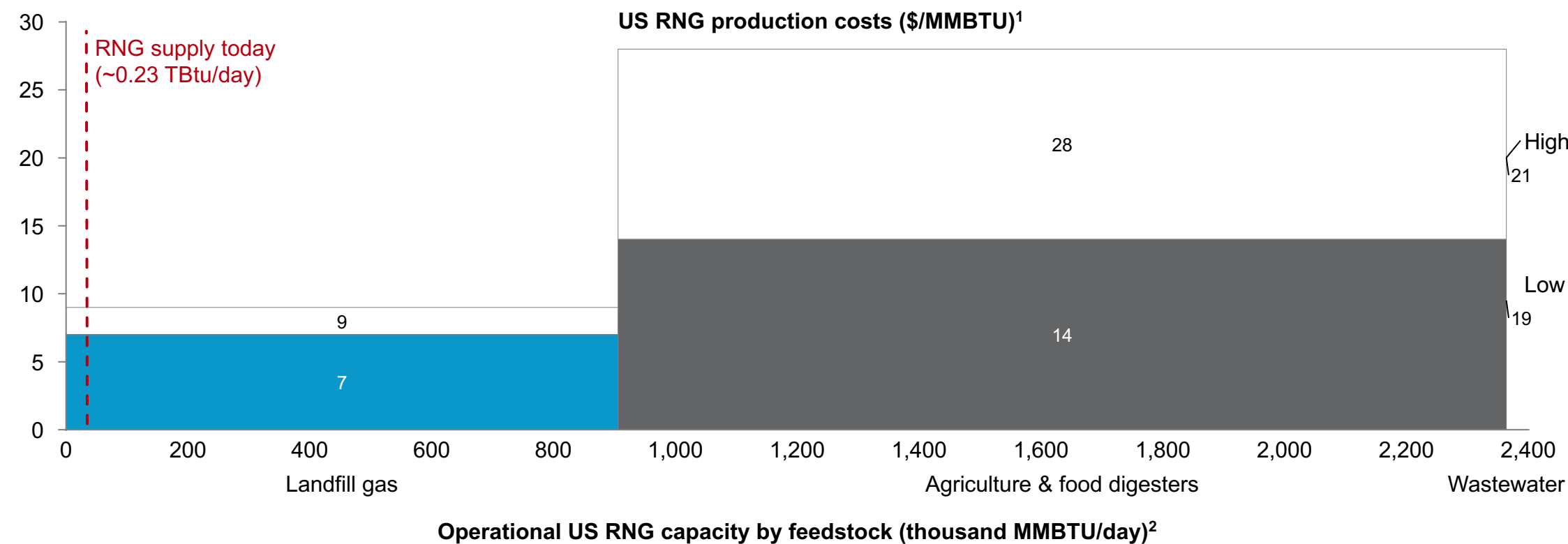


Source: BCG Analysis



# 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

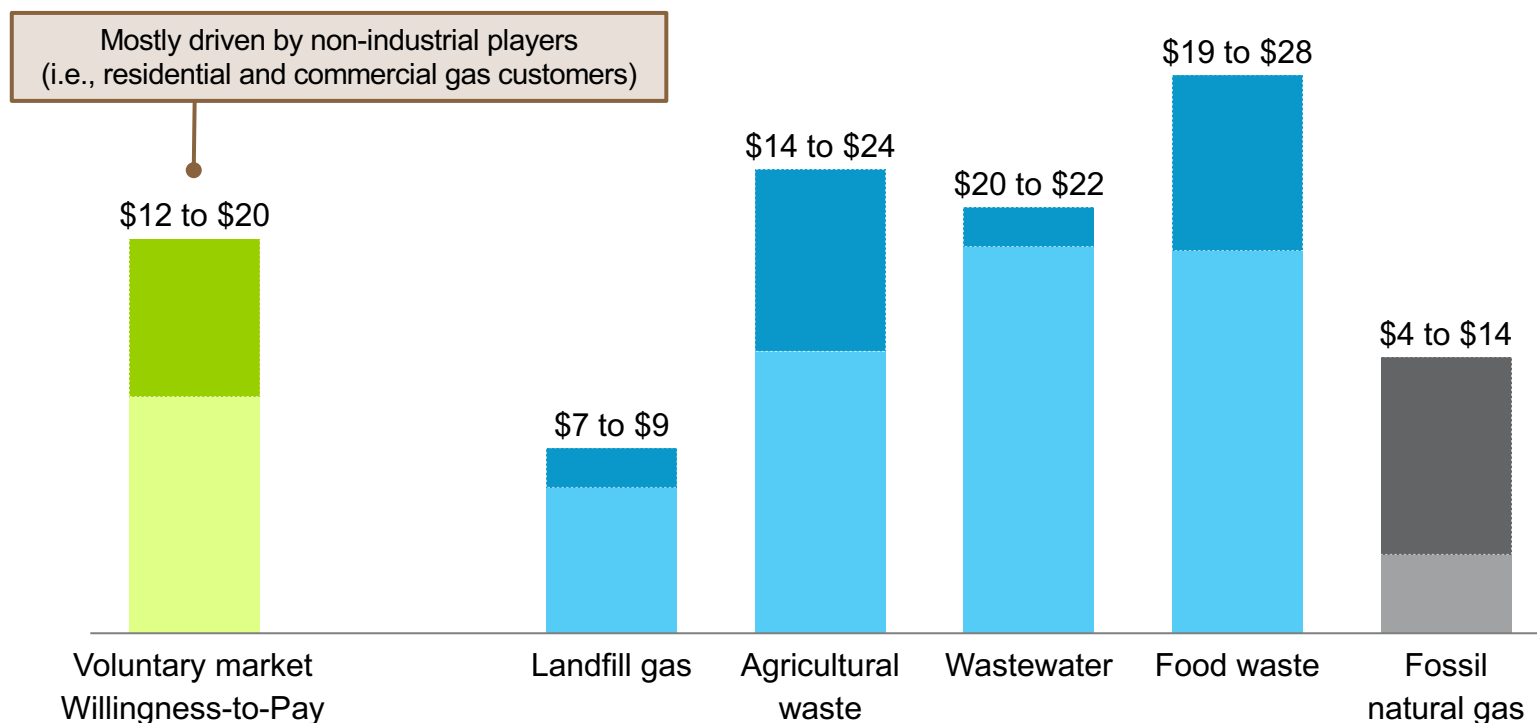


1. Cost ranges include biogas production, upgrading, and interconnection; Derived from IEA averages. 2. Includes LFG to RNG, agriculture sourced RNG, and wastewater sourced RNG; Projects without reported capacity estimated using benchmarks from the EPA and other sources listed below.  
Source: IEA, EPA,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

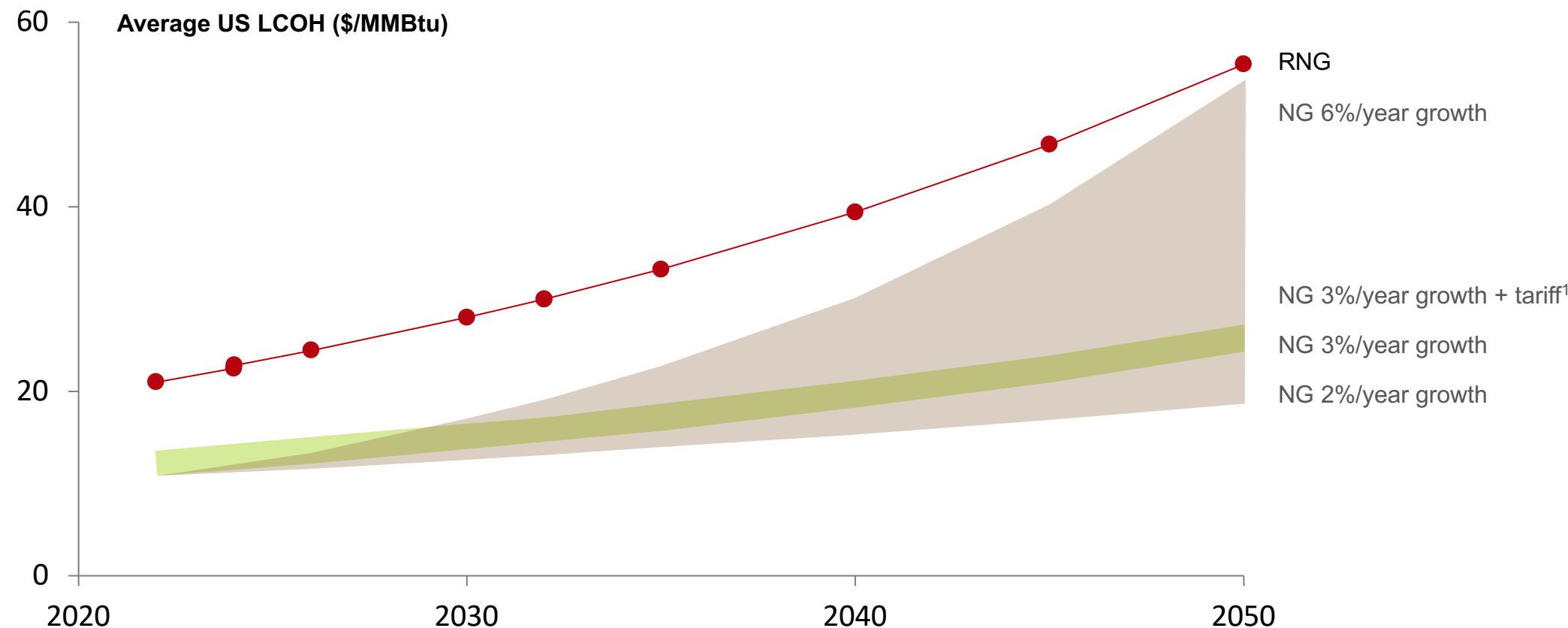


### Policymakers can make RNG more cost competitive by

- 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



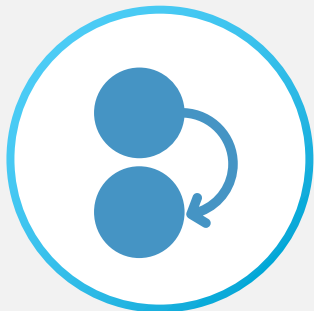
1. Based on \$51/tonne CO<sub>2</sub> social cost of carbon

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%.



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

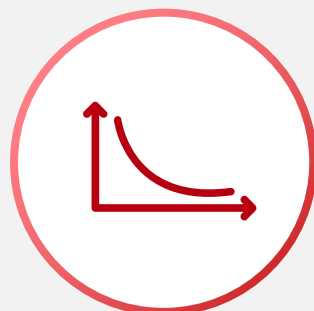
## Barriers



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



# Technology Overview

## Description of technology

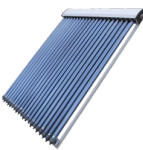
- Solar thermal technologies captures radiant solar energy and directly converts it to heat, which can be stored or used in industrial applications
- There are 2 main types of solar thermal technology
  - Non-concentrating
  - Concentrating
- Concentrated Solar Power (CSP) generates electricity using 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

## Technical characteristics

- **Temperature ranges:** Practically up to 500 °C
  - Non-concentrating: Up to 100 °C
  - Concentrating: Theoretically up to 1,200 °C
  - Molten salt thermal storage: Theoretically up to 560 °C
- **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

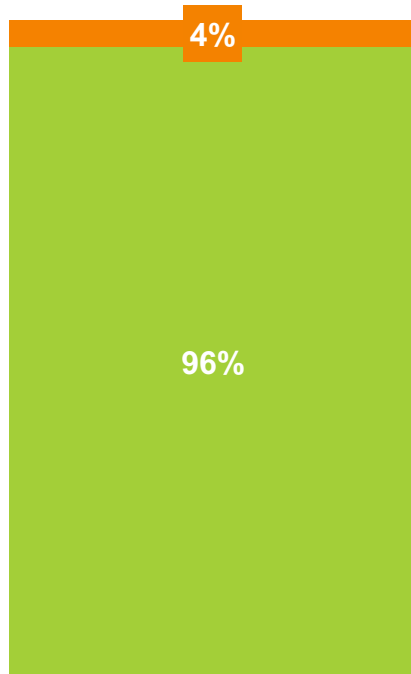




# While total US solar energy use has grown rapidly in the last two decades, solar thermal currently constitutes a small proportion

## Total solar energy in US (2021)

1,500 TBtu



### 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



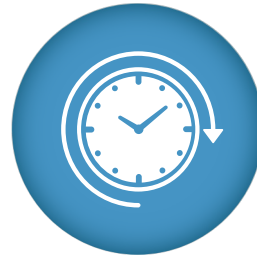


# Technical viability of industrial solar thermal technologies depends on the alignment of three key factors



## 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





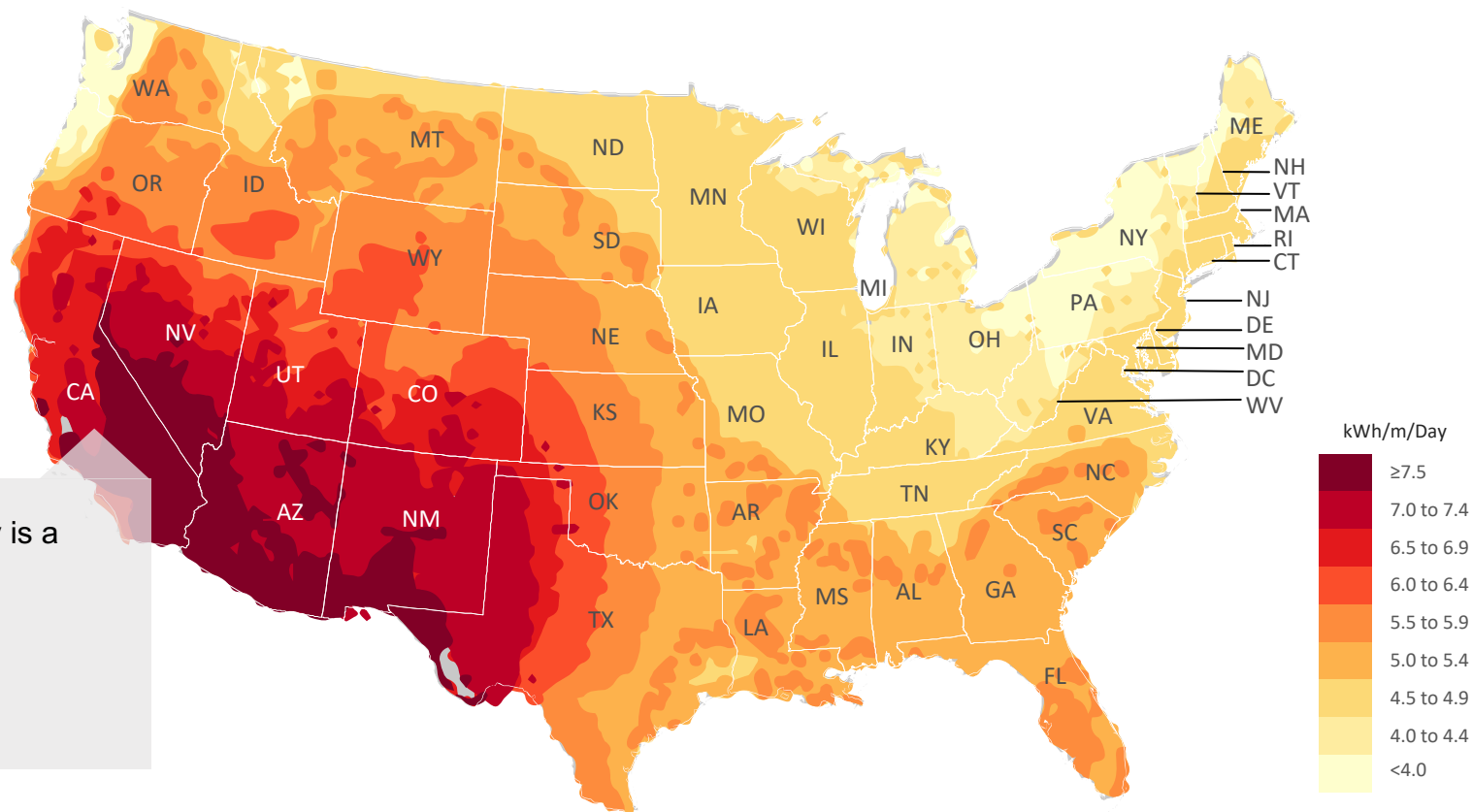
# Spatial | Within the US, the Southwest has the highest level of annual solar irradiation

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:

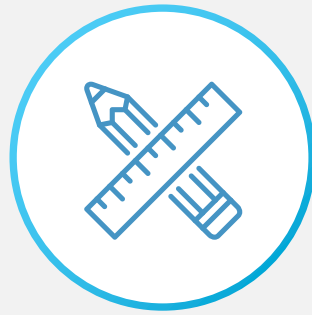
- Rich solar resources
- Potentially available land
- Thermal demand from food and agricultural sectors



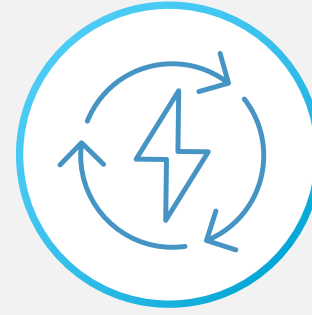


# Temporal | Intermittency of heat supply is a major limitation of widespread solar thermal technology deployment in industry

**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

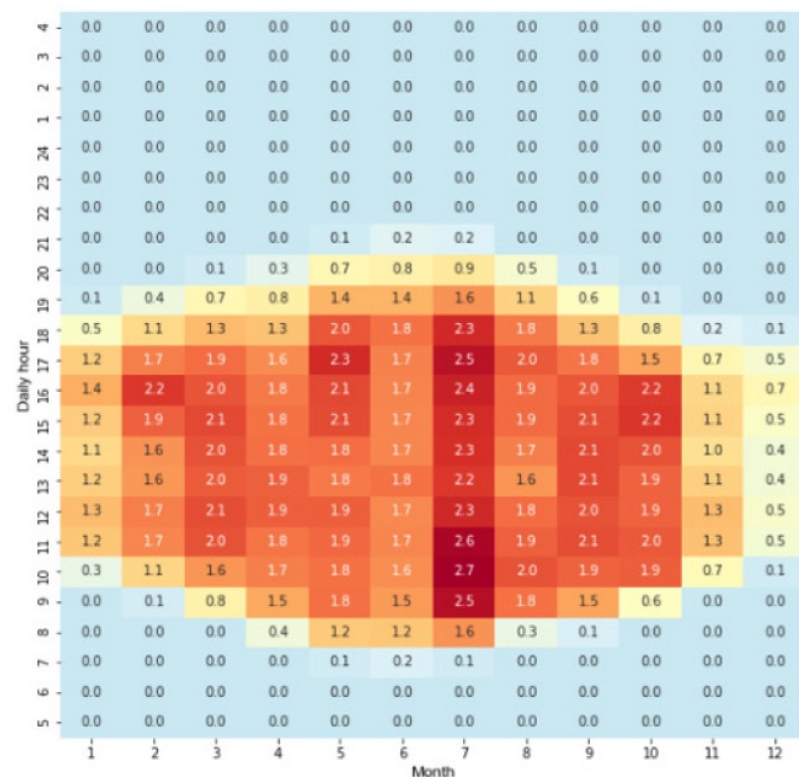


Deployment of thermal energy storage

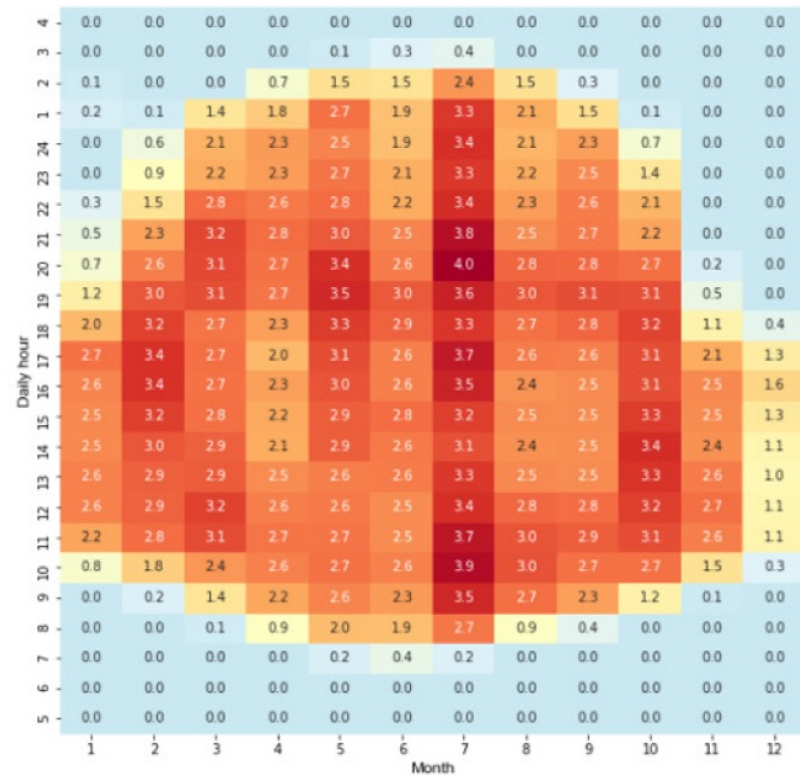


# Temporal | Thermal energy storage can provide substantially more process heating potential beyond the limited hours of high solar irradiation

Example solar fraction<sup>1</sup> of a parabolic trough collector (PTC) system in Polk County, IA



PTC without thermal storage



PTC with 6 hours thermal storage (28% greater)

1. Potential contribution of solar energy to the total load  
Source: NREL

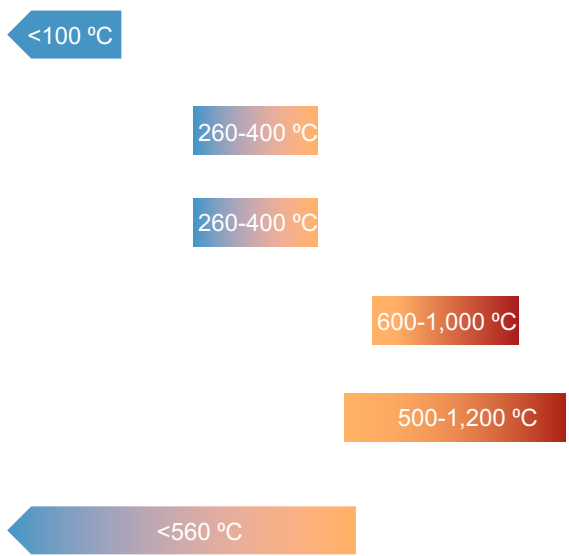


# Temperature | Non-concentrating solar thermal can provide up to 100°C, while concentrating solar thermal can deliver up to 1,200 °C

## Solar thermal technology

- Non-concentrating
- Parabolic trough
- Linear Fresnel
- Power tower
- Parabolic dish
- Molten salt storage

## Operating temperatures



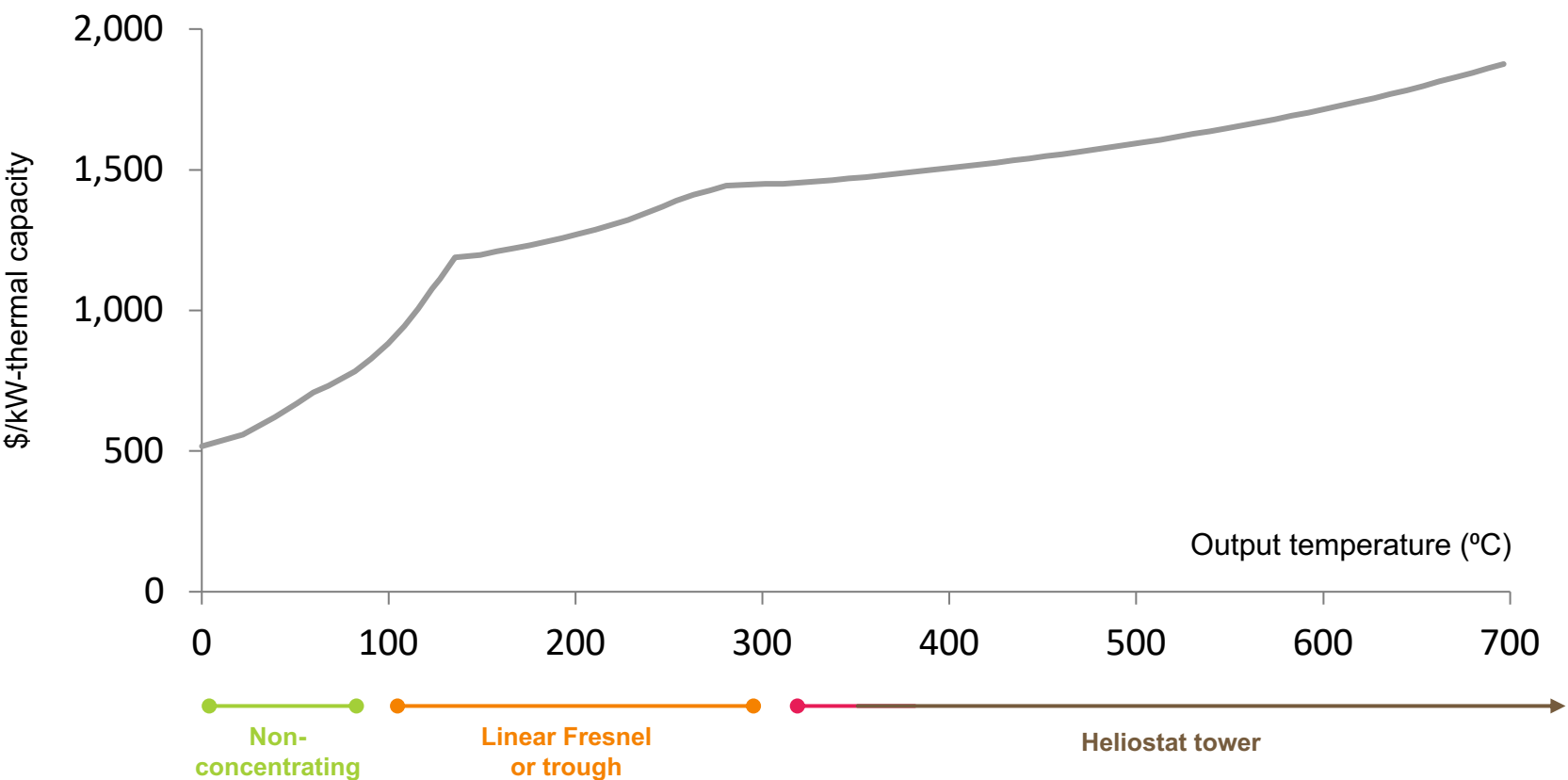
## Characteristics of solar thermal performance

- 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



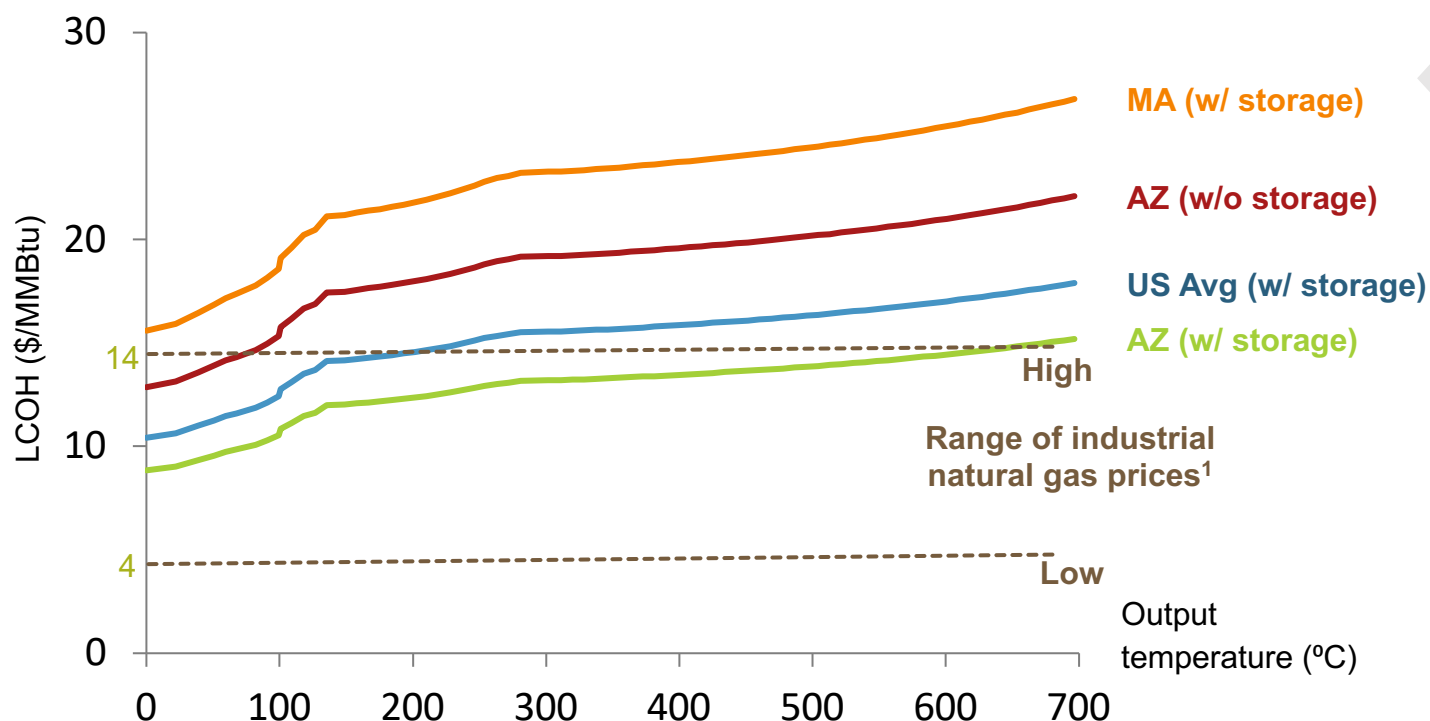
Solar thermal heating cost **increases with output temperatures**





# 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

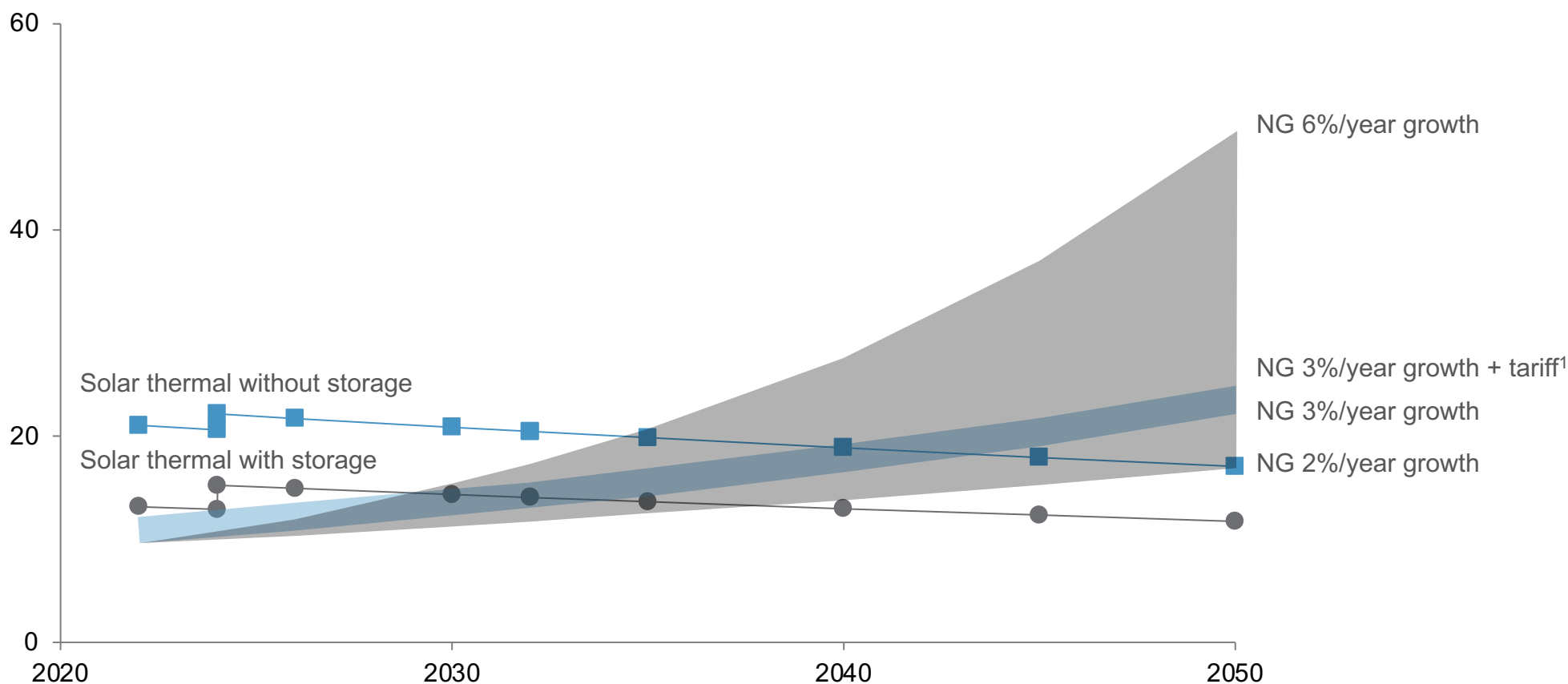
Notes: Does not include cost for land use. Uses solar thermal power plant estimates (central receiver tower with heliostats) with power generation equipment removed for LCOH calculation.

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)

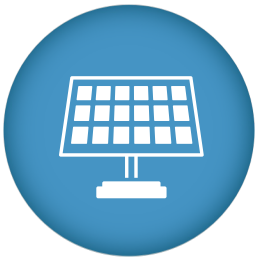


1. Based on \$51/tonne CO2 social cost of carbon

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<sup>1</sup> or CSP<sup>2</sup> 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

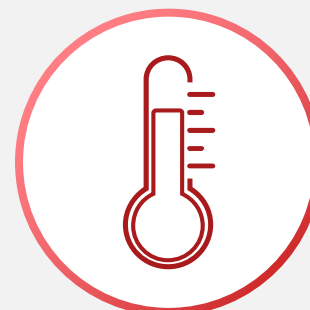
## Barriers



Geographically constrained to high insolation areas



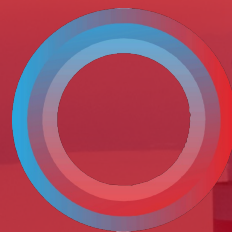
Large footprint



Limited to low and medium temperature applications



Seasonal and diurnal intermittency leading to risk of process disruption



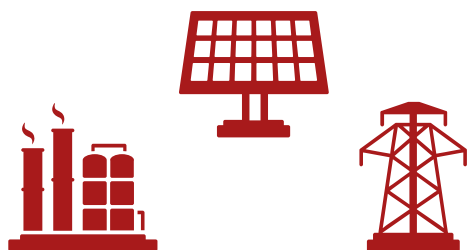
# Thermal Storage

Renewable Thermal Technology





# 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

### Solid

- **Materials:** rock, sand, ceramic, metals
- **Temperature:** Up to 1,500°C delivered
- **Cost:** Low
- **Applicability:** Large utility or industrial scale thermal storage
- **Maturity:** High

*Focus of this fact base*

### Liquid

- **Materials:** water-based, thermal oils, molten salt, molten metal
- **Temperature:** Up to 1,600°C delivered
- **Cost:** Medium
- **Applicability:** Space and water heating for buildings or concentrated solar power
- **Maturity:** Medium high

## Latent (phase change)

### Solid-Liquid

- **Materials:** organic solutions, inorganic solutions
- **Temperature:** Up to 120°C delivered
- **Cost:** High
- **Applicability:** High heat storage in limited volume or rapid heat transfer required
- **Maturity:** Medium low

### Others

- **Materials:** liquid-gas, solid-gas, solid-solid crystal
- **Temperature:** Up to 175°C delivered
- **Cost:** High
- **Applicability:** High heat storage in limited volume or rapid heat transfer required
- **Maturity:** Low



# 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 °C 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                                     |

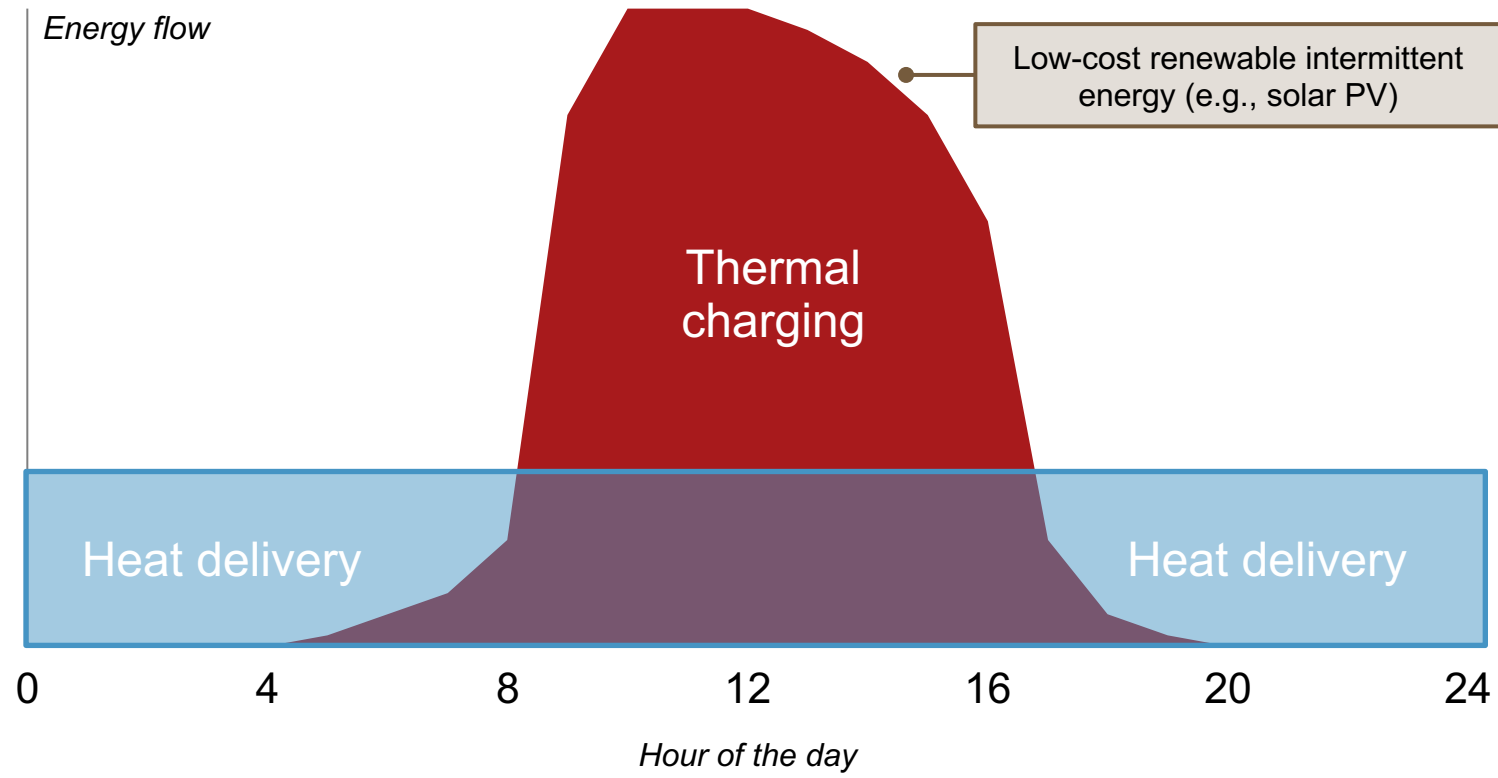
Not applicable

Potentially applicable

Currently deployed



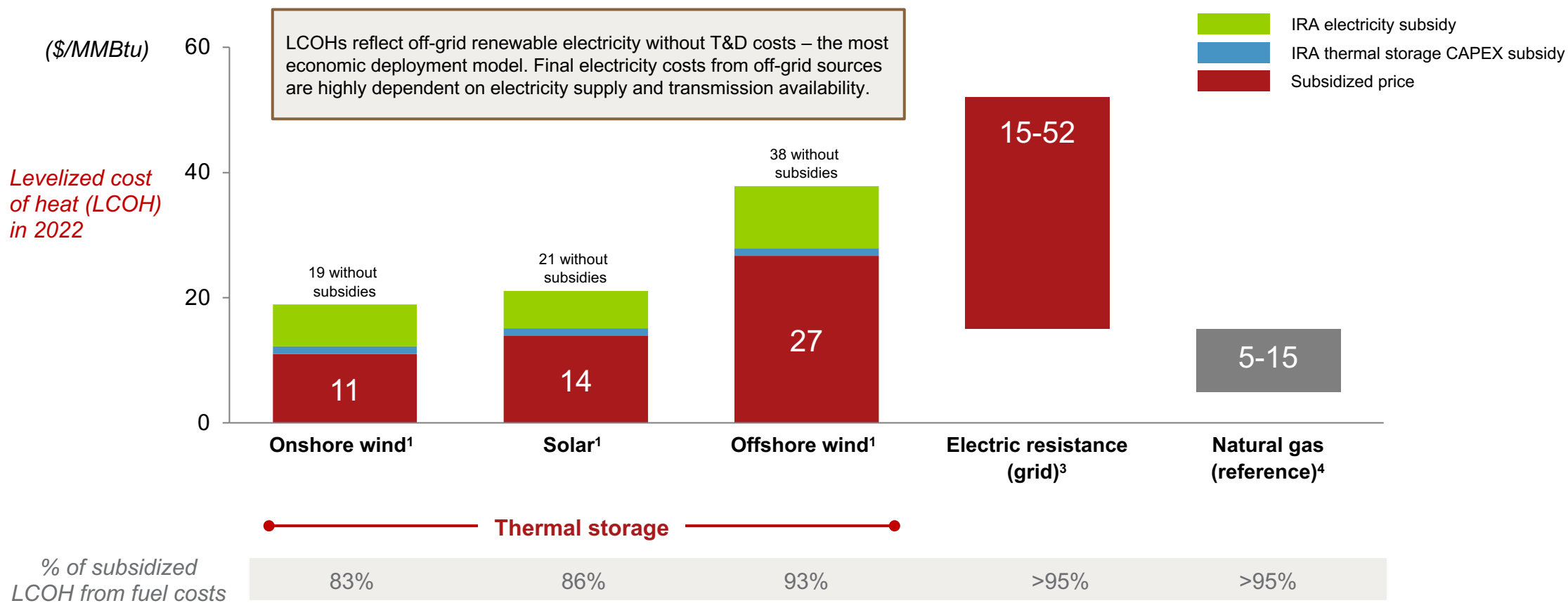
# Intermittency of low-cost renewable or waste energy is the primary driver of thermal energy storage



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

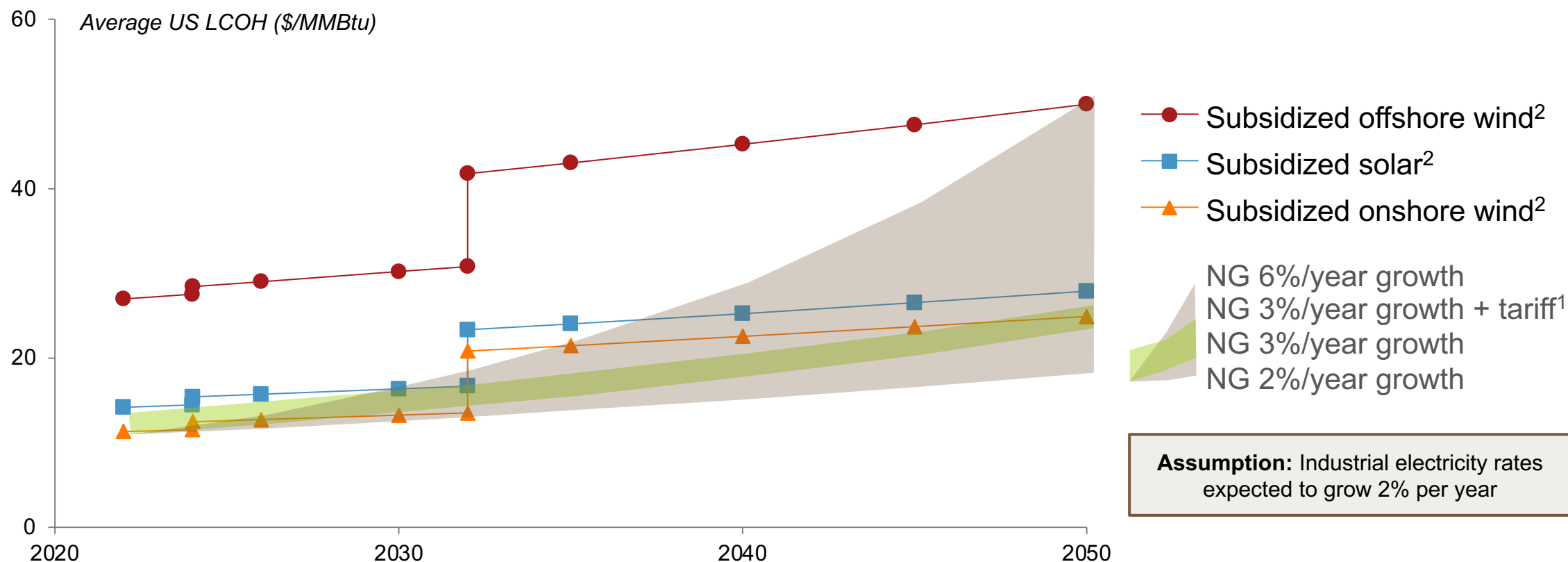


1. Thermal storage combined with electric resistance without T&D costs and with 30% IRA investment tax credits; 2. Thermal storage combined with grid electricity at industrial retail prices in May 2022 from EIA; 3. Range of industrial electricity prices in May 2022 from EIA; 4. Range of industrial natural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



1. Based on \$51/tonne CO<sub>2</sub> 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



- 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 750°C
- System is modular and is fully integrated with heat exchangers and a steam generator



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



- 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 1,500°C
- Achieves 98% efficiency with common insulation materials, and loses 2% energy per day



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





# Technology Overview

## Description of technology

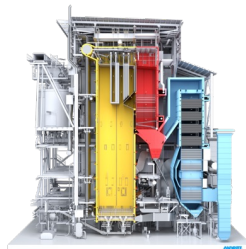
- Biomass is currently the largest source of renewable industrial heating in the US and worldwide, particularly in the wood, and pulp & paper sectors
- Direct combustion of solid biomass is the primary focus of this fact base, rather than conversion to liquid biofuels or gaseous fuels (i.e., pyrolysis)
- 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*

## Technical characteristics

- **Temperature range:** Up to 1,000 °C
  - Fixed bed boilers: 800-1,000 °C
  - Fluidized bed boilers: 760-870 °C
- **Heat flux:** High
  - Dependent on biomass combustion system and heat transfer configuration
- **Heated materials:** Most materials are applicable
- **Emissions:** CO<sub>2</sub> 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 °C max. temp.
-  High heat flux
-  Heats all materials

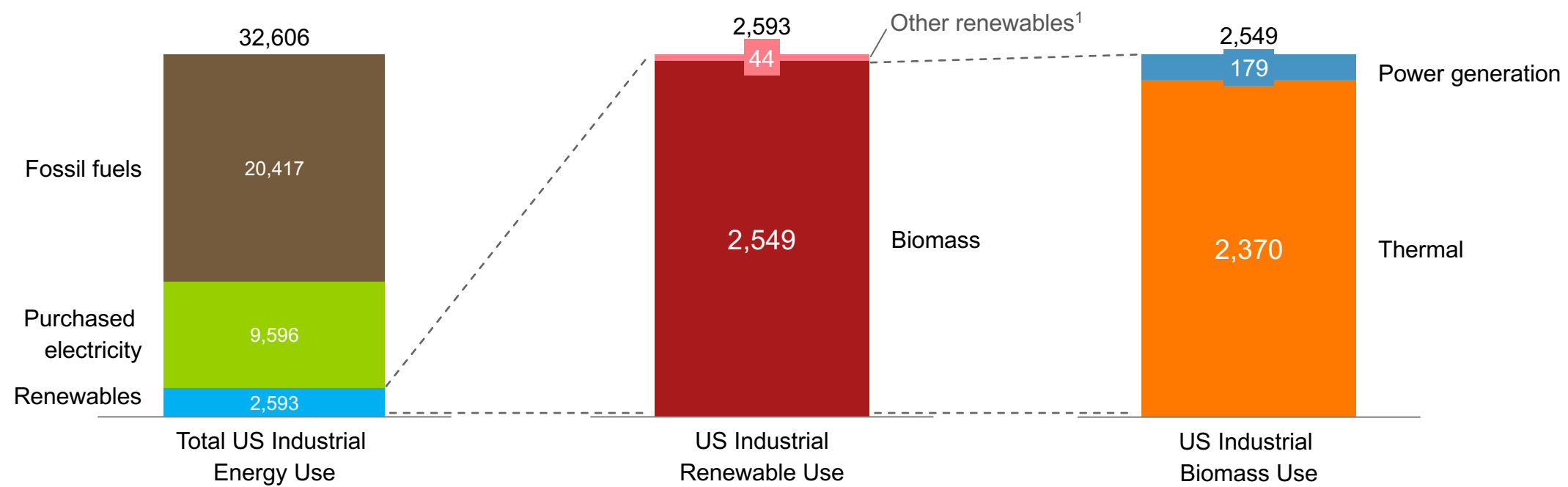
These properties align with requirements for several process heating applications.

| 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"



# 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



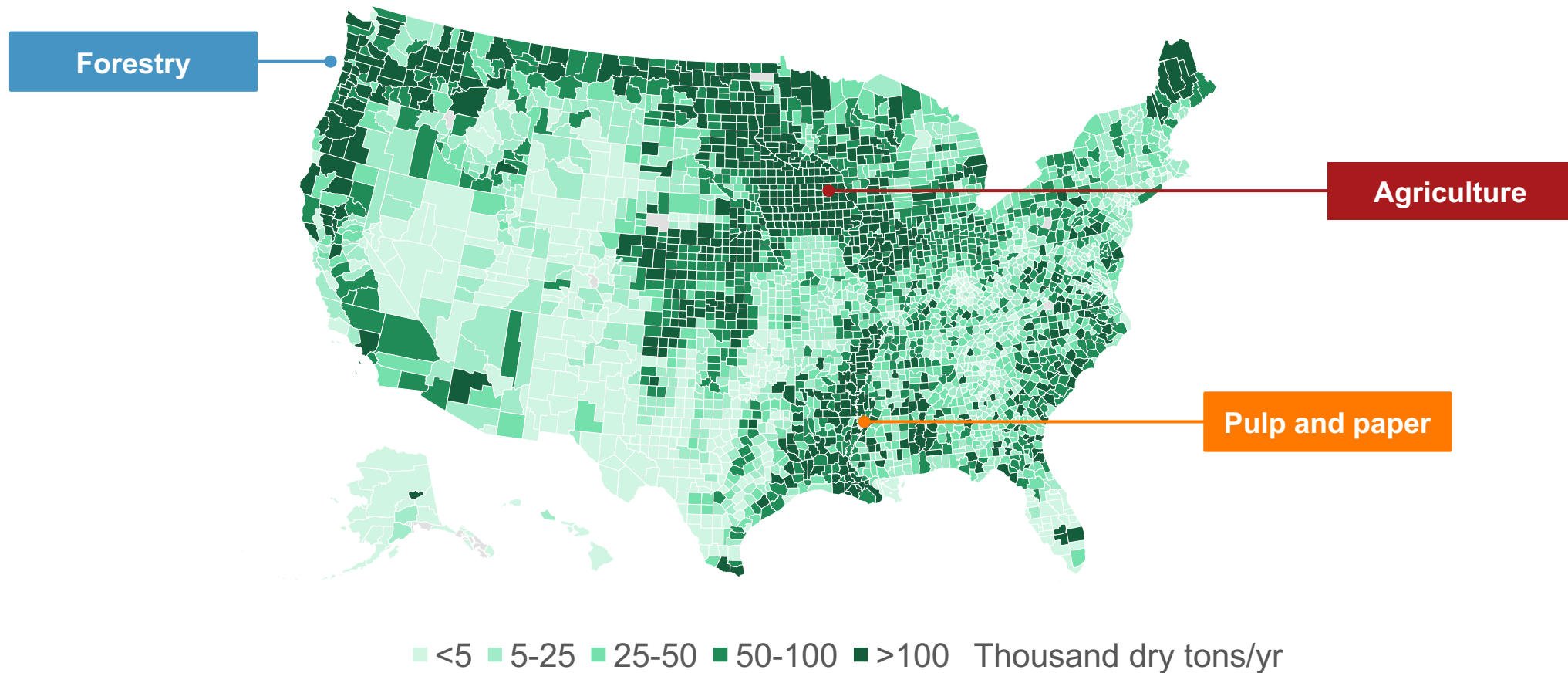
Pulp and paper



Food and agriculture

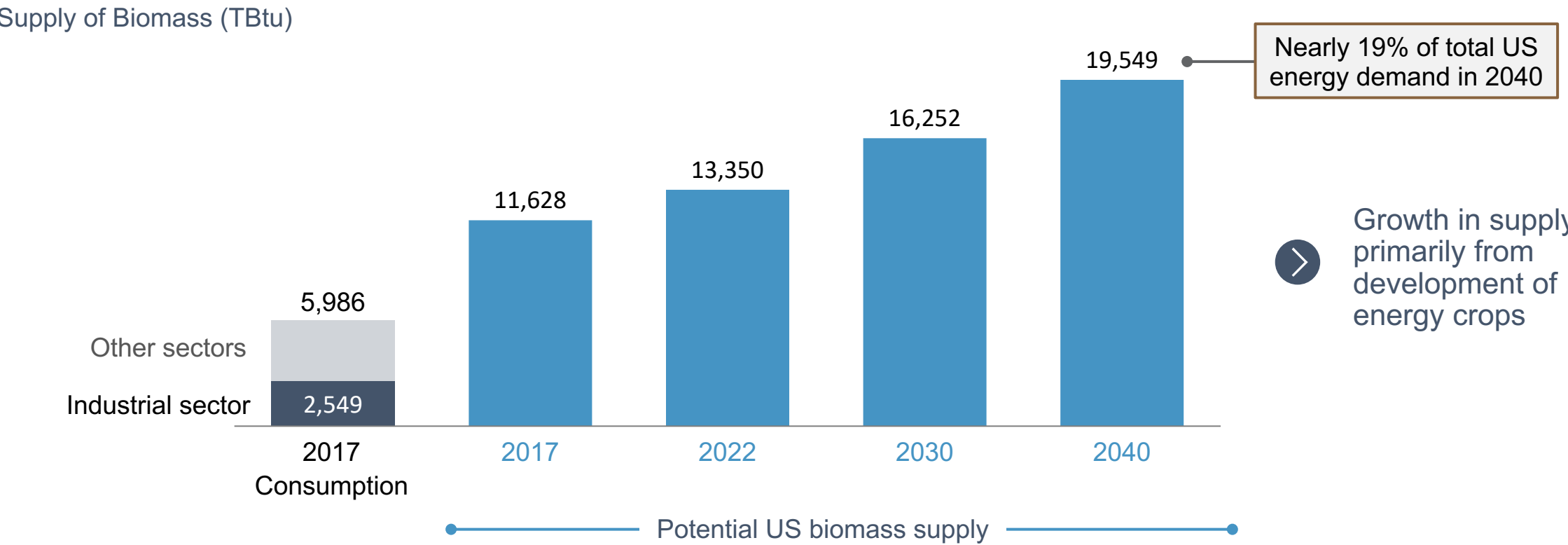


# Biomass supply in the US today is predominantly concentrated in the Midwest, South, and the Pacific Northwest due to the agriculture and forestry sectors





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



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*

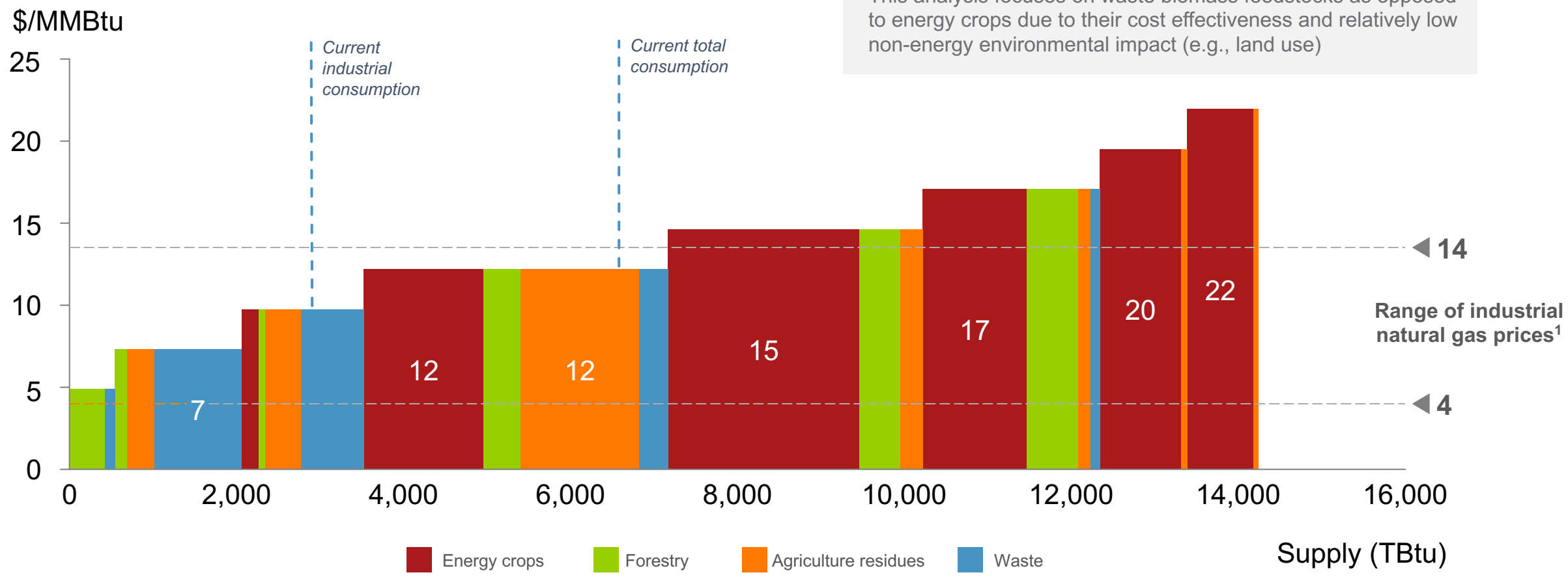


Note: Algae is not included due to its nascent nature and primary use as a feedstock for liquid biofuels



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

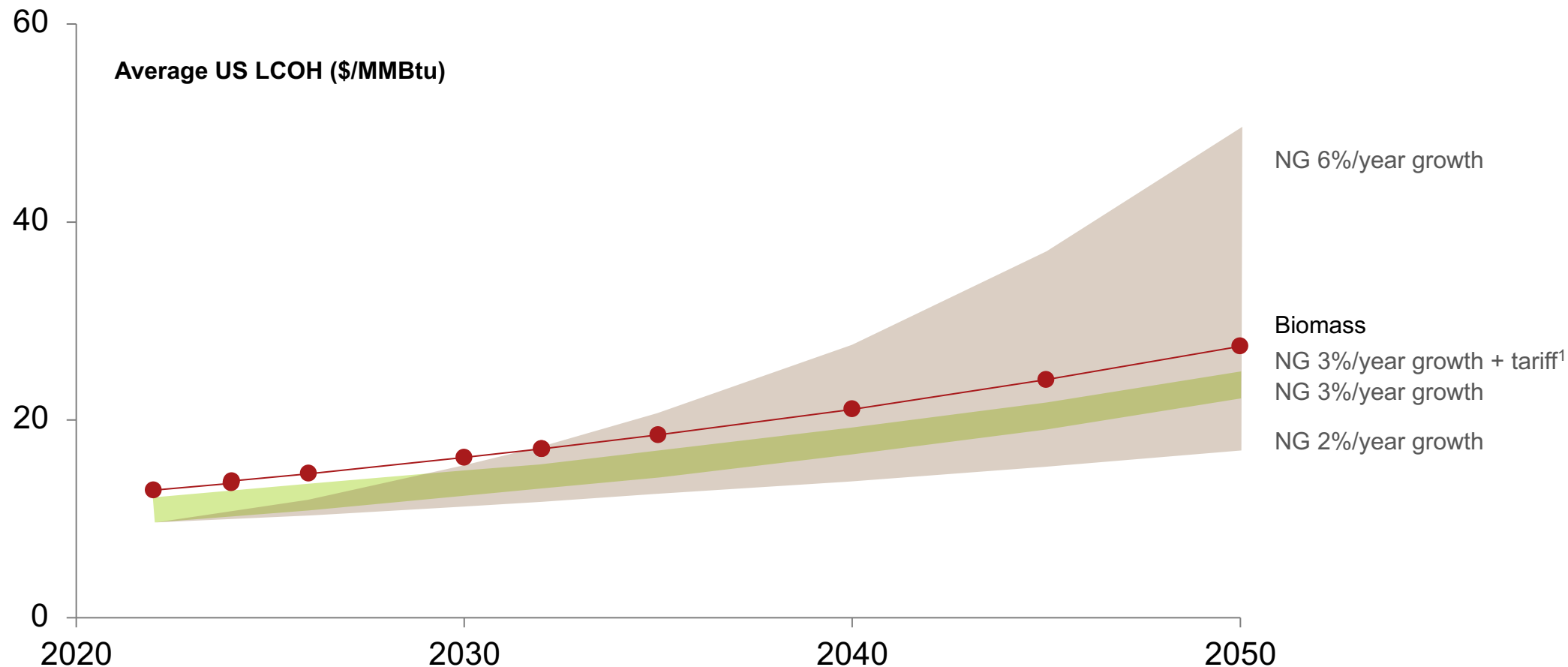
Potential Supply of Biomass by Feedstock Type (TBtu) in 2030



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 CO<sub>2</sub> 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



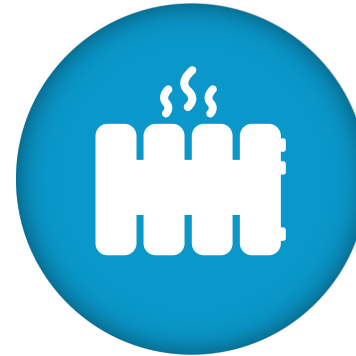
Pulp & paper feedstock

## Power generation



Electricity production

## Building heating



Space and water heating

## Transport



Liquid biofuel production

*Mature applications*

*Emerging applications*





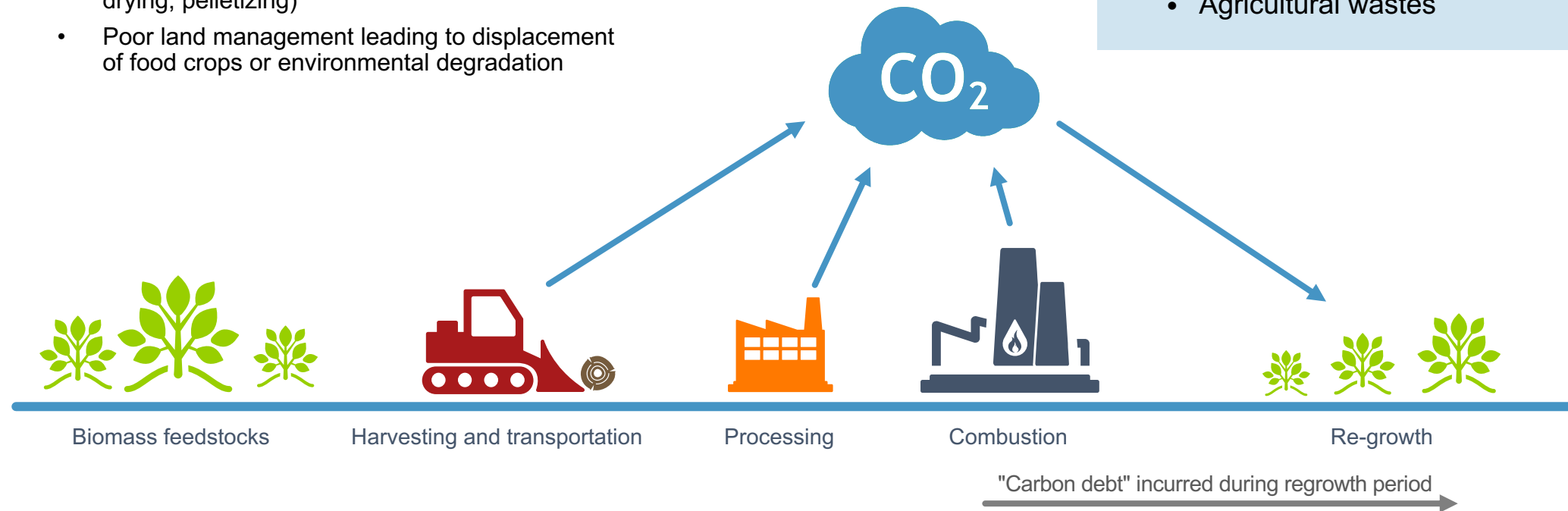
# Carbon neutrality of biomass is contentious and overall carbon footprint can range significantly depending on feedstocks, transportation, and processing

- 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**

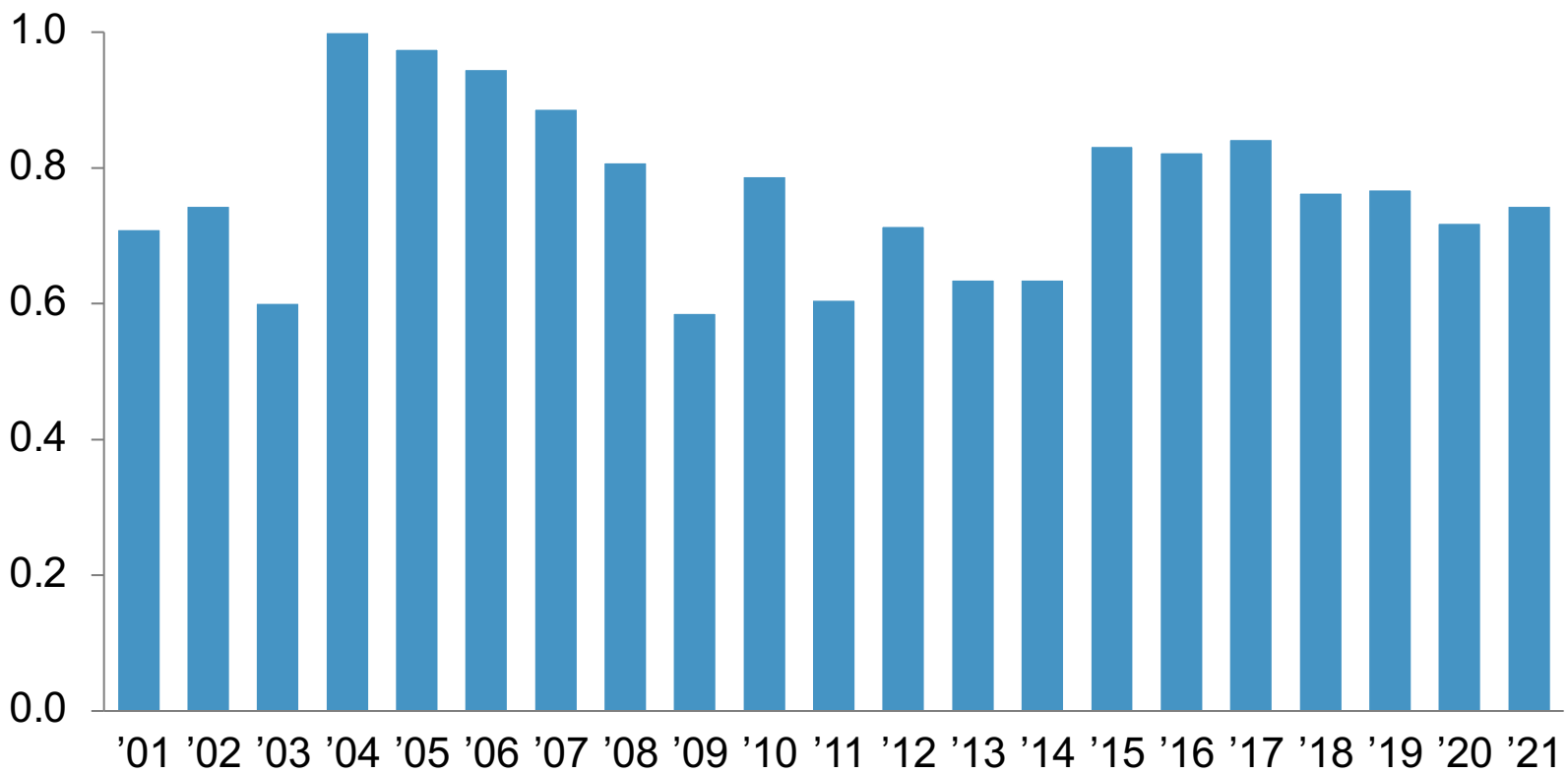
- Pulp and paper wood wastes
- Forestry residuals
- Agricultural wastes





# 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<sub>2</sub>e emissions
- > Due to changing climate conditions, the forest sector will likely become a net emitter by 2040<sup>1</sup>

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

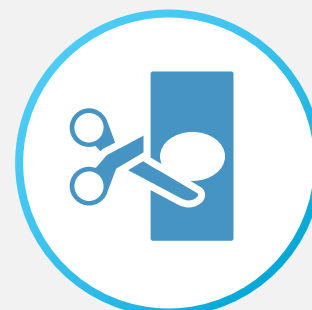
## Advantages



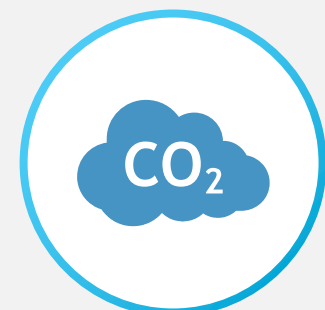
Renewable resource and theoretically carbon neutral



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